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COGNITIVE PSYCHOLOGY

A STUDENT'S HANDBOOK

MICHAEL W. EYSENCK
& MARK T. KEANE

“Eysenck and Keane have reached a remarkable and almost unprecedented seventh edition of their highly successful book, more than 30 years after the first edition so impressed teachers, researchers and students alike. This new edition has attained even greater depth and breadth on leading-edge as well as important established areas of cognitive psychology while retaining its hallmark highly readable style.”

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“No better guide to cognitive psychology for students, or other readers, exists. It is comprehensive, accurate, and insightful.”

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“Eysenck and Keane cover the wide range of topics necessary for a sophisticated cognitive psychology text in a clear and straightforward manner, in lucid and unpretentious prose. Both the experimental and technical aspects as well as the content areas are explained on the basis of numerous well-chosen examples. Importantly, the authors also integrate many current references in an elegant way, providing an up-to-date account of the field. I wish I had had this when I was a student. Even my graduate students and post-docs will benefit from reviewing relevant chapters in this handbook.”

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“The seventh edition of Eysenck and Keane’s outstanding text, *Cognitive Psychology*, shows a commanding understanding of how cognitive psychology has matured since its inception over 50 years ago. Written in a highly accessible style with additional impressive website support it is a text that any student would benefit from using. Particularly impressive is the coverage of neuroscience and neuropsychology along with excellent sections on computational models of cognition. It shares the excitement of our rapidly evolving understanding of the mind and invites the reader to savour recent insights into the workings of vision, memory, problem solving, emotion, and the mysteries of consciousness. It will be the standard text for some years to come.”

Professor Martin Conway, City University London, UK

“A new edition of Eysenck and Keane is always a cause for rejoicing among teachers of cognitive psychology. I have been using this text for longer than I wish to remember, and although as expected the material is brought up to date, the pedagogy and clarity of exposition also improve with each edition. The highest recommendation though is that my students tell me they find this book to be invaluable.”

Professor Trevor Harley, University of Dundee, UK

Cognitive Psychology

Rigorously researched and accessibly written, *Cognitive Psychology: A Student's Handbook* is widely regarded as the leading undergraduate textbook in the field. The book is clearly organised, and offers comprehensive coverage of all the key areas of cognitive psychology. With a strong focus on considering human cognition in context, the book has been designed to help students develop a thorough understanding of the fundamentals of cognitive psychology, providing them with detailed knowledge of the very latest advances in the field.

The seventh edition has been thoroughly updated throughout, and includes:

- extended coverage of cognitive neuroscience
- additional content on computational cognitive science
- new and updated case studies demonstrating real life applications of cognitive psychology
- a fully updated companion website.

Cognitive Psychology: A Student's Handbook will be essential reading for all undergraduate students of psychology. Those taking courses in computer science, education, linguistics, physiology and medicine will also find it an invaluable resource.

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COGNITIVE PSYCHOLOGY

A Student's Handbook

Seventh Edition

**MICHAEL W. EYSENCK
AND MARK T. KEANE**



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To Clementine with love.
(M.W.E.)

*If you can't explain it simply,
you don't understand it well enough.*
(Albert Einstein)

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Preface

The Chinese have a saying, “May you live in interesting times.” That saying is highly appropriate with respect to cognitive psychology, which has become more and more interesting as time goes by. There have been numerous exciting developments in our understanding of human cognition since the publication of the sixth edition of this textbook. The most striking change in recent years has been the ever-increasing emphasis on studying the *brain* as well as *behaviour*. We continue to use the term “cognitive psychology” to refer to this approach, which forms the basis for much of our coverage of human cognition. Note, however, that the term “cognitive neuroscience” is increasingly used to describe this approach. Research using this approach has become markedly more successful at shedding light on important (and controversial!) theoretical issues.

The approaches to human cognition discussed in detail in this book are more varied than implied so far. For example, cognitive neuropsychology is an important and influential approach that involves focusing on the effects of brain damage as a way of understanding cognition in healthy individuals. Another important approach is computational cognitive science, which involves developing computational models of human cognition. Cognitive neuropsychology and computational cognitive science are both discussed at length in the pages of this book.

An important development has been an increase in cognitive research of direct relevance to real life (e.g., fingerprinting, multitasking, emotion regulation, using mobile phones while driving). As a result, our coverage of real-world research has increased considerably since the previous edition.

As was the case with previous editions of this textbook, the authors have had to work hard to keep pace with developments in theory and research. For example, the first author wrote parts of the book in many far-flung places, including Thailand, Australia, Peru and Hong Kong. Sadly, there have been many occasions on which book writing has had to take precedence over sightseeing!

I (Michael Eysenck) became the proud grandfather of a granddaughter, Clementine, in April 2014 and have dedicated this book to her. We (Michael Eysenck and Mark Keane) would both like to thank the very friendly and efficient staff at Psychology Press, including Ceri Griffiths, Michael Fenton, Mike Travers and Katharine Atherton.

We would also like to thank Hervé Abdi, Anthony Atkinson, Linden Ball, Julie Boland, Bruce Bridgeman, Adele Diederich, Andrew Dunn, Jim Grange, Ken Paller, Amanda Ludlow, Ken Manktelow, Nick Perham, Durk Talsma, and Gill Waters, who commented on various chapters. Their comments proved extremely useful when it came to the demanding business of revising the first draft of the manuscript.

Michael Eysenck and Mark Keane

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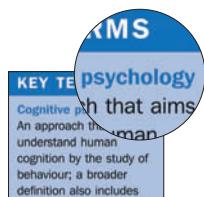
Visual tour (how to use this book)

TEXTBOOK FEATURES

Listed below are the various pedagogical features that can be found both in the margins and within the main text, with visual examples of the boxes to look out for, and descriptions of what you can expect them to contain.

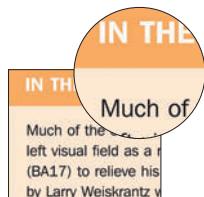
Key terms

Throughout the book, key terms are highlighted in the text and defined in boxes in the margins, helping you to get to grips with the vocabulary fundamental to the subject being covered.



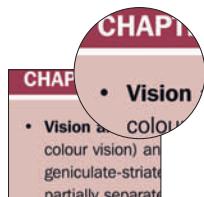
In the real world

Each chapter contains boxes within the main text that explore “real world” examples, providing context and demonstrating how some of the theories and concepts covered in the chapter work in practice.



Chapter summary

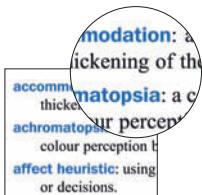
Each chapter concludes with a brief summary of each section of the chapter, helping you to consolidate your learning by making sure you have taken in all of the concepts covered.



Further reading

Also at the end of each chapter is an annotated list of key scholarly books and journal articles that it is recommended you explore through independent study to expand upon the knowledge you have gained from the chapter and plan for your assignments.





Links to companion website features

Whenever you see this symbol (see left), look for the related supplementary material of the same name amongst the resources for that chapter on the companion website at www.psypress.com/cw/eysenck.

Glossary

An extensive glossary appears at the end of the book, offering a comprehensive list that includes definitions not covered by the key terms boxes in the main text.

Approaches to human cognition

INTRODUCTION

We are now well into the third millennium and there is more interest than ever in unravelling the mysteries of the human brain and mind. This interest is reflected in the substantial upsurge of scientific research within cognitive psychology and cognitive neuroscience. It is striking that the cognitive approach has become increasingly important within clinical psychology. In that area, it is recognised that cognitive processes (especially cognitive biases) play an important role in the development and successful treatment of mental disorders. In similar fashion, social psychologists increasingly assume that cognitive processes help to explain much of social communication.

What is cognitive psychology? It is concerned with the internal processes involved in making sense of the environment and deciding what action might be appropriate. These processes include attention, perception, learning, memory, language, problem solving, reasoning and thinking. We can define **cognitive psychology** as aiming to understand human cognition by observing the behaviour of people performing various cognitive tasks. Note, however, that the term “cognitive psychology” can be used more broadly to include brain activity and structure as relevant information for understanding human cognition. It is in this broader sense that it is used in the title of this book.

The aims of cognitive neuroscientists overlap with those of cognitive psychologists. However, there is one important difference between cognitive neuroscience and cognitive psychology in the narrow sense. Cognitive neuroscientists argue convincingly we need to study the *brain* as well as behaviour while people engage in cognitive tasks. After all, the internal processes involved in human cognition occur in the brain. We can define **cognitive neuroscience** as using information about behaviour and the brain to understand human cognition. Thus, the distinction between cognitive neuroscience and cognitive psychology in the broader sense is blurred.

Cognitive neuroscientists explore human cognition in several ways. First, there are brain-imaging techniques of which functional magnetic resonance imaging (fMRI) (discussed later) is probably the best known. Second, there are electrophysiological techniques involving the recording of electrical signals

KEY TERMS

Cognitive psychology

An approach that aims to understand human cognition by the study of behaviour; a broader definition also includes the study of brain activity and structure.

Cognitive neuroscience

An approach that aims to understand human cognition by combining information from behaviour and the brain.



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Cognitive Science

generated by the brain (also discussed later). Third, many cognitive neuroscientists study the effects of brain damage on human cognition. It is assumed the patterns of cognitive impairment shown by brain-damaged patients can inform us about normal cognitive functioning and the brain areas responsible for various cognitive processes.

The huge increase in scientific interest in the workings of the brain is mirrored in the popular media – numerous books, films and television programmes have communicated the more accessible and dramatic aspects of cognitive neuroscience. Increasingly, media coverage includes coloured pictures of the brain indicating the areas most activated when people perform various tasks.

Four main approaches

There are four main approaches to human cognition (see below). Bear in mind, however, that researchers increasingly combine two or even more of these approaches. We will shortly discuss each approach in turn, and you will probably find it useful to refer back to this chapter when reading other chapters. You may find [Table 1.1](#) (towards the end of this chapter) especially useful because it provides a brief summary of the strengths and limitations of all four approaches, which are:

- 1 *Cognitive psychology*: this approach involves trying to understand human cognition by using behavioural evidence. Since behavioural data are also of great importance within cognitive neuroscience and cognitive neuropsychology, cognitive psychology's influence is enormous.
- 2 *Cognitive neuropsychology*: this approach involves studying brain-damaged patients to understand normal human cognition. It was originally closely linked to cognitive psychology but has recently also become linked to cognitive neuroscience.
- 3 *Cognitive neuroscience*: this approach involves using evidence from behaviour and the brain to understand human cognition.
- 4 *Computational cognitive science*: this approach involves developing computational models to further our understanding of human cognition; such models increasingly take account of our knowledge of behaviour and the brain.

COGNITIVE PSYCHOLOGY

It is almost as pointless to ask, “When did cognitive psychology start?”, as to enquire, “How long is a piece of string?” However, the year 1956 was of crucial importance. At a meeting at the Massachusetts Institute of Technology (MIT), Noam Chomsky gave a paper on his theory of language, George Miller discussed the magic number seven in short-term memory (Miller, 1956) and Newell and Simon discussed their extremely influential model called the General Problem Solver (see Newell et al., 1958). In addition, there was the first systematic attempt to study concept formation from a cognitive perspective (Bruner et al., 1956).

At one time, most cognitive psychologists subscribed to the information-processing approach based loosely on an analogy between the mind and the computer. A version of this approach popular in the 1970s is shown in [Figure 1.1](#). A stimulus (an environmental event such as a problem or a task) is presented. This causes certain internal cognitive processes to occur, and these processes

finally produce the desired response or answer. Processing directly affected by the stimulus input is often described as **bottom-up processing**. It was typically assumed that only one process occurs at any moment in time. This is **serial processing**, meaning the current process is completed before the next one starts.

The above approach is drastically oversimplified. Task processing typically also involves **top-down processing**. Top-down processing is processing influenced by the individual's expectations and knowledge rather than simply by the stimulus itself. Read what it says in the triangle shown in Figure 1.2. Unless you know the trick, you probably read it as, "Paris in the spring". If so, look again and you will find the word "the" is repeated. Your expectation that it was a well-known phrase (i.e., top-down processing) dominated the information available from the stimulus (i.e., bottom-up processing).

The traditional approach was also oversimplified in assuming processing is typically serial. In fact, more than one process typically occurs at the same time – this is **parallel processing**. We are much more likely to use parallel processing when performing a highly practised task than a new one (see Chapter 5). For example, someone taking their first driving lesson finds it almost impossible to change gear, steer accurately and pay attention to other road users at the same time. In contrast, an experienced driver finds it easy.

For many years, nearly all research on human cognition consisted of experiments on healthy individuals under laboratory conditions. Such experiments are tightly controlled and "scientific". Researchers have shown great ingenuity in designing experiments to reveal the processes involved in attention, perception, learning, memory, reasoning and so on. This research has had a major (and ongoing) influence on the studies conducted by cognitive neuroscientists. Indeed, nearly all the research discussed in this book owes much to the cognitive psychological approach.

Task processes

An important issue for cognitive psychologists is the task impurity problem – most cognitive tasks require a complex mixture of processes, thus making it hard to interpret the findings. This issue has been addressed in various ways. For example, suppose we are interested in the processes involved when a task requires deliberately inhibiting a dominant response. Miyake et al. (2000) studied three such tasks: the Stroop task; the anti-saccade task; and the stop-signal task. On the Stroop task, participants name the colour in which colour words are presented (e.g., RED printed in green) and avoid saying the colour word (which is hard to inhibit) (see Macleod (2015, *in press*) for a discussion of this task). On the anti-saccade task,

KEY TERMS

Bottom-up processing
Processing that is directly influenced by environmental stimuli.

Serial processing
Processing in which one process is completed before the next one starts; see also **parallel processing**.

Top-down processing
Stimulus processing that is influenced by factors such as the individual's past experience and expectations.

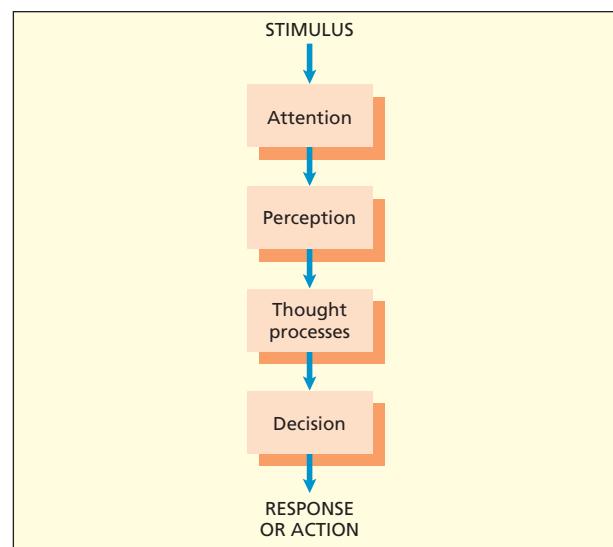


Figure 1.1
An early version of the information processing approach.

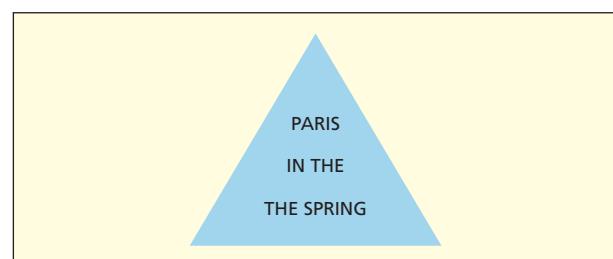


Figure 1.2
Diagram to demonstrate top-down processing.

KEY TERM**Parallel processing**

Processing in which two or more cognitive processes occur at the same time.

a visual cue is presented. The task involves *not* looking at the cue but rather inhibiting that response and looking in the opposite direction. On the stop-signal task, participants categorise words as rapidly as possible, but must inhibit their response when a tone sounds.

Miyake et al. (2000) found all three tasks involved similar processes. They used complex statistical techniques to extract what was common to the three tasks. This was assumed to represent a relatively pure measure of the inhibitory process.

Cognitive psychologists have developed several ways of understanding the processes involved in complex tasks. Here we will briefly consider one example. Participants are presented with five words visually and repeat them back. Performance is worse when the words are long than when they are short (Baddeley et al., 1975; see [Chapter 6](#)). This probably occurs because participants engage in verbal rehearsal (saying the words to themselves) during word presentation and this takes longer with long words than with short ones. However, see [Chapter 6](#) for an alternative account.

How could we show verbal rehearsal is a process used on this task? Baddeley et al. (1975) used articulatory suppression – participants repeated the digits 1 to 8 in order during presentation of the word list to prevent them rehearsing. As predicted, performance was worse when articulatory suppression was used. In addition, the effect of word length disappeared, thus suggesting its existence depended on verbal rehearsal.

Much of this book is devoted to the ingenious strategies cognitive psychologists have used to uncover the processes involved in numerous tasks. Therefore, there is no need to itemise these strategies here.

Strengths

Cognitive psychology was for many years the engine room of progress in understanding human cognition, and all the other approaches listed above have derived substantial benefit from it. For example, cognitive neuropsychology became important 25 years after cognitive psychology. It was only when cognitive psychologists had developed reasonable accounts of healthy human cognition that the performance of brain-damaged patients could be understood fully. Before that, it was hard to decide which patterns of cognitive impairment were of theoretical importance.

In similar fashion, the computational modelling activities of computational cognitive scientists are typically heavily influenced by pre-computational psychological theories. Finally, the great majority of theories driving research in cognitive neuroscience had their origins within cognitive psychology. Indeed, Coltheart (2011) claimed (controversially!) that cognitive neuroscience has so far made no difference to cognitive theorising.

Cognitive psychology has not only had a massive influence on theorising across all four major approaches to human cognition. It has also had a predominant influence on the development of cognitive tasks and on task analysis (working out how a task is accomplished).

However, we must not de-emphasise the substantial contributions of the three other major approaches discussed in detail later.

Limitations

In spite of cognitive psychology's enormous contributions, it has various limitations. First, people's behaviour in the laboratory may differ from that in everyday life. The concern is that laboratory research lacks **ecological validity** – the extent to which laboratory findings are applicable to everyday life. In most laboratory research, the sequence of stimuli presented to participants is based on the experimenter's predetermined plan and is uninfluenced by their behaviour. Wachtel (1973) called this the **implacable experimenter**. In everyday life, in contrast, our cognitive processing often involves deciding how to change the current situation to suit ourselves.

Second, cognitive psychologists typically obtain measures of the speed and accuracy of task performance. These measures provide only *indirect* evidence about internal cognitive processes. For example, it is hard on the basis of such measures to decide whether the processes used on a complex task occur serially or in parallel.

Third, cognitive psychologists have often put forward theories expressed only in verbal terms (although this is becoming less common). Such theories tend to be vague, making it hard to know precisely what predictions follow from them. Thankfully, this limitation can largely be overcome by computational cognitive scientists developing cognitive models specifying precisely any given theory's assumptions.

Fourth, the findings obtained from any given experimental task or paradigm are sometimes *specific* to that paradigm and do not generalise to other (apparently similar) tasks. This is **paradigm specificity**. It means some findings in cognitive psychology are narrow in scope and applicability (Meiser, 2011). More generally, "Once an experimental paradigm has been introduced, it . . . turns from a tool of research to a target of research" (Meiser, 2011, p. 185). The way to minimise the problems of paradigm specificity is by developing theories accounting for performance across several similar tasks or paradigms.

Fifth, what has been lacking within cognitive psychology is a comprehensive theoretical architecture or framework that would clarify the interrelationships among components of the cognitive system. However, some progress has been made here. The Adaptive Control of Thought-Rational [ACT-R] model (e.g., J.R. Anderson et al., 2004; discussed later in the chapter) is an example of a cognitive architecture.

COGNITIVE NEUROPSYCHOLOGY

Cognitive neuropsychology is concerned with the patterns of cognitive performance (intact and impaired) shown by brain-damaged patients. These patients have suffered lesions – structural damage to the brain caused by injury or disease. According to cognitive neuropsychologists, the study of brain-damaged patients can tell us much about normal human cognition.

The above idea does not sound very promising, does it? In fact, however, cognitive neuropsychology has contributed a substantial amount to our understanding of normal human cognition. For example, in the 1960s nearly all memory researchers thought the storage of information in long-term memory depended on previous processing in short-term memory (see [Chapter 6](#)). However, Shallice and Warrington (1970) reported the case of a brain-damaged man, KF. His short-term

KEY TERMS

Ecological validity

The applicability (or otherwise) of the findings of laboratory studies to everyday settings.

Implacable experimenter

The situation in experimental research in which the experimenter's behaviour is uninfluenced by the participant's behaviour.

Paradigm specificity

This occurs when the findings with a given experimental task or paradigm are not obtained even when apparently very similar tasks or paradigms are used.



Weblink:

[Cognitive neuropsychology](#)



Max Coltheart.

Courtesy of Max Coltheart.

KEY TERMS

Modularity

The assumption that the cognitive system consists of many fairly independent or separate modules or processors, each specialised for a given type of processing.

Domain specificity

The notion that a given module responds selectively to certain types of stimuli (e.g., faces) but not others.

memory was severely impaired but his long-term memory was intact. These findings played an important role in changing theories of normal human memory.

Since cognitive neuropsychologists study brain-damaged patients, it would be easy to imagine they are interested in the workings of the brain. In fact, the leading cognitive neuropsychologist Max Coltheart (see photo) and many other cognitive neuropsychologists pay little attention to the brain itself. In the words of Coltheart (2010, p. 3), “The principal aim of cognitive neuropsychology is not to learn about the brain. Its principal aim is instead to learn about the mind, that is, to elucidate the functional architecture of cognition.”

Other cognitive neuropsychologists disagree with Coltheart (2010). An increasing number take account of the brain, using techniques such as magnetic resonance imaging to identify the brain areas damaged in any given patient. In addition, there is an increasing willingness to consider neuroimaging findings.

Theoretical assumptions

The main assumptions of cognitive neuropsychology have been discussed often over the years (e.g., Davies, 2010). Here we will focus on Coltheart’s (2001) very clear account. One key assumption is **modularity**, meaning the cognitive system consists of numerous modules or processors operating fairly independently or separately of each other. It is assumed these modules exhibit **domain specificity** (they respond to only one given class of stimuli). For example, there may be a face-recognition module that responds only when a face is presented.

Is the modularity assumption correct? This issue is very controversial. Probably the majority position is that the human cognitive system exhibits some modularity, but cognitive neuropsychologists often exaggerate its importance. This complex issue is discussed in more detail below.

The second major assumption of cognitive neuropsychology is that of *anatomical modularity*. According to this assumption, each module is located in a specific brain area. Why is this assumption important? Cognitive neuropsychologists are most likely to make progress when studying patients with brain damage limited to a single module. Such patients may not exist if there is no anatomical modularity. Suppose all modules were distributed across large areas of the brain. If so, the great majority of brain-damaged patients would suffer damage to most modules. As a result, it would be impossible to work out the number and nature of modules they possessed.

There is evidence of some anatomical modularity in the visual processing system (see [Chapter 2](#)). However, there is much less support for anatomical modularity with most complex tasks. For example, Duncan and Owen (2000)

found the same areas within the frontal lobes were activated when very different complex tasks were performed. The findings of Yarkoni et al. (2011) are also relevant. Across more than 3,000 studies, brain areas such as the dorsolateral prefrontal cortex and anterior cingulate cortex were activated in 20% of them in spite of the huge diversity of tasks involved.

The third major assumption is what Coltheart (2001, p. 10) called “uniformity of functional architecture across people”. This assumption is important as can be seen if we consider the consequences if it is false. In that case, we would not be able to use the findings from individual patients to draw conclusions about other people’s functional architecture.

Related ideas are also common within cognitive neuroscience. For example, it has often been claimed that face processing in virtually everyone depends heavily on the fusiform face area (Weiner & Grill-Spector, 2012). If there are large individual differences in functional architecture and the brain areas involved in any given cognitive process, this greatly complicates the task of understanding human cognition.

The fourth assumption is *subtractivity*. The basic idea is that brain damage impairs one or more processing modules but does not change or add anything. Why is this assumption important? Suppose it is incorrect and patients develop new modules to compensate for cognitive impairments caused by brain damage. That would greatly complicate the task of learning much about intact cognitive systems by studying brain-damaged patients.

The subtractivity assumption is sometimes incorrect. There is often partial recovery of the cognitive processes impaired by brain damage (Cus et al., 2011). This recovery of cognitive processes can involve recovery of function within the damaged area or the recruitment of different brain regions.

Modularity assumption

Modular systems typically involve mostly serial processing in which processing within one module is completed before processing in the next module starts. As a result, there is very limited *interaction* among modules. There is some support for modularity from the evolutionary approach. Species with larger brains tend to have more specialised brain regions that could be involved in modular processing.

The notion that human cognition is heavily modular is rather difficult to reconcile with neuroimaging and other evidence based on brain activity. The human brain possesses a moderately high level of connectivity (Bullmore & Sporns, 2012; see below). This suggests there is more parallel processing than assumed by most cognitive neuropsychologists.

Research in cognitive neuropsychology

How do cognitive neuropsychologists set about understanding the cognitive system? Of major importance is the search for **dissociations**, which occur when a patient performs normally on one task (task X) but is impaired on a second one (task Y). For example, amnesic patients perform almost normally on short-term memory tasks but are greatly impaired on many long-term memory tasks (see Chapter 6). It is tempting (but dangerous!) to use such findings to argue that the

KEY TERM

Dissociation

As applied to brain-damaged patients, intact performance on one task but severely impaired performance on a different task.

KEY TERMS

Double dissociation

The finding that some brain-damaged individuals have intact performance on one task but poor performance on another task, whereas other individuals exhibit the opposite pattern.

Association

The finding that certain symptoms or performance impairments are consistently found together in numerous brain-damaged patients.

Syndrome

The notion that symptoms that often co-occur have a common origin.

two tasks involve different processing modules and that the module or modules needed on long-term memory tasks have been damaged by brain injury.

Why do we need to avoid drawing sweeping conclusions from dissociations?

A patient may perform well on one task but poorly on a second one simply because the second task is more complex. Thus, dissociations may reflect task differences in complexity rather than the use of different modules.

Cognitive neuropsychologists argue that the solution to the above problem is to find double dissociations. A **double dissociation** between two tasks (X and Y) is shown when one patient performs normally on task X and at an impaired level on task Y, whereas another patient shows the opposite pattern. If a double dissociation is found, we cannot explain the findings away as occurring because one task is harder. For example, we have just seen that amnesic patients have impaired long-term memory but intact short-term memory. Earlier we saw that other brain-damaged patients (e.g., KF studied by Shallice and Warrington (1970)) have impaired short-term memory but intact long-term memory. The double dissociation involved here strongly suggests that there is an important distinction between short-term and long-term memory and that they involve different brain regions.

The approach based on double dissociations has limitations. First, it is based on the assumption that separate modules exist (which may be misguided). Second, double dissociations can generally be explained in various ways and so provide *indirect* evidence for separate modules underlying each task (Davies, 2010). Third, it is hard to decide which of the numerous double dissociations in the literature are theoretically important.

Finally, we consider associations. An **association** occurs when a patient is impaired on tasks X and Y. Associations are sometimes taken as evidence for a **syndrome** (sets of symptoms or impairments often found together). However, there is a serious flaw with the syndrome-based approach. An association may be found between tasks X and Y because the mechanisms on which they depend are adjacent in the brain rather than because they depend on the same underlying mechanism. Gerstmann's syndrome is an example. It is defined by four very different symptoms: problems of finger identification; problems in calculation; impaired spelling; and left-right disorientation. It is improbable that the same mechanisms or modules are involved in all four tasks. What is much more likely is that these four symptoms depend on different mechanisms that happen to be anatomically adjacent in the brain.

Single-case studies vs. case series

For much of the history of cognitive neuropsychology, there was a strong emphasis on single-case studies. There were two main reasons. First, researchers can often gain access to only one patient having a given pattern of cognitive impairment. Second, it is often assumed every patient is *unique* because no two patients have precisely the same pattern of brain damage. It was concluded it would be misleading and uninformative to average the performance of several patients even though they allegedly had the same disorder.

You may be surprised to discover that so much research in cognitive neuropsychology has involved individuals. After all, the general recommendation in most psychological research is to use reasonably large samples so we can have confidence in the findings. Within cognitive neuropsychology, there is a movement

towards the **case-series study**. Several patients thought to have similar cognitive impairments are tested and then the data of individual patients are compared and variation across patients assessed.

There are several reasons why the case-series approach is generally preferable to the single-case approach (Lambon Ralph et al., 2011). First, it provides much richer data. Using the case-series approach we can actually *assess* the extent of variation among patients rather than simply being concerned about it (as in the single-case approach).

Second, we can develop theories based on most patients within a case series, de-emphasising patients who are “outliers”. In contrast, with the single-case approach we do not know whether the one and only patient is representative of patients with that condition or is an outlier.

KEY TERM

Case-series study

A study in which several patients with similar cognitive impairments are tested; this allows consideration of individual data and of variation across individuals.

Strengths

Cognitive neuropsychology has made numerous major contributions to our understanding of human cognition. Here we will briefly consider its strengths. First, it has played a major role in informing theories of language. For example, consider patients reading visually presented regular words (words whose pronunciation is predictable from the pattern of letters), irregular words (words whose pronunciation is not predictable from the pattern of letters) and non-words aloud. We might imagine that patients with damage to language areas would have problems in reading *all* words and non-words. In fact, that is not the case (see [Chapter 9](#)). Some patients perform reasonably well when reading regular words or non-words but poorly when reading irregular words. Other patients can read regular words but have problems with unfamiliar words and non-words. These fascinating patterns of impairment have transformed theories of reading (Coltheart, 2015, *in press*).

Second, findings from brain-damaged patients have often had a substantial impact on memory theories. Perhaps the clearest example is HM, now known to be Henry Molaison. He was an amnesic patient whose long-term memory was severely impaired, except his ability to learn motor skills, whereas his short-term memory was intact (see [Chapter 7](#)). These findings provided striking support for three hypotheses. First, there is a major distinction between short-term and long-term memory. Second, long-term memory is divided into at least two different systems. Third, HM had suffered severe damage to the hippocampus, and so the research identified this area as of crucial importance in long-term memory. Eichenbaum (2015, *in press*) discusses the enormous impact of research on HM in detail.

Limitations

What are the limitations of the cognitive neuropsychological approach? First, the crucial assumption that the cognitive system is fundamentally modular is reasonable but seems too strong. Modular systems tend to be relatively inflexible and based on serial processing. In contrast, human cognitive processing is noted for its *flexibility* and extensive interactions throughout the brain. If the modularity assumption is mistaken, this has implications for the whole enterprise of cognitive neuropsychology (Patterson & Plaut, 2009).



Weblink:

Michael Gazzinga in conversation

KEY TERMS**Sulcus**

A groove or furrow in the surface of the brain.

Gyri

Prominent elevated areas or ridges on the brain's surface ("gyrus" is the singular).

Dorsal

Superior, or towards the top of the brain.

Ventral

Inferior, or towards the bottom of the brain.

Rostral

Anterior, or towards the front of the brain.

Posterior

Towards the back of the brain.

Lateral

Situated at the side of the brain.

Medial

Situated in the middle of the brain.

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Cognitive neuroscience society

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Atlas of the brain

Second, other major theoretical assumptions also seem too extreme. For example, neuroimaging research provides only modest support for the assumption of anatomical modularity. In addition, there is little or no convincing evidence supporting the assumption of uniformity of functional architecture.

Third, it is assumed the cognitive performance of patients provides fairly direct evidence concerning the impact of brain damage on previously intact cognitive systems. However, some of the impact of brain damage may be camouflaged because patients develop *compensatory strategies* as they recover. For example, patients with pure alexia (a condition involving severe reading problems) read words by the compensatory strategy of identifying each letter separately. There are also complications resulting from changes in brain functioning during the recovery process (Cus et al., 2011). In other words, many patients exhibit considerable neural plasticity following brain damage (Overgaard & Mogensen, 2011).

Fourth, cognitive neuropsychologists have historically shown relatively little interest in the details of brain functioning and cognitive neuroscience. This seems paradoxical since their focus is on brain-damaged patients. However, findings from cognitive neuroscience are increasingly being combined fruitfully with those from cognitive neuropsychology. For example, this has been done with respect to recognition memory (discussed later).

Fifth, there has been too much emphasis on single-case studies. Some single-case studies (e.g., the famous amnesic patient, HM) have deservedly had a huge impact. However, there are real limitations with single-case studies and the case-study approach provides a richer source of data.

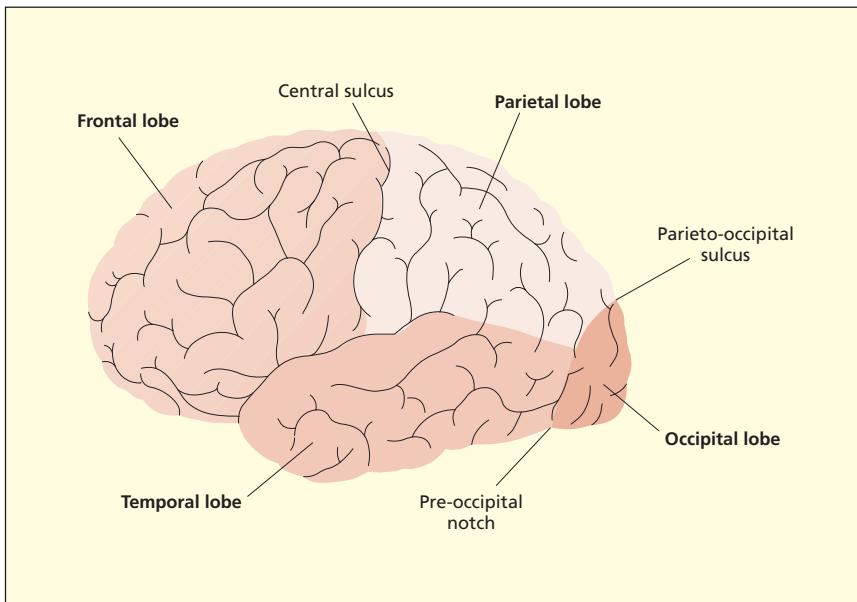
COGNITIVE NEUROSCIENCE: THE BRAIN IN ACTION

Cognitive neuroscience involves intensive study of the brain as well as behaviour. Alas, the brain is complicated (to put it mildly!). It consists of 100 billion neurons and these neurons are connected in very complex ways. To understand research involving functional neuroimaging, we must consider how the brain is organised and how the different areas are described. Various ways of describing specific brain areas are used. Below we will discuss the three main ones.

First, the cerebral cortex is divided into four main divisions or lobes (see [Figure 1.3](#)). There are four lobes in each brain hemisphere: frontal, parietal, temporal and occipital. The frontal lobes are divided from the parietal lobes by the central sulcus (**sulcus** means furrow or groove), and the lateral fissure separates the temporal lobes from the parietal and frontal lobes. In addition, the parieto-occipital sulcus and pre-occipital notch divide the occipital lobes from the parietal and temporal lobes. The main **gyri** (or ridges; *gyrus* is the singular) within the cerebral cortex are shown in [Figure 1.3](#).

Researchers use various terms to describe more precisely the area(s) of the brain activated during the performance of a given task:

- **dorsal** (or superior): towards the top;
- **ventral** (or inferior): towards the bottom;
- **rostral** (or anterior): towards the front;
- **posterior**: towards the back;
- **lateral**: situated at the side;
- **medial**: situated in the middle.

**Figure 1.3**

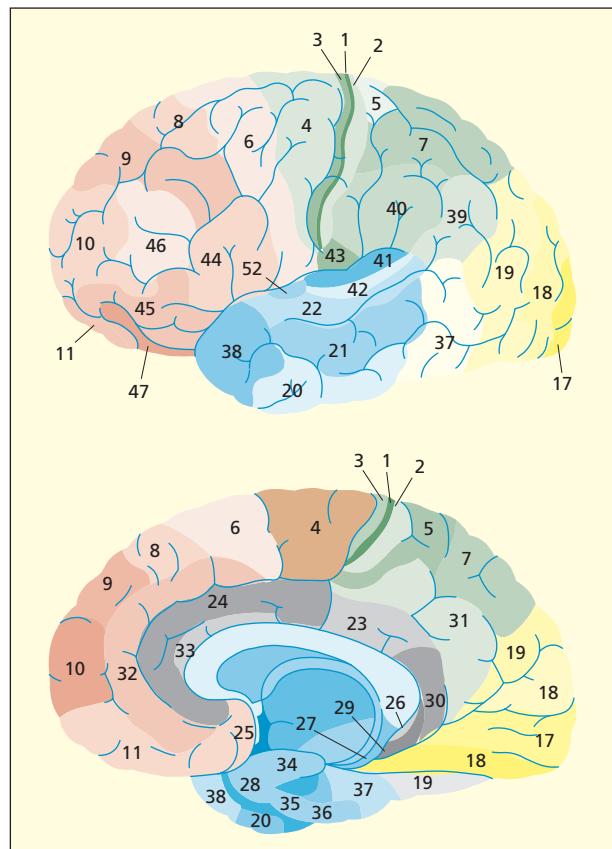
The four lobes, or divisions, of the cerebral cortex in the left hemisphere.

Second, the German neurologist Korbinian Brodmann (1868–1918) produced a map of the brain based on differences in the distributions of cell types across cortical layers (see Figure 1.4). Brodmann identified 52 different areas, and we will often refer to areas such as BA17, which simply means Brodmann Area 17.

Third, we can focus on the functions of different brain areas. For example, consider Brodmann Area 17 (BA17). This is often referred to as primary visual cortex because it is an area strongly associated with the early processing of visual stimuli.

Brain network organisation

Bullmore and Sporns (2012) argued that two major principles might determine brain organisation. First, there is the *principle of cost control*: costs (e.g., in terms of energy and space) would be minimised if the brain consisted of limited, short-distance connections (see Figure 1.5). Second, there is the *principle of efficiency*: efficiency in terms of the ability to integrate information across the brain. This can be achieved by having very numerous connections, many of which are long-distance (see Figure 1.5). The problem is that these two principles are in conflict – you cannot have high efficiency at low cost.

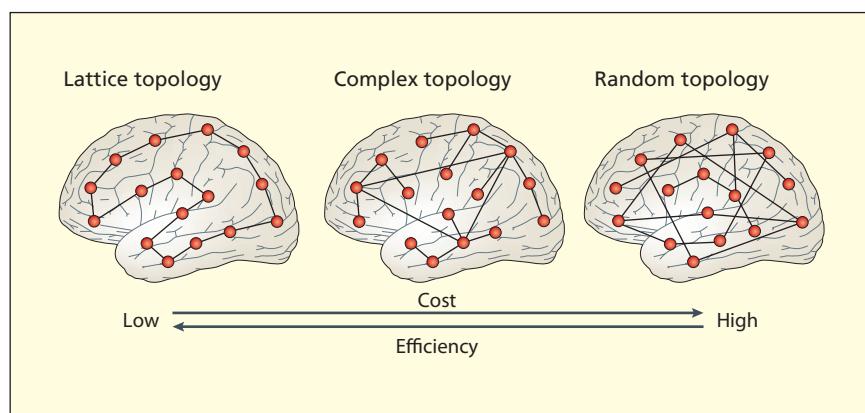
**Figure 1.4**

Brodmann brain areas on the lateral (top figure) and medial (bottom figure) surfaces.

Figure 1.5

The left panel shows a brain network low in cost and efficiency; the right panel shows a brain network high in cost and efficiency; the middle panel shows the actual human brain in which there is moderate efficiency at moderate cost. Nodes are shown as orange circles.

From Bullmore and Sporns (2012). Reprinted with permission of Nature Reviews.



You might think it would be best if our brains were organised purely on the basis of efficiency. However, this would be hugely costly. If all 100 billion neurons in the brain were interconnected, the brain would need to be 12½ miles wide (Ward, 2010)! In fact, neurons mostly connect with nearby neurons and no neuron is connected to more than about 10,000 neurons. As a result, the human brain has achieved a near-optimal trade-off between cost and efficiency (see Figure 1.5). Our brains are reasonably efficient and this has been achieved at manageable cost. Within our brain network, there are *modules* (small areas of tightly clustered connections) and *hubs* (regions that have large numbers of connections to other regions). These hubs include areas (e.g., the anterior cingulate) associated with high-level cognitive processes and consciousness (see Chapter 16).

What light does a focus on brain network organisation shed on individual differences in cognitive ability? Van den Heuvel et al. (2009) found IQ did not correlate with the total number of brain network connections. However, there were impressive associations between IQ and the global efficiency of functional brain networks. The correlation was +0.75 in medial prefrontal cortex (BA9/10) and +0.72 in inferior parietal regions (BA39/40). Thus, how the brain is wired has important implications for the efficiency of cognition.

Techniques for studying the brain: introduction

Technological advances mean we have numerous exciting ways of obtaining detailed information about the brain's functioning and structure. In principle, we can work out *where* and *when* specific cognitive processes occur in the brain. This allows us to determine the order in which different brain areas become active when someone performs a task. It also allows us to find out whether two tasks involve the same brain areas in the same way or whether there are important differences.

Major techniques used to study the brain are:

- **Single-unit recording:** This technique (also known as single-cell recording) involves inserting a micro-electrode one 10,000th of a millimetre in diameter into the brain to study activity in single neurons. It is very sensitive, since electrical charges of as little as one-millionth of a volt can be detected.



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A visual overview of imaging techniques

- **Event-related potentials (ERPs):** The same stimulus (or very similar ones) is presented repeatedly, and the pattern of electrical brain activity recorded by several scalp electrodes is averaged to produce a single waveform. This technique allows us to work out the timing of various cognitive processes very precisely but its spatial resolution is poor.
- **Positron emission tomography (PET):** This technique involves the detection of positrons (atomic particles emitted from some radioactive substances). PET has reasonable spatial resolution but poor temporal resolution, and measures neural activity only indirectly.
- **Functional magnetic resonance imaging (fMRI):** This technique involves imaging blood oxygenation using an MRI machine (described later). Functional MRI has superior spatial and temporal resolution to PET, but also provides an indirect measure of neural activity.
- **Event-related functional magnetic resonance imaging (efMRI):** This “involves separating the elements of an experiment into discrete points in time, so that the cognitive processes (and associated brain responses) associated with each element can be analysed independently” (Huettel, 2012, p. 1152). Event-related fMRI is generally very informative and has become markedly more popular recently.
- **Magneto-encephalography (MEG):** This technique involves measuring the magnetic fields produced by electrical brain activity. It provides fairly detailed information at the millisecond level about the time course of cognitive processes, and its spatial resolution is reasonably good.
- **Transcranial magnetic stimulation (TMS):** This is a technique in which a coil is placed close to the participant’s head and a very brief pulse of current is run through it. This produces a short-lived magnetic field that generally (but not always) inhibits processing in the brain area affected. When the pulse is repeated several times in rapid succession, we have **repetitive transcranial magnetic stimulation (rTMS)**. Repetitive TMS is used very widely.

It has often been argued that TMS or rTMS causes a very brief “**lesion**”, a lesion being a structural alteration caused by brain damage. This technique has (jokingly!) been compared to hitting someone’s brain with a hammer. The effects of TMS are often more complex than suggested so far. In fact, there is often *interference* because the brain area to which TMS is applied is involved in task processing as well as the activity resulting from the TMS stimulation.

Which technique is the best? There is no single (or simple) answer. Each technique has its own strengths and limitations, and so experimenters match the technique to the research question. At the most basic level, the various techniques vary in the precision with which they identify the brain areas active when a task is performed (*spatial resolution*), and the time course of such activation (*temporal resolution*). Thus, the techniques differ in their ability to provide precise information concerning where and when brain activity occurs.

The spatial and temporal resolutions of various techniques are shown in [Figure 1.6](#). High spatial and temporal resolutions are advantageous if a very detailed account of brain functioning is required. In contrast, low temporal resolution can be more useful if a general overview of brain activity during an entire task is needed.

KEY TERMS

Single-unit recording

An invasive technique for studying brain function, permitting the study of activity in single neurons.

Event-related potentials (ERPs)

The pattern of electroencephalograph (EEG) activity obtained by averaging the brain responses to the same stimulus (or very similar stimuli) presented repeatedly.

Positron emission tomography (PET)

A brain-scanning technique based on the detection of positrons; it has reasonable spatial resolution but poor temporal resolution.

Functional magnetic resonance imaging (fMRI)

A technique based on imaging blood oxygenation using an MRI machine; it provides information about the location and time course of brain processes.

Event-related functional magnetic resonance imaging (efMRI)

This is a form of functional magnetic resonance imaging in which patterns of brain activity associated with specific events (e.g., correct vs. incorrect responses on a memory test) are compared.

Magneto-encephalography (MEG)

A non-invasive brain-scanning technique based on recording the magnetic fields generated by brain activity.

KEY TERMS

Transcranial magnetic stimulation (TMS)

A technique in which magnetic pulses briefly disrupt the functioning of a given brain area. It is often claimed that it creates a short-lived “lesion”. More accurately, TMS causes interference when the brain area to which it is applied is involved in task processing as well as activity produced by the applied stimulation.

Repetitive transcranial magnetic stimulation (rTMS)

The administration of **transcranial magnetic stimulation** several times in rapid succession.

Lesions

Structural alterations within the brain caused by disease or injury.

Electroencephalography (EEG)

Recording the brain's electrical potentials through a series of scalp electrodes.



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Hubel and Wiesel



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EEG and MEG

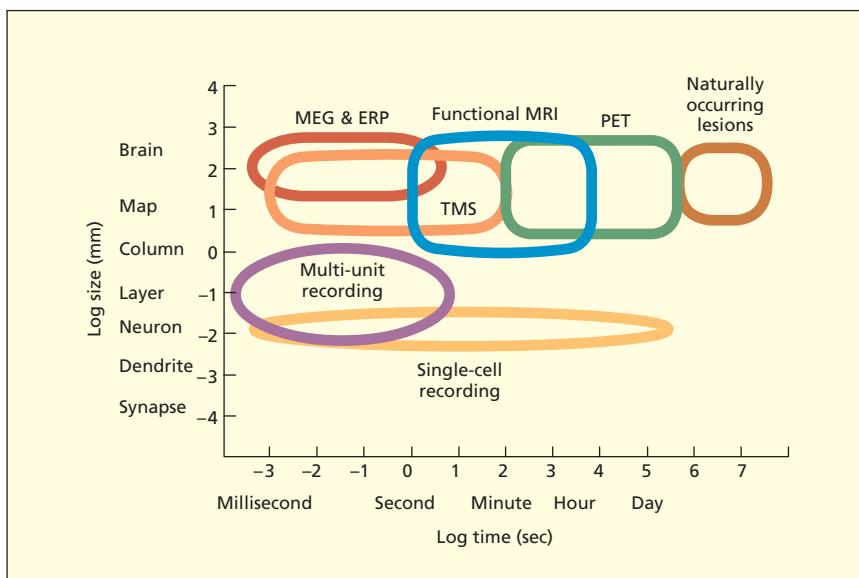


Figure 1.6

The spatial and temporal resolution of major techniques and methods used to study brain functioning.

From Ward (2006), adapted from Churchland and Sejnowski (1991).

Techniques for studying the brain: detailed analysis

We have introduced the main techniques for studying the brain. In what follows, we consider each one in more detail.

Single-unit recording

The single-unit (or cell) recording technique is more fine-grained than any other technique (see [Chapter 2](#)). However, it is invasive and so rarely used with humans. An interesting exception is a study by Quiroga et al. (2005) on epileptic patients implanted with electrodes to identify the focus of seizure onset (see [Chapter 3](#)). A neuron in the medial temporal lobe responded strongly to pictures of Jennifer Aniston (the actress from *Friends*) but not to pictures of other famous people. This finding needs to be interpreted carefully. It is highly improbable that only a single neuron responds to Jennifer Aniston – only a tiny fraction of the neurons in the medial temporal lobe were studied.

Event-related potentials

Electroencephalography (EEG) is based on recordings of electrical brain activity measured at the surface of the scalp. Very small changes in electrical activity within the brain are picked up by scalp electrodes and can be seen on a computer screen. However, spontaneous or background brain activity can obscure the impact of stimulus processing on the EEG recording.

The answer to the above problem is to present the same stimulus (or very similar stimuli) several times. After that, the segment of EEG following each

stimulus is extracted and lined up with respect to the time of stimulus onset. These EEG segments are then averaged together to produce a single waveform. This method produces event-related potentials (ERPs) from EEG recordings and allows us to distinguish genuine effects of stimulation from background brain activity.

ERPs have excellent temporal resolution. Indeed, they can often indicate when a given process occurred to within a few milliseconds (ms). The ERP waveform consists of a series of positive (P) and negative (N) peaks, each described with reference to the time in milliseconds after stimulus presentation. Thus, for example, N400 is a negative wave peaking at about 400 ms. ERPs provide very detailed information about the time course of brain activity. A behavioural measure (e.g., reaction time) typically provides only a *single* measure of time on each trial, whereas ERPs provide a *continuous* measure. However, ERPs do not indicate with precision *which* brain regions are most involved in processing, in part because skull and brain tissues distort the brain's electrical fields. In addition, ERPs are mainly of value when stimuli are simple and the task involves basic processes (e.g., target detection) triggered by task stimuli. Finally, we cannot study most complex forms of cognition (e.g., problem solving) with ERPs.

Positron emission tomography (PET)

Positron emission tomography (PET) is based on the detection of positrons – atomic particles emitted by some radioactive substances. Radioactively labelled water (the tracer) is injected into the body and rapidly gathers in the brain's blood vessels. When part of the cortex becomes active, the labelled water moves there rapidly. A scanning device measures the positrons emitted from the radioactive water, which leads to pictures of the activity levels in different brain regions. Note that tiny amounts of radioactivity are involved.

PET has reasonable spatial resolution in that any active brain area can be located to within 5–10 mm. However, it has very poor temporal resolution – PET scans indicate the amount of activity in any given brain region over 30–60 seconds.

Magnetic resonance imaging (MRI and fMRI)

Magnetic resonance imaging (MRI) involves the use of an MRI scanner (see photo) containing a very large magnet (weighing up to 11 tons). A strong magnetic field causes an alignment of protons (subatomic particles) in the brain. A brief radio-frequency pulse is applied, which causes the aligned protons to spin and then regain their original orientations, giving up a small amount of energy as they do so. The brightest regions in the MRI scan are those emitting the greatest energy. MRI scans can be obtained from numerous angles but tell us only about brain *structure* rather than its *functions*.

Happily enough, the same principles used to produce MRI can also be used to provide functional information in the form of functional magnetic resonance imaging (fMRI). Oxyhaemoglobin is converted into deoxyhaemoglobin when neurons consume oxygen, and deoxyhaemoglobin produces distortions in the local magnetic field. This distortion is assessed by fMRI, and provides a measure of the concentration of deoxyhaemoglobin in the blood.

Technically, what is measured in fMRI is known as **BOLD** (blood oxygen level-dependent contrast). Changes in the BOLD signal produced by increased

KEY TERM

BOLD

blood oxygen level-dependent contrast; this is the signal measured by **functional magnetic resonance imaging (fMRI)**.



Weblink:
PET



Weblink:
fMRI

The magnetic resonance imaging (MRI) scanner has proved an extremely valuable source of data in psychology.
© Shutterstock.



neural activity take some time to occur, so the temporal resolution of fMRI is about two or three seconds. However, its spatial resolution is very good (approximately 1 mm). Since fMRI has superior temporal and spatial resolution to PET, it has largely replaced it in neuroimaging research.

Suppose we want to understand why our participants remember some items but not others. We can use event-related fMRI (efMRI), in which we consider each participant's patterns of brain activation for remembered and forgotten items. Wagner et al. (1998) recorded fMRI while participants learned a list of words. There was more brain activity during learning for words subsequently recognised than those subsequently forgotten. These findings suggest forgotten words were processed less thoroughly than remembered words at the time of learning.

What are fMRI's limitations? First, it provides an indirect measure of underlying neural activity. Second, there are distortions in the BOLD signal in some brain regions (e.g., close to sinuses, close to the oral cavity). Third, the scanner is noisy, which can cause problems for studies involving auditory stimuli. Fourth, some people (especially those with claustrophobia) find it uncomfortable to be encased in the scanner. Cooke et al. (2007) found 43% of participants in an fMRI study were at least a bit upset by the experience and 33% reported side effects (e.g., headaches).

Fifth, there are constraints on the kinds of stimuli that can be presented to participants lying in a scanner. There are also constraints on the responses they can be asked to produce because even small movements can distort the BOLD signal.

Magneto-encephalography (MEG)

Magneto-encephalography (MEG) involves using a superconducting quantum interference device (SQUID) to measure the magnetic fields produced by electrical brain activity. The technology is complex because the size of the magnetic field created by the brain is extremely small relative to the earth's magnetic field.

IN THE REAL WORLD: CAN COGNITIVE NEUROSCIENTISTS READ OUR BRAINS/MINDS?

There is increasing evidence that cognitive neuroscientists can work out what we are looking at just by studying our brain activity (Tong & Pratte, 2012). For example, Haxby et al. (2001) asked participants to view pictures from eight different categories (e.g., cats, faces, houses) while patterns of brain activity were assessed by fMRI. Computer-based analysis of patterns of brain activity allowed the researchers to predict accurately the category of object being viewed on 96% of trials!

Kay et al. (2008) argued that most previous research on “brain reading” or “mind reading” was limited in two ways. First, the visual stimuli were much less complex than those encountered in everyday life. Second, the experimenters’ task of predicting what participants had viewed was simplified by comparing their patterns of brain activity on test trials to those obtained when the same objects or categories had been presented previously.

Kay et al. (2008) overcame the above limitations by presenting two participants with 120 previously unseen natural images of moderate complexity. The fMRI data permitted correct identification of the image being viewed on 92% of the trials for one participant and 72% for the other. This is remarkable given that chance performance was 0.8%! Findings such as these have exciting implications for understanding the brain’s precise role in visual perception.

Studies such as that of Kay et al. (2008) indicate that much more information can be extracted from patterns of brain activity than was previously believed. However, these studies are not *directly* involved in mind reading. Many aspects of the brain activity in response to visual stimuli are very relevant to the participant’s perceptual representation, whereas other aspects are probably irrelevant (Vilarroya, 2013). Support for this viewpoint was reported by Hung et al. (2005). Computer analysis of brain activity in macaques successfully classified various stimuli presented to them that the macaques themselves were unable to distinguish.

However, MEG provides very accurate measurement of brain activity in part because the skull is virtually transparent to magnetic fields.

MEG has excellent temporal resolution (at the millisecond level) and often has very good spatial resolution as well. However, it is extremely expensive. In addition, some people find it uncomfortable to take part in MEG studies. Cooke et al. (2007) discovered that 35% of participants found the experience “a bit upsetting”, and the same percentage reported side effects such as muscle aches or headaches.

Transcranial magnetic stimulation (TMS)

Transcranial magnetic stimulation (TMS) is a technique in which a coil (often in the shape of a figure of eight) is placed close to the participant’s head (see photo). A very brief (less than 1 ms) but large magnetic pulse of current is run through it. This causes a short-lived magnetic field that generally (but not always) leads to inhibited processing in the affected area (generally about 1 cubic centimetre in extent). More specifically, the magnetic field created leads to electrical stimulation in the brain. In practice, several magnetic pulses are typically given in a short period of time – this is repetitive transcranial magnetic stimulation (rTMS). Most research has used rTMS but we will often simply use the more general term TMS.



Weblink:
TMS



Transcranial magnetic stimulation coil.
University of Durham/Simon Fraser/Science Photo Library.

What is an appropriate control condition against which to compare the effects of TMS or rTMS? One possibility is to compare task performance with and without it. However, TMS creates a loud noise and muscle twitching at the side of the forehead, and these effects might lead to impaired performance. Applying TMS to a non-critical brain area (irrelevant to task performance) is often a satisfactory control condition. The prediction is that task performance will be worse when TMS is applied to a critical area than a non-critical one.

Why are TMS and rTMS useful? As mentioned earlier, they often create a “temporary

lesion” so the role of any given brain area in task performance can be assessed. If TMS applied to a particular brain area impairs task performance, we can conclude that brain area is necessary for task performance. Conversely, if TMS has no effects on task performance, then the brain area affected by it is not necessary. Thus, we can often make stronger causal statements about the brain area’s underlying performance with TMS than with most other techniques.

TMS can also indicate *when* any given brain area is most involved in task performance. For example, Cracco et al. (1999) asked participants to detect letters. Performance was maximally impaired when TMS was applied to occipital cortex 80–100 ms after letter presentation rather than at shorter or longer delays.

Evaluation

In principle, the greatest advantage of TMS (and rTMS) over neuroimaging techniques is that they increase our confidence that a given brain area is necessary for task performance. TMS allows us to manipulate the availability of a brain region for involvement in the performance of some cognitive task. In contrast, we only establish associations or correlations between activation in various brain areas and task performance with functional neuroimaging.

TMS can be regarded as producing a brief “lesion”. However, it has various advantages over research on brain-damaged patients having genuine lesions. For example, we can compare any given individual’s performance with and without a lesion with TMS but this is rarely possible with brain-damaged patients. In addition, the experimenter controls the brain area(s) affected by TMS but such control is impossible with brain-damaged patients.

What are TMS’s limitations? First, its effects are complex and not fully understood. For example, Allen et al. (2007) found rTMS applied to the early visual cortex of cats not engaged in any task caused an *increase* of spontaneous brain activity lasting up to one minute. However, activity in the visual cortex produced by viewing gratings was reduced by up to 60% by rTMS. The effects of TMS on performance are generally negative but sometimes positive.

Why does TMS sometimes enhance performance? Consider an area x that typically inhibits the functioning of area y. TMS applied to area x will reduce this inhibition and so might enhance the functioning of area y. More generally, brain functioning is remarkably complex and so we would expect TMS to have somewhat variable effects.

Second, it has proved difficult to establish the precise brain areas affected by TMS, some of which can be distant from the stimulation point. However, progress can be made by combining TMS with neuroimaging techniques to clarify the effects of TMS on brain activity (Ziemann, 2011).

Third, TMS can only be applied to brain areas lying beneath the skull but not to areas with overlying muscle. That limits its overall usefulness.

Fourth, there are safety issues with TMS. For example, it has very occasionally caused seizures in participants in spite of stringent rules designed to ensure their safety.

KEY TERM

Meta-analysis

A form of statistical analysis based on combining the findings from numerous studies on a given issue.

Overall strengths

Do the various techniques for studying the brain answer all our prayers? That would be an overstatement. However, cognitive neuroscientists have made substantial contributions to our understanding of human cognition. The major strengths of cognitive neuroscience will be discussed here.

First, cognitive neuroscience has increasingly helped to resolve theoretical controversies that had remained intractable with purely behavioural studies (White & Poldrack, 2013). We will briefly consider two examples. The first concerns speech perception (see [Chapter 9](#)). Listeners presented with degraded speech find it much more intelligible when the words are predictable. The crucial issue is *when* knowledge of what is being presented influences speech perception. It might occur *early* and thus directly affect basic auditory processes. Alternatively, it might occur *late* and only after basic auditory processing has finished. Theorists differ in their favoured explanation (Mattys et al., 2012).

Wild et al. (2012) addressed this issue. Listeners heard degraded speech accompanied by visual stimuli that matched or did not match the auditory input. There was more activity in primary auditory cortex (involved in early auditory processing) when the visual input matched the auditory input than when it did not. This strongly suggests knowledge of what was being presented *directly* affected basic auditory processes.

The second example concerns visual imagery (see [Chapter 3](#)). There has been much controversy as to whether visual imagery resembles visual perception. Most behavioural evidence is inconclusive. However, brain-imaging research has shown two-thirds of the brain areas activated during visual perception are also activated during visual imagery (Kosslyn, 2005). Kosslyn and Thompson (2003) found in a **meta-analysis** that even brain areas involved in the early stages of visual perception are often activated during visual imagery.

The above findings strongly suggest the processes in visual imagery resemble those in visual perception. However, R.J. Lee et al. (2012) identified important differences using neuroimaging. Participants viewed or imagined common objects and attempts were then made to decide *which* objects were involved based on patterns of brain activation. Identification of perceived objects was much better based on activation in early visual processing areas than subsequent ones, whereas the opposite was the case for imagined objects. Thus, there is more involvement of low-level visual processes in perception than imagery.

Second, it is a major challenge to understand the complexities of the cognitive system and its underlying brain organisation. As we saw earlier, Bullmore and Sporns (2012) argued that the brain is organised into many tight clusters or modules plus long-distance connections among them. The incredible richness of

KEY TERM**Functional specialisation**

The assumption that each brain area or region is specialised for a specific function (e.g., colour processing, face processing).

the data obtained from neuroimaging studies means cognitive neuroscientists can (at least in principle) construct theoretical models accurately mimicking the complexities of brain functioning. In contrast, cognitive neuropsychology seems less flexible and more committed to the notion of a modular brain organisation.

Third, another advantage arises from the remarkable richness of neuroimaging data. If it becomes clear that one approach to analysing such data is limited, it is easy to reanalyse them within a different theoretical framework. For example, it used to be assumed that most face processing occurs in the fusiform face area, but this was a substantial oversimplification (Weiner & Grill-Spector, 2012; see [Chapter 3](#)). An approach based on the assumption that face processing involves a *network* of brain regions provides a more accurate account (Atkinson & Adolphs, 2011). Thus, cognitive neuroscience can be self-correcting.

More generally, cognitive neuroscientists attach less importance than they used to the assumption of **functional specialisation** – the notion that each brain region is specialised for a different function. Instead, they accept there is substantial *integration* and coordination across the brain. Such functional integration can be studied by correlating activity across different brain regions – if a network of brain areas is involved in a given process, activity in all of them should be positively correlated when that process occurs. There is strong evidence for such functional integration with conscious perception, which seems to depend on coordinated activity across several brain regions (see [Chapter 16](#)).

Cognitive neuroscientists have identified an increasing number of major brain networks. For example, Corbetta and Shulman (2002; see [Chapter 5](#)) used findings from cognitive neuroscience to identify two attention networks, one concerned with goal-directed attention and the other with stimulus-driven attention. Other brain networks are discussed by Anderson et al. (2013).

Fourth, cognitive neuroscience is often especially useful when combined with other approaches. Here is an example based on the notion that recognition memory depends on two different processes: recollection and familiarity (see [Chapter 6](#) for the full story). These processes differ in that only recollection involves the conscious retrieval of contextual information. It has been argued theoretically that recollection involves the hippocampal system whereas familiarity involves the nearby perirhinal system.

Research within cognitive neuropsychology has produced a double dissociation supporting the above theory. Patients with damage to the hippocampus have impaired recollection but intact familiarity, whereas those with damage to the perirhinal system have impaired familiarity but intact recollection. Neuroimaging research has strengthened the support for the theory. Recollection is associated with more activation in the hippocampus than the perirhinal cortex, whereas the opposite is the case for familiarity (Diana et al., 2007).

General limitations

We turn now to various issues raised by cognitive neuroscience. First, cognitive neuroscientists often *over-interpret* their findings by assuming there are one-to-one links between cognitive processes and brain areas (Brown, 2012). Thus, for example, activation in a small brain region (a “blob”) is interpreted as being the “love area” or the “religion area”. This approach has been referred to unflatteringly as “blobology”.

Blobology is in decline. However, there is still undue reliance on **reverse inference** – a researcher infers the involvement of a given cognitive process based on activation within a given brain region. Here is an example. Individuals exposed to threat-related information typically show activation of the amygdala (part of the limbic system; Sander, 2009). This led many researchers to conclude the amygdala is central to a fear system.

What is wrong with the above conclusion? Other research has shown the processing of most emotions is associated with amygdala activation (Lindquist et al., 2012; see [Figure 1.7](#)). This illustrates a key problem with reverse inference – most brain regions are involved in several different cognitive processes and so activation of any given brain area is not very informative (Brown, 2012). This was shown clearly by Yarkoni et al. (2011), who considered areas of brain activation across 3,489 studies. Some brain areas (e.g., dorsolateral prefrontal cortex, anterior cingulate cortex and anterior insula) were activated in 20% of the studies. Such areas are involved in several different cognitive processes.

Second, it is very difficult to bridge the divide between psychological processes and concepts on the one hand and patterns of brain activation on the other. As Harley (2012) pointed out, we may never find brain patterns corresponding closely to psychological processes such as “attention” or “planning”.

KEY TERM

Reverse inference

As applied to functional neuroimaging, it involves arguing backwards from a pattern of brain activation to the presence of a given cognitive process.

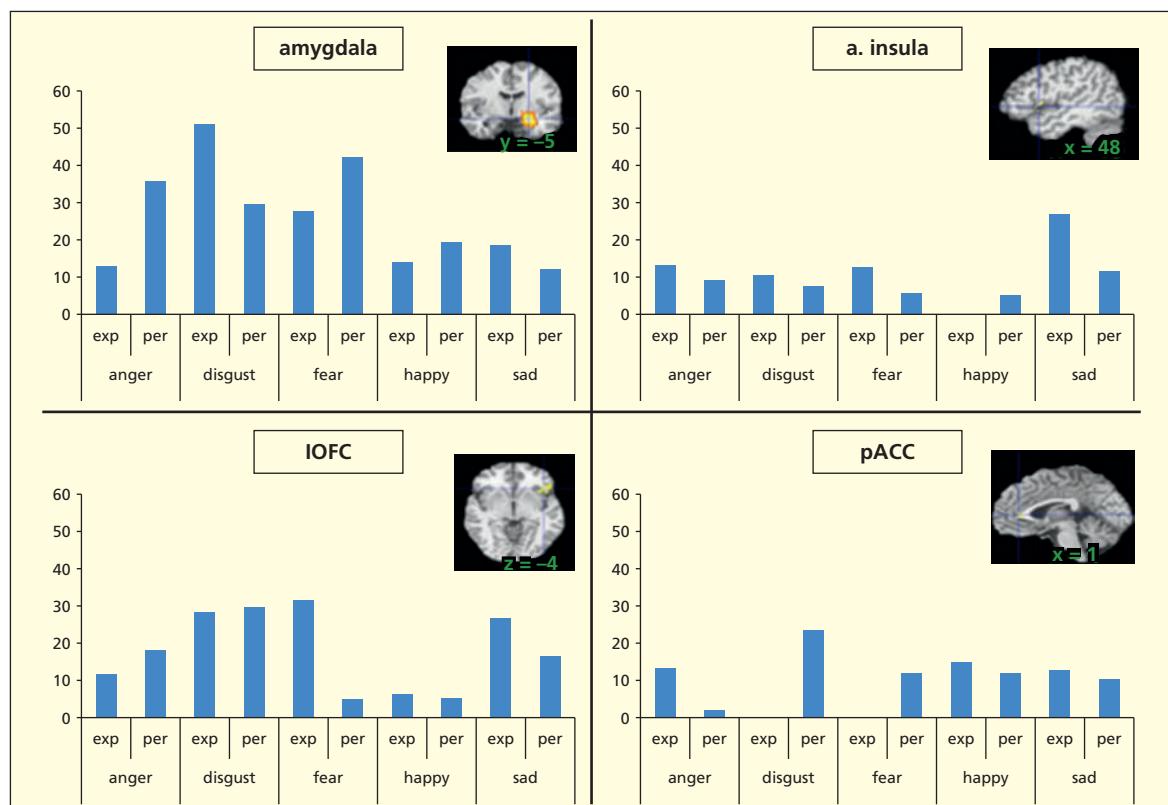


Figure 1.7

Proportion of studies on the experience (exp) and perception (per) of various emotional states (anger, disgust, fear, happiness and sadness) showing amygdala activity. IOFC = lateral orbitofrontal cortex; pACC = pregenual anterior cingulate cortex.

From Lindquist et al. (2012). Reprinted with permission of Cambridge University Press.

Harley (2012, p. 1372) concluded as follows: “Our language and thought may not divide up in the way in which the brain implements these processes.”

Third, most neuroimaging studies are *underpowered*, typically using 20 participants or fewer. This produces the problem that “most fMRI analyses will detect only a fraction of the true effects, producing a deceptive illusion of ‘selective’ activation” (Yarkoni et al., 2010, p. 489). One solution to this problem is to combine findings across studies. As already mentioned, Yarkoni et al. (2011) considered 3,489 studies from which 100,953 activation points were identified. This greatly increased the chances of identifying most true effects while reducing the percentage of false positives. It also made it much easier to identify precisely which cognitive processes were associated with activation in any given area.

Fourth, false positive results (i.e., mistakenly concluding that random activity in a given brain area is task-relevant activation) are common and may occur as often as 15% of the time (Yarkoni et al., 2010). False positives arise because most neuroimaging studies produce huge amounts of data and some researchers fail to correct their statistical thresholds (p values required for significance) to take full account of it.

Bennett et al. (2009) provided an amusing example of a false positive finding. They asked their participant to determine the emotions shown in pictures of people in social situations. When they did not correct their statistical thresholds, there was significant evidence of brain activation (see [Figure 1.8](#)). The interesting feature of this study was that the participant was a dead salmon! Thus, we know for certain the “finding” was a false positive.

Fifth, most brain-imaging techniques reveal only *associations* between patterns of brain activation and behaviour. For example, performance on a reasoning task is associated with activation of the prefrontal cortex. Such associations are purely correlational and do not show that the brain regions activated are essential for task performance. Brain activation might also be caused by participants engaging in unnecessary monitoring of their performance or attending to non-task stimuli.

Transcranial magnetic stimulation (TMS) offers a partial solution to this causality issue. We can show a given brain area is necessary for the performance of a task by finding that TMS disrupts that performance. However, the complexities of TMS’s effects on the brain sometimes mean that caution in interpretation is needed.

Sixth, many cognitive neuroscientists assume that most brain activity is driven by environmental or task demands. If that assumption is correct, we might expect most brain activity in response to such demands. Surprisingly, that is *not* the case. In fact, the increased brain activity occurring when someone performs a cognitive task typically adds less than 5% to resting brain activity. This is probably much less than the brain energy consumption devoted to *intrinsic* activity within the brain that occurs in unstimulating environments.

Why is the brain so active even when the environment is unstimulating? Part of the answer is that people often devote cognitive resources to

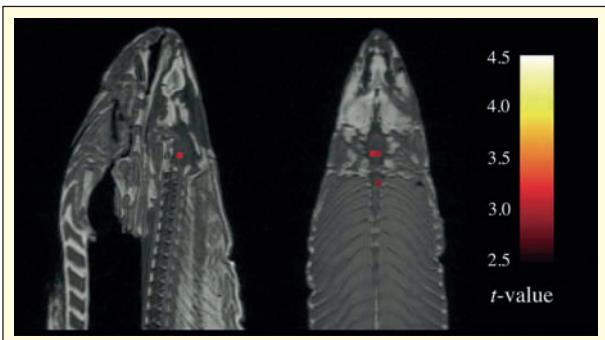


Figure 1.8

Areas showing greater activation in a dead salmon when presented with photographs of people than when at rest. From Bennett et al. (2009). With kind permission of the authors.

predicting future environmental changes (Raichle, 2010). However, the finding that patterns of brain activity are similar in different states of consciousness, including coma, anaesthesia and slow-wave sleep, suggests most intrinsic brain activity reflects basic brain functioning. As a result of intrinsic brain activity, task performance is often associated with *decreased* brain activity in some brain regions rather than the expected *increase*.

Seventh, cognitive neuroscience shares with cognitive psychology problems of ecological validity (applicability to everyday life) and paradigm specificity (findings do not generalise across paradigms). Indeed, the problem of ecological validity may be greater in cognitive neuroscience. Participants in fMRI studies (the most used technique) lie on their backs in somewhat claustrophobic and noisy conditions and have very restricted movement – not much like everyday life!

Gutches and Park (2006) compared the effects of being in an MRI scanner or simply in the laboratory on long-term recognition memory. Memory was significantly worse in the scanner, presumably because it provided a more distracting or anxiety-creating environment.

Eighth, we must avoid “the neuroimaging illusion”, which involves overvaluing the contribution pictures of brain activity make to our understanding of human cognition (see Chapter 14). Keehner et al. (2011) presented neuroscience articles accompanied by brain images. The more three-dimensional the images appeared to be, the more positively the articles were evaluated. Here is a concrete example of the neuroimaging illusion. On 28 August 2007, *The Guardian* had the following headline: “Brain scans pinpoint how chocoholics are hooked.” In essence, the researchers involved (Rolls & McCabe, 2007) had found that the sight of chocolate produced more activation in reward centres of the brain in chocolate cravers than in non-cravers. Thus, the findings that so impressed *The Guardian* tell us little more than that chocolate cravers find chocolate rewarding (Beck, 2010)!

COMPUTATIONAL COGNITIVE SCIENCE

We will start by distinguishing between computational modelling and artificial intelligence. **Computational modelling** involves programming computers to model or mimic aspects of human cognitive functioning. In contrast, **artificial intelligence** involves constructing computer systems that produce intelligent outcomes but may do so in ways bearing little resemblance to those used by humans. Consider Deep Blue, the chess program that defeated the World Champion Garry Kasparov on 11 May 1997. Deep Blue considered up to 200 million positions per second, which is vastly more than any human chess players (see Chapter 12).

Computational cognitive scientists develop computational models to understand human cognition. A good computational model shows us how a given theory can be specified and allows us to predict behaviour in new situations. Early mathematical models made predictions but often lacked an explanatory component. For example, having three traffic violations predicts well whether someone is a bad risk for car insurance but it is not clear why. A major benefit of the computational models developed in computational cognitive science is that they often provide an exploratory and predictive basis for a phenomenon (Costello & Keane, 2000).

KEY TERMS

Computational modelling

This involves constructing computer programs that simulate or mimic human cognitive processes.

Artificial intelligence

This involves developing computer programs that produce intelligent outcomes.



Weblink:

AI on the web

KEY TERMS

Cognitive architecture:

A comprehensive framework for understanding human cognition in the form of computer programs.

Connectionist models

Models in computational cognitive science consisting of interconnected networks of simple units; the networks exhibit learning through experience and specific items of knowledge are distributed across numerous units.

In the past (and even nowadays), many experimental cognitive psychologists expressed their theories in vague verbal statements, which made it hard to decide whether the evidence fitted the theory. As Murphy (2011) pointed out, verbal theories provide theorists with undesirable “wiggle room”. In contrast, a computational model “requires the researcher to be explicit about a theory in a way that a verbal theory does not” (Murphy, 2011, p. 300). Implementing a theory as a program is a good way to check it contains no hidden assumptions or imprecise terms. This often reveals that the theory makes predictions the theorist concerned had not realised!

There are issues concerning the relationship between the performance of a computer program and human performance (Costello & Keane, 2000). It is rarely meaningful to relate a program’s speed doing a simulated task to the reaction times of human participants, because its processing times are affected by psychologically irrelevant features. For example, programs run faster on more powerful computers. However, the various materials presented to the program should result in differences in program operation time correlating closely with differences in participants’ reaction times when processing the same materials.

Types of models

Most computational models focus on relatively specific aspects of human cognition. For example, some of the most successful computational models provide accounts of reading words and non-words aloud (Plaut et al., 1996; Coltheart et al., 2001; Perry et al., 2007) (see [Chapter 9](#)). However, some computational models are more ambitious. This is especially the case with **cognitive architectures**, which are “cognitive models that are domain-genetic [cover many domains or areas] and encompass a wide range of cognitive applicabilities” (Sun, 2007, p. 160). Byrne (2012) evaluated some of the major cognitive architectures including J.R. Anderson et al.’s (2004) Adaptive Control of Thought-Rational [ACT-R], which is discussed later.

There are more computational models than you can shake a stick at. However, numerous otherwise diverse models can be categorised as connectionist models, and so we will focus on them. Many other models are based on production systems, and will be discussed briefly. Our emphasis will be on *what* various computational approaches achieve rather than the details of *how* this happens.

Connectionism



Weblink:
Connectionism

Connectionist models typically consist of interconnected networks of simple units exhibiting learning. Within such networks, each item of knowledge is represented by a pattern of activation spread over numerous units rather than by a single location. Connectionist networks often (but not always) have the following characteristics (see [Figure 1.9](#)):

- The network consists of elementary or neuron-like *units* or *nodes* connected together, with a single unit having many links to other units.
- Units influence other units by exciting or inhibiting them.
- The unit usually takes the weighted sum of all the input links, and produces a single output to another unit if the weighted sum exceeds some threshold value.

- The network as a whole is characterised by the properties of the units that make it up, by the way they are connected together, and by the rules used to change the strength of connections among units.
- Networks can have different structures or layers; they can have a layer of input links, intermediate layers (“hidden units”) and a layer of output units (see Figure 1.9).
- A representation of a concept can be stored in a *distributed* way by an activation pattern throughout the network.
- The same network can store several patterns without disruption if they are sufficiently distinct.
- An important learning rule used in networks is called *backward propagation of errors* (*BackProp*) (see below).

KEY TERM**Back-propagation**

A learning mechanism in connectionist models based on comparing actual responses to correct ones.

Connectionist networks model cognitive performance without using any explicit rules. They do this by storing patterns of activation within the network in which various inputs are associated with various outputs. Connectionist models typically consist of several layers. One layer consists of input units that encode a stimulus as a pattern of activation. Another layer is an output layer producing some response as a pattern of activation. When the network has learned to produce a given response at the output layer following the presentation of a given stimulus at the input layer, it exhibits behaviour that looks rule-based.

“Backward propagation of errors”, or BackProp, is an extremely important learning rule. **Back-propagation** is a mechanism allowing a network to learn to associate a given input pattern with a given output pattern by comparing actual responses against correct ones. The network is initially set up with random weights on the links among the units. During the early stages of learning, the output units often produce an incorrect pattern or response following presentation of the input pattern. BackProp compares the imperfect pattern with the known required response, noting the errors. It then back-propagates activation through the network so the weights between the units are adjusted to produce the required pattern. This process is repeated until the network produces the required pattern. Thus, the model learns the appropriate behaviour without being explicitly programmed to do so. Sadly, research in cognitive neuroscience has found little or no evidence of back-propagation in the human brain (Mayor et al., 2014).

Several connectionist models (e.g., the parallel distributed processing approach of Rumelhart et al., 1986) assume representations are stored in a *distributed* fashion across the brain. There are potential problems with this assumption. Suppose we encode two words at the same time. That would cause numerous units or nodes to become activated, making it hard (or even impossible) to decide which units or nodes belonged to which word (Bowers, 2002). There is also evidence that much information is stored in a given brain

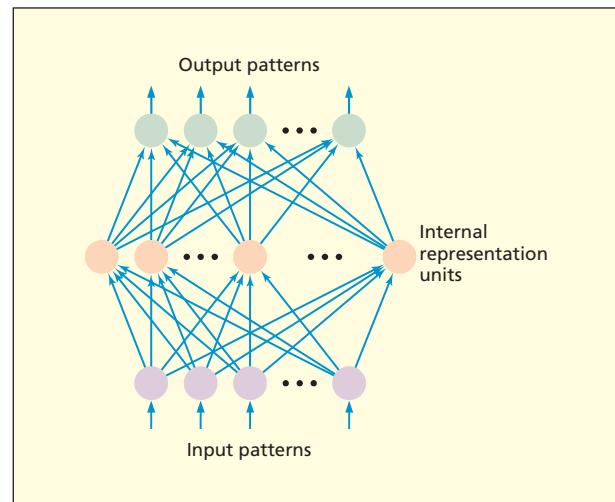


Figure 1.9

A multi-layered connectionist network with a layer of input units, a layer of internal representation units, or hidden units, and a layer of output units, in a form that allows the appropriate output pattern to be generated from a given input pattern.

Reproduced with permission from Rumelhart and McClelland (1986). Copyright © 1986 Massachusetts Institute of Technology, by permission of The MIT Press.

KEY TERMS

Production systems

These consist of very large numbers of “if . . . then” **production rules** and a working memory containing information.

Production rules

“If . . . then” or condition-action rules in which the action is carried out whenever the appropriate condition is present.

Working memory

A system holding information currently being processed.

location rather than in a distributed fashion (see Bowers (2009) for a review). For example, as mentioned earlier, Quiroga et al. (2005) discovered a neuron in the medial temporal lobe that responded strongly when pictures of the actress Jennifer Aniston were presented but not other famous people (see [Chapter 3](#)).

Some connectionist models assume there is *local* representation of knowledge. Localist connectionist models include the reading model of Coltheart et al. (2001; see [Chapter 9](#)); the TRACE model of word recognition (McClelland & Elman, 1986; see [Chapter 9](#)); and the models of speech production put forward by Dell (1986) and by Levelt et al. (1999; see [Chapter 11](#)). It is likely some knowledge is represented locally and some is distributed (see [Chapter 7](#)).

Production systems

Production systems consist of numerous “If . . . then” production rules. **Production rules** can take many forms. However, an everyday example is, “If the green man is lit up, then cross the road.” There is also a **working memory** (i.e., a system holding information currently being processed). If information from the environment that “the green man is lit up” reaches working memory, it will match the IF-part of the rule in long-term memory and trigger the THEN-part of the rule (i.e., cross the road).

Production systems come in various shapes and sizes but generally have the following characteristics:

- numerous “If . . . then” rules;
- a working memory containing information;
- a production system that operates by matching the contents of working memory against the IF-parts of the rules and executing the THEN-parts;
- if information in working memory matches the IF-parts of two rules, a conflict-resolution strategy selects one.

Many aspects of cognition can be specified as sets of “If . . . then” rules. For example, chess knowledge can readily be represented as a set of productions based on rules such as, “If the Queen is threatened, then move the Queen to a safe square.” In this way, people’s basic knowledge can be regarded as a collection of productions.

Newell and Simon (1972) first established the usefulness of production system models in their General Problem Solver, which identified cognitive processes involved in problem solving (see [Chapter 12](#)). However, these models have a wider applicability. For example, there is J.R. Anderson et al.’s (2004) ACT-R. This is a cognitive architecture and is discussed next.

ACT-R

John Anderson has produced several versions of Adaptive Control of Thought-Rational [ACT-R]. The version described by J.R. Anderson et al. (2004) is based on the assumption that the cognitive system consists of several modules (relatively independent subsystems). ACT-R combines computational cognitive science with cognitive neuroscience by identifying the brain regions associated with each module (see [Figure 1.10](#)). Four modules are of particular importance to human cognition:

- 1 *Retrieval module*: it maintains the retrieval cues needed to access information; its proposed location is the inferior ventrolateral prefrontal cortex.
- 2 *Imaginal module*: it transforms problem representations to assist in problem solving; it is located in the posterior parietal cortex.
- 3 *Goal module*: it keeps tracks of an individual's intentions and controls information processing; it is located in the anterior cingulate cortex.
- 4 *Procedural module*: it uses production (if . . . then) rules to determine what action will be taken next; it is located at the head of the caudate nucleus within the basal ganglia.

Each module has a buffer associated with it containing a limited amount of important information. How is information from these buffers integrated? According to J.R. Anderson et al. (2004, p. 1058), "A central production system can detect patterns in these buffers and take co-ordinated action." If several productions could be triggered by the information contained in the buffers, one is selected based on the value or gain associated with each outcome plus the amount of time or cost incurred in achieving that outcome.

ACT-R represents an impressive attempt to provide a theoretical framework for understanding information processing and performance on numerous cognitive tasks. It is an ambitious attempt to integrate computational cognitive science with cognitive neuroscience.

What are the limitations of ACT-R? First, it is very hard to provide adequate tests of such a wide-ranging theory. Second, it can be argued that areas of prefrontal cortex (e.g., dorsolateral prefrontal cortex) generally assumed to be of major importance in cognition are de-emphasised. Third, as discussed earlier, research within cognitive neuroscience increasingly reveals the importance to cognitive processing of brain networks rather than specific regions.

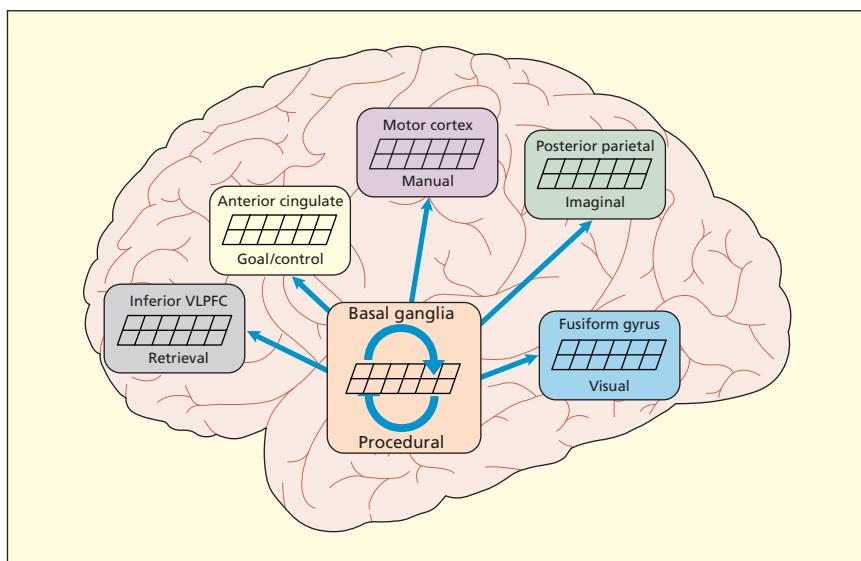


Figure 1.10

The main modules of the ACT-R (Adaptive Control of Thought-Rational) cognitive architecture with their locations within the brain.

Reprinted from Anderson et al. (2008). Reprinted with permission of Elsevier.

Links with other approaches

The great majority of computational models until fairly recently were designed to predict and understand behavioural data from experiments in cognitive psychology. Recently, however, there has been a substantial increase in computational models of direct relevance to cognitive neuropsychology and cognitive neuroscience (e.g., ACT-R).

How are computational models applied to cognitive neuropsychological data from brain-damaged patients? Typically, the starting point is to develop a computational model that accounts for the performance of healthy individuals on some task. After that, aspects of the computational model or program are altered to simulate “lesions”, and the effects on task performance are assessed. Finally, the lesioned model’s performance can be compared against that of brain-damaged patients (Dell & Caramazza, 2008).

Overall evaluation

Computational cognitive science has several strengths. First, the development of cognitive architectures offers the prospect of providing an overarching framework within which to understand the cognitive system. Such a framework could be very valuable. This is especially so given that much empirical research in cognitive psychology is limited in scope and suffers from paradigm specificity (see Glossary). However, there is controversy concerning the extent to which this goal has been achieved.

Second, the scope of computational cognitive science has increased over time. Initially, it was applied mainly to behavioural data. More recently, computational modelling has been applied to functional neuroimaging data. In addition, many computational cognitive scientists “lesion” their models to see the effects of damage to various parts of the model and to compare their findings against behavioural data from brain-damaged patients.

Third, the development of computational models requires theorists to think carefully and rigorously. This is the case because computer programs must contain detailed information about the processes involved in performing any given task. In contrast, many theories in verbal form are vaguely expressed and it is unclear precisely what predictions follow from their assumptions.

Fourth, it is often possible to make progress by using what is known as *nested incremental modelling*. In essence, a new model builds upon the strengths of previous related models while eliminating their weaknesses and accounting for additional data. For example, Perry et al. (2007) put forward a connectionist dual-process model (CDP+) of reading aloud that improved on the dual-process model from which it was derived.

What are the main limitations of the computational cognitive science approach? First, there is Bonini’s paradox: “As a model of a complex system becomes more complete, it becomes less understandable. Alternatively, as a model grows more realistic, it also becomes just as difficult to understand as the real-world processes it represents” (Dutton & Starbuck, 1971, p. 4).

The relation between a map and a territory provides a simple example of Bonini’s paradox. A map the same size as the territory it represents would be maximally precise but also completely unusable. In practice, however, the increased complexity of computational models has been accompanied by a substantial increase in their power.

Second, it is sometimes difficult to falsify computational models although typically easier than with theories expressed only in verbal terms. Why is this? The ingenuity of computational modellers means that many models can account for numerous behavioural findings. Of promise for the future is the prospect of computational models being applied more systematically to neuroimaging findings as well as behavioural ones.

Third, there are various ways in which computational modellers increase the apparent success of their model. One example is overfitting (Ziegler et al., 2010). This happens when a model accounts extremely well for a given data set but fails to generalise to other data sets. This can occur when a model accounts for noise in the data as well as genuine effects.

Fourth, human cognition is influenced by several potentially conflicting motivational and emotional factors. Most computational models ignore these factors, although ACT-R (Anderson et al., 2008) has a motivational component in its goal module. We can distinguish between a cognitive system (the Pure Cognitive System) and a biological system (the Regulatory System) (Norman, 1980). Much activity of the Pure Cognitive System is determined by the Regulatory System's needs (e.g., survival, food and water). Computational cognitive science (like most of cognitive psychology) typically de-emphasises the Regulatory System's key role.

Fifth, it is difficult to assess most computational models in detail. As Addyman and French (2012, p.332) pointed out, there are several reasons for this:

Everyone still programs in his or her own favourite programming language, source code is rarely made available, accessibility of models to non-programming researchers is essentially non-existent, and even for other modellers, the profusion of source code in a multitude of programming languages, writing without programming guidelines, makes it almost impossible to access, check, explore, re-use or continue to develop.

COMPARISONS OF MAJOR APPROACHES

We have discussed the major approaches to human cognition at length, and you may be wondering which one is the most useful and informative. In fact, that is *not* the best way of thinking about the issues for various reasons. First, an increasing amount of research involves two or more of the approaches.

Second, each approach makes its own distinctive contribution, and so all are needed. In terms of an analogy, it is pointless asking whether a driver is more or less useful than a putter to a golfer – both are essential.

Third, as well as its own strengths, each approach also has its own limitations. This can be seen clearly in [Table 1.1](#). What is optimal in such circumstances is to use **converging operations** – several different research methods are used to address a given theoretical issue with the strength of one method balancing out the limitations of the other methods. If two or more methods produce the same answer, that provides stronger evidence than could be obtained using a single method. If different methods produce different answers, then further research is needed to clarify the situation.

The major goal of research is to enhance our understanding of human cognition. In writing this book, our central aim with each topic discussed has been to focus on research that best achieves that goal. As a result, any given approach

KEY TERM

Converging operations

An approach in which several methods with different strengths and limitations are used to address a given issue.



Weblink:

Comparison between production systems and connectionist models

TABLE 1.1 STRENGTHS AND LIMITATIONS OF MAJOR APPROACHES TO HUMAN COGNITION

Strengths	Limitations
Experimental cognitive psychology	
1. The first systematic approach to understanding human cognition.	1. Most cognitive tasks are complex and involve many different processes.
2. The source of most of the theories and tasks used by the other approaches.	2. Behavioural evidence provides only indirect evidence concerning internal processes.
3. It is enormously flexible and can be applied to any aspect of cognition.	3. Theories are sometimes vague and hard to test empirically.
4. It has produced numerous important replicated findings.	4. Findings sometimes do not generalise because of paradigm specificity.
5. It has strongly influenced social, clinical, and developmental psychology.	5. There is a lack of an overarching theoretical framework.
Cognitive neuropsychology	
1. Double dissociations have provided strong evidence for various major processing modules.	1. Patients may develop compensatory strategies not found in healthy individuals.
2. Causal links can be shown between brain damage and cognitive performance.	2. Most of the theoretical assumptions (e.g., that the mind is modular) seem too extreme.
3. It has revealed unexpected complexities in cognition (e.g., language).	3. It minimises the interconnectedness of cognitive processes.
4. It transformed memory research.	4. There has been excessive reliance on single-case studies.
5. It straddles the divide between cognitive psychology and cognitive neuroscience.	5. There is insufficient focus on the brain and its functioning.
Cognitive neuroscience: Functional neuroimaging + ERPs + TMS	
1. Great variety of techniques offering excellent temporal or spatial resolution.	1. Functional neuroimaging techniques provide essentially correlational data.
2. Functional specialisation and brain integration can be studied.	2. Much over-interpretation of data involving reverse inferences.
3. TMS is flexible and permits causal inferences.	3. Most studies are underpowered and there are many false positives.
4. Rich data permit assessment of integrated brain processing as well as specialised functioning.	4. Brain functioning is dauntingly complex.
5. Resolution of complex theoretical issues.	5. Difficulty in relating brain activity to psychological processes.
Computational cognitive science	
1. Theoretical assumptions are spelled out in precise detail.	1. Many computational models do not make new predictions.
2. Comprehensive cognitive architectures have been developed.	2. There is some overfitting, which restricts generalisation to other data sets.
3. Computational models are increasingly used to model effects of brain damage.	3. It is sometimes hard to falsify computational models.
4. Computational cognitive neuroscience is increasingly used to model patterns of brain activity.	4. Computational models generally de-emphasise motivational factors.
5. The emphasis on parallel processing fits well with functional neuroimaging data.	5. Computational models tend to ignore emotional factors.

(e.g., cognitive neuroscience, cognitive neuropsychology) is strongly represented when we cover certain topics but is much less represented with other topics.

OUTLINE OF THIS BOOK

One problem with writing a textbook of cognitive psychology is that virtually all the processes and systems in the cognitive system are interdependent. Consider, for example, a student *reading* a book to prepare for an examination. The student is *learning*, but several other processes are going on as well. *Visual perception* is involved in the intake of information from the printed page, and there is *attention* to the content of the book.

In order for the student to benefit from the book, he/she must possess considerable *language skills*, and must have extensive relevant knowledge stored in *long-term memory*. There may be an element of *problem solving* in the student's attempts to relate the book's content to the possibly conflicting information he/she has learned elsewhere. *Decision making* may also be involved when the student decides how much time to devote to each chapter.

In addition, what the student learns depends on his/her *emotional state*. Finally, the acid test of whether the student's learning has been effective comes during the examination itself, when the material from the book must be *retrieved* and *consciously* evaluated to decide its relevance to the examination question.

The words italicised in the previous paragraphs indicate major ingredients of human cognition and form the basis of our coverage. In view of the *interdependence* of all aspects of the cognitive system, there is an emphasis in this book on how each process (e.g., perception) depends on other processes and structures (e.g., attention, long-term memory). This should aid the task of understanding the complexities of human cognition.

CHAPTER SUMMARY

- **Introduction.** Cognitive psychology used to be unified by an approach based on an analogy between the mind and the computer. This information-processing approach viewed the mind as a general-purpose, symbol-processing system of limited capacity. Today there are four main approaches to human cognition: experimental cognitive psychology; cognitive neuroscience; cognitive neuropsychology; and computational cognitive science. However, the four approaches are increasingly combined with information from behaviour and brain activity being integrated.
- **Cognitive psychology.** Cognitive psychologists assume that top-down and bottom-up processes are both involved in the performance of cognitive tasks. These processes can be serial or parallel. Various methods (e.g., latent-variable analysis) have been used to address the task impurity problem and to identify the processes within cognitive tasks. In spite of the enormous contribution made by cognitive psychology, it sometimes lacks ecological validity, suffers from paradigm specificity and possesses theoretical vagueness.

- **Cognitive neuropsychology.** Cognitive neuropsychology is based on various assumptions including modularity, anatomical modularity, uniformity of functional architecture and subtractivity. Double dissociations provide reasonable (but not definitive) evidence for separate modules or systems. The case-study approach is generally (but not always) more informative than the single-case approach. Cognitive neuropsychology is limited because patients can develop compensatory strategies, because it de-emphasises findings in cognitive neuroscience, because it underestimates integrated brain functioning and because the brain damage is often so extensive it is hard to interpret the findings.
- **Cognitive neuroscience: the brain in action.** Cognitive neuroscientists study the brain as well as behaviour using techniques varying in spatial and temporal resolution. Functional neuroimaging techniques provide basically correlational evidence, but TMS can indicate that a given brain area is necessarily involved in a particular cognitive function. The richness of the data obtained from neuroimaging studies is so great that functional specialisation and brain integration can both be assessed. Cognitive neuroscience is a flexible and potentially self-correcting approach. However, findings are sometimes over-interpreted. More research is needed into possible problems with ecological validity in fMRI studies.
- **Computational cognitive science.** Computational cognitive scientists develop computational models to understand human cognition. Connectionist networks make use of elementary units or nodes connected together. They can learn using rules such as back-propagation. Production systems consist of production or "If . . . then" rules. ACT-R is one of the most developed theories based on production systems. Computational models have increased in scope to provide detailed theoretical accounts of findings from cognitive neuroscience and cognitive neuropsychology. They have shown progress via the use of nested incremental modelling. Computational models are often hard to falsify and they generally de-emphasise motivational and emotional factors.
- **Comparisons of different approaches.** The major approaches are increasingly used in combination. Each approach has its own strengths and limitations, which makes it useful to use converging operations. When two approaches produce the same findings, this is stronger evidence than can be obtained from a single approach on its own. If two approaches produce different findings, this indicates additional research is needed to understand what is happening.

Further reading

- Byrne, M.D. (2012). Unified theories of cognition. *Wiley Interdisciplinary Reviews – Cognitive Science*, 3: 431–8. Several major cognitive architectures are discussed and evaluated.
- Moran, J.M. & Zaki, J. (2013). Functional neuroimaging and psychology: What have you done for me lately? *Journal of Cognitive Neuroscience*, 25: 834–42. Joseph Moran and Jamil Zaki discuss how cognitive neuroscience is enhancing our theoretical understanding of human cognition.
- Patterson, K. & Plaut, D.C. (2009). “Shallow draughts intoxicate the brain”: Lessons from cognitive science for cognitive neuropsychology. *Topics in Cognitive Science*, 1: 39–58. This article identifies several key issues with respect to cognitive neuropsychology.
- Shallice, T. & Cooper, R.P. (2011). *The organisation of mind*. Oxford: Oxford University Press. This is an authoritative account of the contributions made by cognitive neuroscience.
- Ward, J. (2010). *The student’s guide to cognitive neuroscience* (2nd edn). Hove: Psychology Press. The first five chapters of this textbook provide detailed information about the main techniques used by cognitive neuroscientists.
- White, C.N. & Poldrack, R.A. (2013). Using fMRI to constrain theories of cognition. *Perspectives on Psychological Science*, 8(1): 79–83. Corey White and Russell Poldrack indicate ways in which functional neuroimaging can help to resolve theoretical controversies.
- Wilshire, C. (2014). *Cognitive neuropsychology: Exploring the mind through brain dysfunction*. Hove: Psychology Press. Carolyn Wilshire discusses the ways in which cognitive neuropsychology has enhanced our understanding of human cognition.

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Visual perception and attention

Visual perception is of enormous importance in our everyday lives. It allows us to move around freely, to see people with whom we are interacting, to read magazines and books, to admire the wonders of nature and to watch movies and television. Visual perception is also extremely important in helping to ensure our survival. For example, if we misperceive how close cars are to us as we cross the road, the consequences could be fatal. Thus, it is unsurprising that far more of the cortex (especially the occipital lobes at the back of the brain) is devoted to vision than to any other sensory modality.

We will start by considering what is meant by *perception*: “The acquisition and processing of sensory information in order to see, hear, taste, or feel objects in the world; also guides an organism’s actions with respect to those objects” (Sekuler & Blake, 2002, p. 621).

Visual perception seems so simple and effortless we typically take it for granted. In fact, it is very complex and numerous processes transform and interpret sensory information. Some of the complexities of visual perception became clear when researchers in artificial intelligence tried to programme computers to “perceive” the environment. Even when the environment was artificially simplified (e.g., consisting only of white solids) and the task was apparently easy (e.g., deciding how many objects were present), computers required very complicated programming to succeed. It remains the case that no computer can match more than a fraction of the skills of visual perception possessed by nearly every human adult.

There is a rapidly growing literature on visual perception (especially from the cognitive neuroscience perspective). The next three chapters provide reasonably detailed coverage of the main issues. In [Chapter 2](#), our coverage focuses on basic processes involved in visual perception. There is an emphasis on the enormous advances that have been made in understanding the various brain systems involved. It seems commonsensical to assume that the processes leading to object recognition also guide vision-for-action. However, we will see that that assumption is oversimplified. Finally, [Chapter 2](#) contains a detailed consideration of important aspects of visual perception such as colour perception, perception without awareness and depth perception.

A major achievement of perceptual processing is object recognition, which involves identifying objects in the world around us. The central focus of [Chapter 3](#) is on the processes underlying this achievement. Initially, we discuss perceptual organisation, and how we decide which parts of the visual input belong together and so form an object. We then move on to theories of object recognition, including a discussion of the relevant behavioural and neuroscience evidence.

Are the same recognition processes used regardless of the type of object? This issue remains controversial. However, most (but by no means all) experts agree that face recognition differs in important ways from ordinary object recognition. Accordingly, face recognition is discussed separately from the recognition of other objects.

The final part of [Chapter 3](#) is devoted to another major controversial issue, namely, whether the main processes involved in visual imagery are the same as those involved in visual perception. As we will see, there are good grounds for arguing that this controversy has largely been resolved (turn to [Chapter 3](#) to find out how!).

The central focus of [Chapter 4](#) is on how we process a constantly changing environment and manage to respond appropriately to those changes. Of major importance here is our ability to predict the speed and direction of objects and to move in the direction we want whether walking or driving. The ability to reach for and grasp objects is also important. Humans are also skilled at the more complex task of making sense of the movements of other people, and this is another topic discussed in [Chapter 4](#).

There are clearly important links between visual perception and attention. The final topic discussed in [Chapter 4](#) is concerned with the notion that we may need to *attend* to an object to perceive it consciously. Failures of attention can prevent us from noticing changes in objects or the presence of an unexpected object.

Issues relating directly to attention are considered in detail in [Chapter 5](#). In that chapter, we start with the processes involved in focused attention in the visual and auditory modalities. After that, we consider how we use visual processes when engaged in the everyday task of searching for some object (e.g., a pair of socks in a drawer). There has been a large increase in the amount of research concerned with disorders of visual attention, and this research has greatly increased our understanding of visual attention in healthy individuals. Finally, as we all know to our cost, it can be very hard to do two things at once. We conclude [Chapter 5](#) by considering the factors determining the extent to which we do this successfully.

In sum, the area spanning visual perception and attention is among the most exciting and important within cognitive psychology and cognitive neuroscience. There has been tremendous progress in unravelling the complexities of perception and attention over the past decade. Some of the choicest fruits of that endeavour are set before you in the four chapters forming this section of the book.

Basic processes in visual perception

INTRODUCTION

Much progress has been made in understanding visual perception in recent years. Much of this is due to the efforts of cognitive neuroscientists, thanks to whom we now have a good knowledge of the brain systems involved in visual perception. We start by considering the main brain areas involved in vision and the functions served by each area. This is followed by a discussion of theories of brain systems in vision. After that, there is a detailed analysis of basic aspects of visual perception (e.g., colour perception, depth perception). Finally, we consider the issue of whether perception can occur in the absence of conscious awareness.

Chapter 3 focuses mostly on the various processes involved in object and face recognition. In the interests of clarity, we generally deal with a single aspect of visual perception in any given section. In fact, however, all the processes involved in visual perception interact with each other.

The specific visual processes we use depend very much on what we are looking at and our perceptual goals (Hegdé, 2008). For example, we can sometimes perceive the gist of a natural scene extremely rapidly (Thorpe et al., 1996). Observers saw photographs, some of which contained an animal, for only 20 ms. EEG recordings (see Glossary) indicated the presence of an animal was detected within about 150 ms.

In contrast, look at the photograph shown in Figure 2.1 and decide how many animals are present. It probably took you several seconds to perform this task. Bear in mind the diversity of visual perception as you read this and the two following chapters.

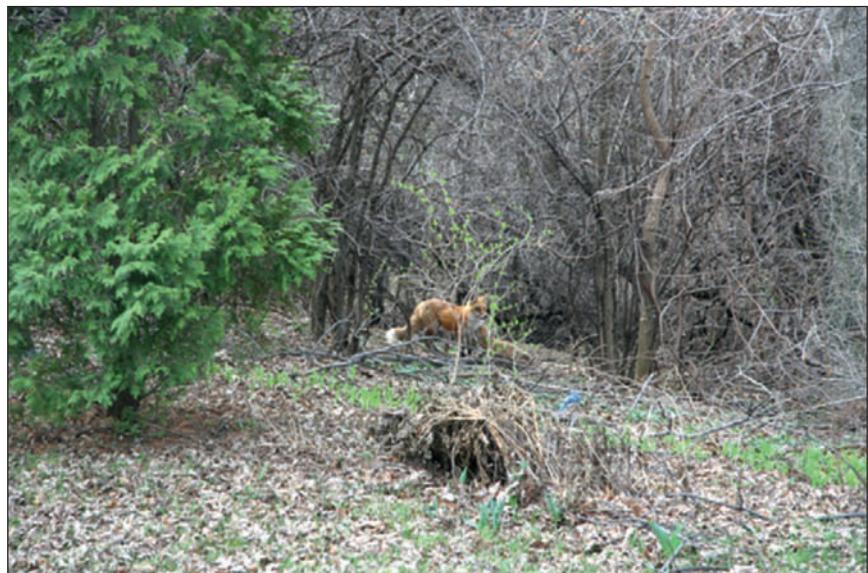
VISION AND THE BRAIN

In this section, we consider the brain systems involved in visual perception. Much of the posterior (back) half of the cortex is devoted to vision, and visual processing occurs in approximately 25 distinct brain areas (Felleman & Van Essen, 1991). More specifically, the visual cortex consists of the whole of the occipital cortex at the back of the brain and also extends well into the temporal and parietal lobes. However, to understand fully visual processing in the brain, we need first to

Figure 2.1

Complex scene that requires prolonged perceptual processing to understand fully. Study the picture and identify the animals within it.

Reprinted from Hegdé (2008). Reprinted with permission of Elsevier.



consider briefly what happens between the eye and the cortex. Accordingly, we start with that before moving on to visual processing in the cortex.

**Weblink:**

Structure of the eye

KEY TERMS**Retinal ganglion cells**

Retinal cells providing the output signal from the retina.

Retinotopy

The notion that there is mapping between receptor cells in the retina and points on the surface of the visual cortex.

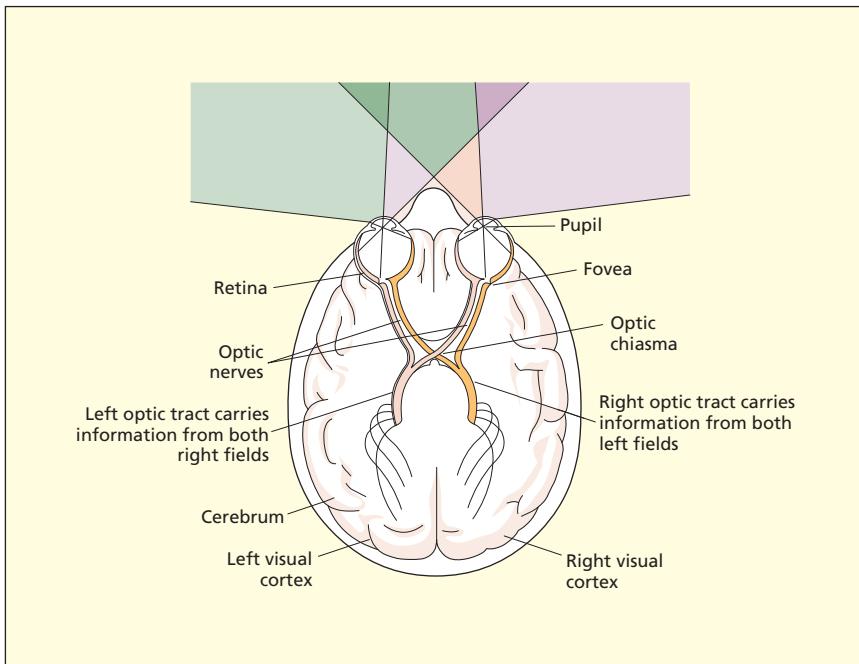
From eye to cortex

There are two types of visual receptor cells in the retina of the eye: cones and rods. Cones are used for colour vision and sharpness of vision (see later section on colour vision). There are 125 million rods concentrated in the outer regions of the retina. Rods are specialised for vision in dim light. Many differences between cones and rods stem from the fact that a **retinal ganglion cell** receives input from only a few cones but from hundreds of rods. Thus, only rods produce much activity in retinal ganglion cells in poor lighting conditions.

The main pathway between the eye and the cortex is the retina-geniculocaliate-striate pathway. It transmits information from the retina to V1 and then V2 (both discussed shortly) via the lateral geniculate nuclei of the thalamus. The entire retina-geniculocaliate-striate system is organised similarly to the retinal system. For example, two stimuli adjacent to each other in the retinal image will also be adjacent at higher levels within that system. The technical term is **retinotopy**: retinal receptor cells are mapped to points on the surface of the visual cortex.

Each eye has its own optic nerve, and the two optic nerves meet at the optic chiasma. At this point, the axons from the outer halves of each retina proceed to the hemisphere on the same side, whereas those from the inner halves cross over and go to the other hemisphere. As a result, each side of visual space is represented within the opposite brain hemisphere. Signals then proceed along two optic tracts within the brain. One tract contains signals from the left half of each eye, and the other signals from the right half (see [Figure 2.2](#)).

After the optic chiasma, the optic tract proceeds to the lateral geniculate nucleus (LGN), which is part of the thalamus. Nerve impulses finally reach V1 in primary visual cortex within the occipital lobe at the back of the head before spreading out to nearby visual cortical areas such as V2.

**Figure 2.2**

Route of visual signals. Note that signals reaching the left visual cortex come from the left sides of the two retinas, and signals reaching the right visual cortex come from the right sides of the two retinas.

There are two relatively independent channels or pathways within the retina-geniculate-striate system:

- 1 The parvocellular (or P) pathway: it is most sensitive to colour and to fine detail; most of its input comes from cones.
- 2 The magnocellular (or M) pathway: it is most sensitive information about movement; most of its input comes from rods.

As stated above, these two pathways are only *relatively* independent. In fact, there are numerous interconnections between them, and it is becoming increasingly apparent that the visual system is extremely complex (Wade & Swanston, 2013). For example, there is clear intermingling of the two pathways in V1 (Nassi & Callaway, 2009; Leopold, 2012). Finally, it should be mentioned there is also a Koniocellular pathway, but its functions are still not well understood.

Brain systems

As we have just seen, neurons from the P and M pathways mainly project to V1 in the primary visual cortex. What happens after V1? The answer is given in [Figure 2.3](#). In order to understand this Figure, note that V3 is generally assumed to be involved in form processing, V4 in colour processing and V5/MT in motion processing (all discussed in more detail shortly). The P pathway associates with the ventral or “what” pathway that proceeds to the inferotemporal cortex. In contrast, the M pathway associates with the dorsal or “how” pathway (previously described as the “where” pathway) that proceeds to the posterior parietal cortex. The assertions in the last two sentences are very approximate reflections of a complex reality. For example, some parvocellular neurons project into dorsal visual areas (Parker, 2007).

KEY TERMS

Receptive field

The region of the retina in which light influences the activity of a particular neuron.

Lateral inhibition

Reduction of activity in one neuron caused by activity in a neighbouring neuron.

We will consider the P and M pathways in more detail later. For now, bear three points in mind:

- 1 The ventral or “what” pathway culminating in the inferotemporal cortex is mainly concerned with form and colour processing and with object recognition (see [Chapter 3](#)). In contrast, the dorsal or “how” pathway culminating in the parietal cortex is more concerned with movement processing.
- 2 There is no rigid distinction between the types of information processed by the two streams. For example, Gilaie-Dotan et al. (2013b) studied patients with brain damage limited to the ventral or “what” pathway. These patients had widespread impairments in motion perception even though visual motion perception is primarily associated with the dorsal or “how” pathway.
- 3 The two pathways are *not* totally segregated. There are numerous interconnections between the ventral and dorsal pathways or streams (Felleman & Van Essen, 1991; Pisella et al., 2009). For example, both streams project to the primary motor cortex (Rossetti & Pisella, 2002).

As already indicated, [Figure 2.3](#) provides only a rough sketchmap of visual processing in the brain. A more complex picture is presented in [Figure 2.4](#), which reveals three important points. First, the interconnections among the various visual cortical areas are complicated. Second, the brain areas within the ventral pathway or stream are more than twice as large as those within the dorsal pathway. Third, cells in the lateral geniculate nucleus respond fastest when a visual stimulus is presented followed by activation of cells in V1. However, cells are activated in several other areas (V3/V3A, MT, MST) very shortly thereafter.

Finally, note that [Figure 2.3](#) is limited in other important ways. Kravitz et al. (2013) proposed a contemporary account of the ventral pathway ([Figure 2.5](#)). The

traditional view was that the ventral pathway involved a serial hierarchy proceeding from simple to complex. In contrast, Kravitz argued that the ventral pathway actually consists of several overlapping recurrent networks. Of key importance, there are connections in both directions between the components of the networks.

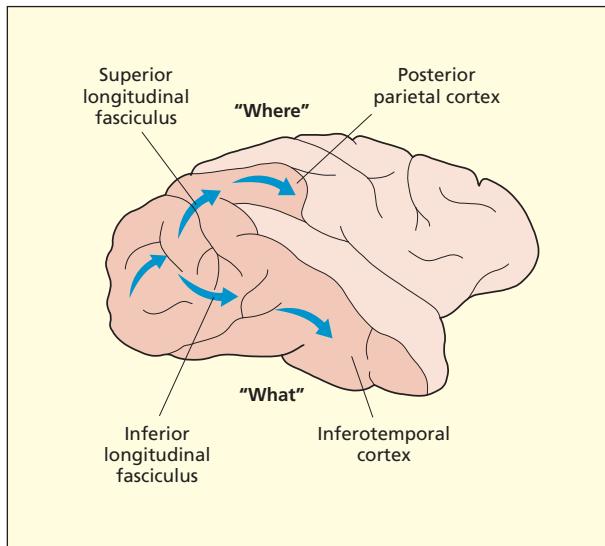


Figure 2.3

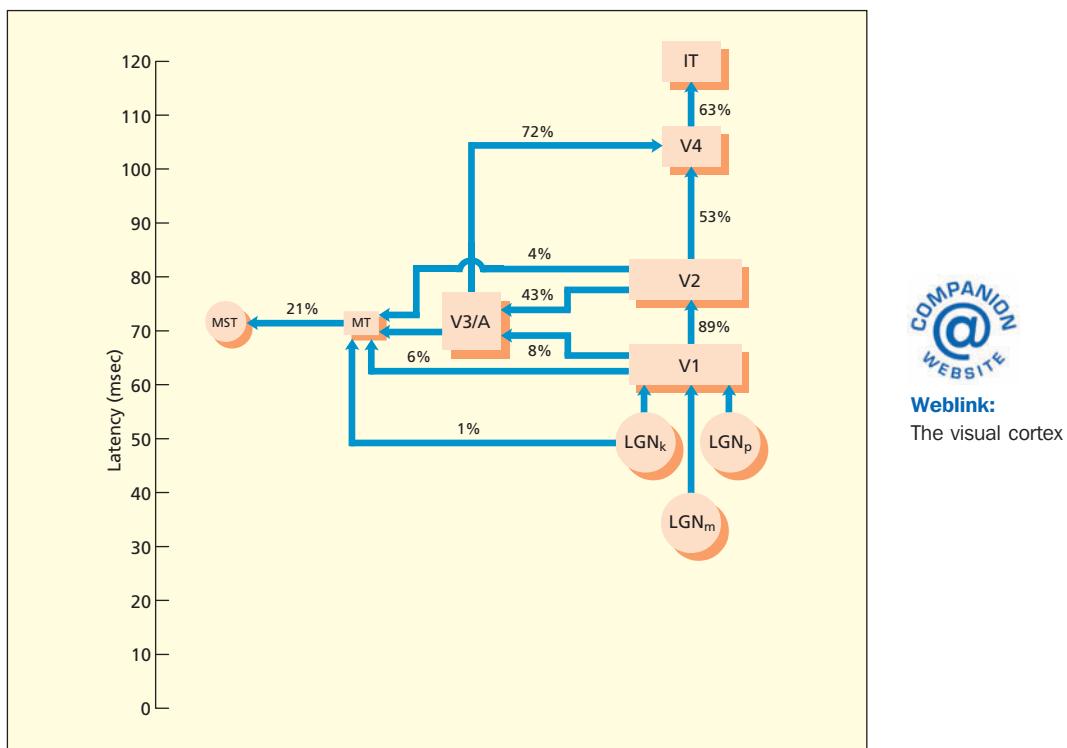
The ventral (what) and dorsal (where or how) pathways involved in vision have their origins in primary visual cortex (V1).

From Gazzaniga et al. (2008). Copyright © 2009, 2002, 1998. Used by permission of W.W. Norton & Company, Inc.

V1 and V2

We start with three general points. First, to understand visual processing in primary visual cortex (V1; also described as BA17) and secondary visual cortex (V2; also described as BA18), we must consider the notion of **receptive field**. The receptive field for any given neuron is that region of the retina in which light affects its activity. Receptive field can also refer to visual space because it is mapped in a one-to-one manner onto the retinal surface.

Second, neurons often influence each other. For example, there is **lateral inhibition**, in which a reduction of activity in one neuron is caused by

**Figure 2.4**

Some distinctive features of the largest visual cortical areas. The relative size of the boxes reflects the relative area of different regions. The arrows labelled with percentages show the proportion of fibres in each projection pathway. The vertical position of each box represents the response latency of cells in each area, as measured in single-unit recording studies. IT = inferotemporal cortex; MT = medial or middle temporal cortex; MST = medial superior temporal cortex. All areas are discussed in detail in the text.

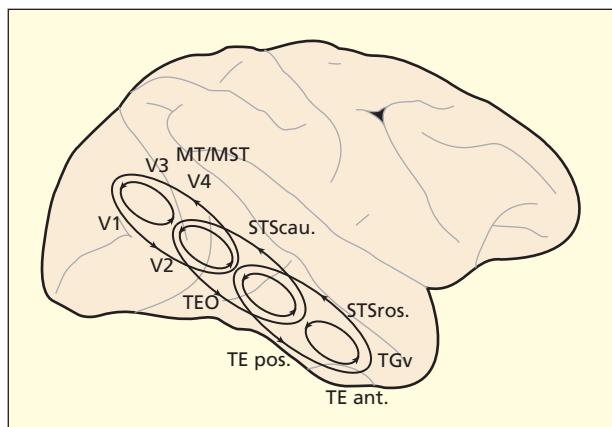
From Mather (2009). Copyright © 2009 George Mather. Reproduced with permission.

activity in a neighbouring neuron. Lateral inhibition is useful because it increases the contrast at the edges of objects, making it easier to identify the dividing line between objects. The phenomenon of simultaneous contrast depends on lateral inhibition (see Figure 2.6). The two central squares are physically identical but the one on the left appears lighter than the one on the right. This difference is due to simultaneous contrast produced because the left surround is much darker than the right surround.

Figure 2.5

Connectivity within the ventral pathway on the lateral surface of the macaque brain. Brain areas involved include V1, V2, V3, V4, the middle temporal (MT)/medial superior temporal (MST) complex, the superior temporal sulcus (STS) and the inferior temporal cortex (TE).

From Kravitz et al. (2013). Reprinted with permission of Elsevier.



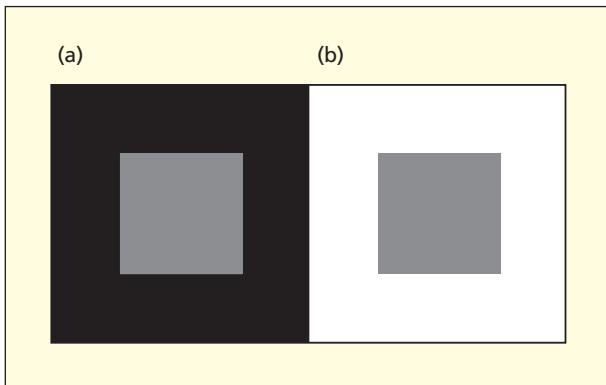


Figure 2.6

The square on the right looks darker than the identical square on the left because of simultaneous contrast involving lateral inhibition.

From Lehar (2008). Reproduced with permission of the author.

Third, the primary visual cortex (V1) and secondary visual cortex (V2) occupy relatively large areas (see [Figure 2.4](#)). Early visual processing in these areas is fairly extensive. Hegdé and Van Essen (2000) found in macaques that one-third of V2 cells responded to complex shapes and to differences in orientation and size.

V1 and V2 are both involved in the early stages of visual processing. However, that is not the complete story. There is an initial “feedforward sweep” proceeding through the visual areas starting with V1 and then V2. In addition, there is a second phase of processing (recurrent processing) in which processing proceeds in the opposite direction (Lamme, 2006). Some recurrent processing can occur in V1 within 120 ms of stimulus onset. Boehler et al. (2008) found greater visual awareness of the stimulus when recurrent processing was strongly present (see [Chapter 16](#)).

Functional specialisation

Zeki (1993, 2001) put forward a functional specialisation theory. According to this theory, different cortical areas are specialised for different visual functions. The visual system resembles a team of workers, each working on his/her own to solve part of a complex problem. The results of their labours are then combined to produce the solution (i.e., coherent visual perception).

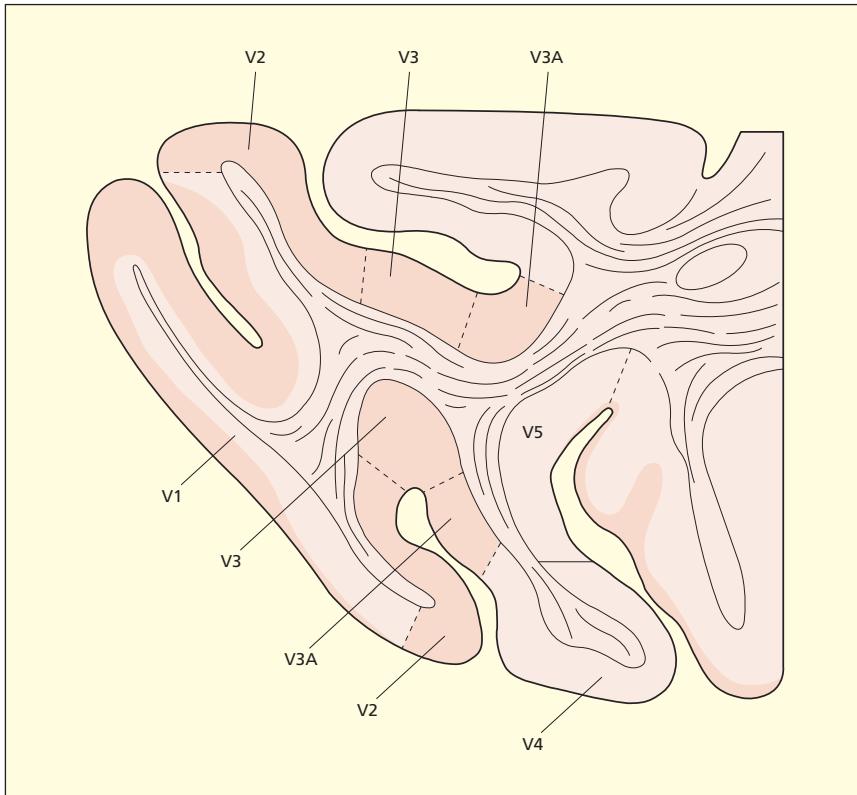
Why might there be functional specialisation in the visual brain? Zeki (2005) suggested two reasons. First, object attributes occur in unpredictable combinations. For example, a green object may be a car, a sheet of paper or a leaf, and a car may be red, black or green. Thus, we must often process *all* an object’s attributes to perceive it accurately.

Second, the required processing differs considerably across attributes. For example, motion processing involves integrating information from two or more points in *time*. In contrast, form or shape processing involves considering the *spatial* relationship of elements to each other at one point in time.

The organisation of the main visual areas in the macaque monkey is shown in [Figure 2.7](#). The organisation of the human visual system closely resembles that of the macaque and so reference is often made to human V1, V2 and so on.

Here are the main functions Zeki (1993, 2005) ascribed to these areas:

- V1 and V2: They are involved at an early stage of visual processing; they contain different groups of cells responsive to colour and form.
- V3 and V3A: Cells in these areas are responsive to form (especially the shapes of objects in motion) but not colour.
- V4: The majority of cells in this area are responsive to colour; many are also responsive to line orientation.
- V5: This area is specialised for visual motion. In studies with macaque monkeys, Zeki found all the cells in this area were responsive to motion but not colour. In humans, the areas specialised for visual motion are referred to as MT and MST.

**Figure 2.7**

A cross-section of the visual cortex of the macaque monkey

From Zeki (1992). Reproduced with permission from Carol Donner.

Zeki assumed that colour, form and motion are processed in anatomically separate parts of the visual cortex. Much of the original evidence came from studies on monkeys. Relevant human evidence is considered below.

Form processing

Several areas are involved in form processing in humans, including areas V1, V2, V3 and V4 and culminating in inferotemporal cortex (Kourtzi & Connor, 2011). There is evidence that neurons in inferotemporal cortex respond to specific semantic categories (e.g., animals, body parts; see Chapter 3). There is also strong evidence that neurons in inferotemporal cortex are involved in form processing. In one study (Yamane et al., 2008), neurons within inferotemporal cortex responded to three-dimensional object shape. Baldassi et al. (2013) measured neuronal activity within anterior inferotemporal cortex in two monkeys. Many neurons responded on the basis of aspects of form or shape (round, star-like, horizontal thin, pointy, vertical thin) rather than object category.

If form processing occurs in different brain areas from colour and motion processing, we might anticipate some patients would have severely impaired form processing but intact colour and motion processing. That does *not* seem to be the case. According to Zeki (1991), a lesion large enough to destroy areas V3, V4 and inferotemporal cortex would probably destroy area V1 as well. As a result, the patient would suffer from total blindness rather than simply loss of form perception.

KEY TERMS

Achromatopsia

A condition involving brain damage in which there is little or no colour perception but form and motion perception are relatively intact.

Akinetopsia

A brain-damaged condition in which motion perception is severely impaired even though stationary objects are perceived reasonably well.

Colour processing

The assumption that V4 is specialised for colour processing has been tested in several ways. These include studying brain-damaged patients; using brain-imaging techniques; and using transcranial magnetic stimulation (TMS; see Glossary) to produce a temporary “lesion”. We will discuss these three kinds of studies in turn.

Suppose area V4 and related areas are specialised for colour processing. If so, patients with damage mostly limited to those areas should show little or no colour perception with fairly intact form and motion perception and ability to see fine detail. This is approximately the case in some patients with **achromatopsia** (also known as cerebral achromatopsia).

Bouvier and Engel (2006) carried out a meta-analysis (see Glossary) involving all known cases of achromatopsia. A small brain area within ventral (bottom) occipital cortex in (or close to) area V4 was damaged in nearly all these cases. The loss of colour vision in these patients was often only partial, suggesting V4 is not the only area involved in colour processing. In addition, most patients had significant impairments of spatial vision.

Functional neuroimaging evidence that V4 plays an important role in colour processing was reported by Goddard et al. (2011). Observers viewed movie segments presented in full or no colour. There was substantially more activation in ventral V4 with the full-colour segments. Wade et al. (2002) had previously found area V4 was actively involved in colour processing but other areas (V1 and V2) were also activated.

Banissy et al. (2012) found that performing a task on a stimulus (diamond shape) was faster when preceded by a prime in the same colour. However, this priming effect was no longer present when transcranial magnetic stimulation (TMS) was administered to V4. This finding occurred because TMS reduced colour processing in V4.

In sum, area V4 and adjacent areas are undoubtedly involved in colour processing. However, V4 is *not* a “colour centre”. First, V4 is a relatively large area involved in spatial processing, shape processing and depth perception, as well as colour processing (Roe et al., 2012). Second, some ability to process colour is present in most individuals with achromatopsia and monkeys with lesions to V4 (Heywood & Cowey, 1999). Third, several areas outside V4 (including V1 and V2) are also involved in colour processing.

Motion processing

Area V5 (also known as motion processing area MT) is heavily involved in motion processing. Functional neuroimaging studies indicate motion processing is *associated* with activity in V5 (or MT) but do not show that V5 (or MT) is *necessary* for motion perception. This issue was addressed by McKeefry et al. (2008), who used transcranial magnetic stimulation (TMS; see Glossary) to disrupt motion perception. When TMS was applied to V5/MT, it produced a subjective slowing of stimulus speed and impaired observers’ ability to discriminate between different speeds.

Additional evidence that area V5/MT is important in motion processing comes from research on patients with **akinetopsia**. Akinetopsia is a condition in which stationary objects are perceived fairly normally but motion perception is grossly deficient. Zihl et al. (1983) studied LM, a woman with akinetopsia who

had suffered bilateral damage to the motion area (V5/MT). She could locate stationary objects by sight, had good colour discrimination and her binocular vision was normal. However, her motion perception was grossly deficient:

She had difficulty . . . in pouring tea or coffee into a cup because the fluid appeared to be frozen, like a glacier. In addition, she could not stop pouring at the right time since she was unable to perceive the movement in the cup (or a pot) when the fluid rose . . . In a room where more than two people were walking, . . . “people were suddenly here or there but I have not seen them moving”.

(p. 315)

S.A. Cooper et al. (2012) reported the case of a 61-year-old with akinetopsia. She perceived static objects normally, but smooth movements of people were seen as “freeze frames”. People close to the opening of a train door appeared to “move in slow motion”.

V5 (MT) is not the only area involved in motion processing. There is also area MST (medial superior temporal), which is adjacent to and just above V5/MT. Vaina (1998) studied two patients with damage to MST. Both patients performed normally on some tests of motion perception, but had various problems relating to motion perception. One patient, RR, “frequently bumped into people, corners and things in his way, particularly into moving targets (e.g., people walking)” (Vaina, 1998, p. 498). These findings suggest MST is involved in the visual guidance of walking.

There is an important distinction between first-order and second-order motion. With first-order displays, the moving shape differs in luminance (intensity of reflected light) from its background. For example, the shape might be dark whereas the background is light. With second-order displays, there is no difference in luminance between the moving shape and the background. In everyday life, we encounter second-order displays infrequently (e.g., movement of grass in a field caused by the wind).

There is an ongoing controversy as to whether different mechanisms underlie the perception of first-order and second-order motion. Evidence that different mechanisms are involved was reported by Ashida et al. (2007). Repeated presentation of first-order displays led to a substantial reduction in activation in motion areas MT and MST. This adaptation occurred because many of the same neurons were activated by each display. Very similar reductions in activation in the motion areas occurred with repeated presentations of second-order displays. However, there was *no* evidence of adaptation in MT and MST when first-order displays were followed by second-order displays or vice versa. The implication is the two display types activated *different* sets of neurons and thus probably involved different processes.

Support for the notion of different mechanisms for perception of first-order and second-order motion was also reported by Rizzo et al. (2008). They identified 22 patients with a deficit in perception of first-order but not second-order motion, and one patient with a deficit only in perception of second-order motion. This double dissociation suggests different processes are involved in perception of the two types of motion.

However, some evidence suggests first-order and second-order motion perception depend on the same mechanisms. Hong et al. (2012) found direction-

KEY TERM**Binding problem**

The issue of integrating different types of information to produce coherent visual perception.

selective responses to both types of motion in several brain areas (V1, V2, V3, V3A, V4 and MT+). These findings suggest none of these areas is specialised for processing only one type of motion. More importantly, the patterns of activation associated with the perception of first- and second-order motion were similar.

Further support for the same-mechanism assumption was reported by Cowey et al. (2006). They disrupted activity in V2/V3 or V5/MT+ via transcranial magnetic stimulation (TMS; see Glossary) and found this led to impairments in the perception of first-order and second-order motion.

How can we reconcile the various findings? First- and second-order motion perception probably depend on similar (but not identical) underlying mechanisms. That assumption provides a potential explanation for the apparently inconsistent findings in this area.

Binding problem

Zeki's functional specialisation approach poses the obvious problem of how information about an object's motion, colour and form is combined and integrated to produce coherent perception. This is the famous **binding problem**, which concerns "how items that are encoded by distinct brain circuits can be combined for perception, decision, and action" (Feldman, 2013, p. 1).

One approach to the binding problem is to argue there is less functional specialisation than Zeki claimed, which would reduce the complexity of the problem. For example, Seymour et al. (2009) presented observers with red or green dots that rotated clockwise or counterclockwise. Assessment of brain activity indicated colour-motion conjunctions were processed in several brain areas including V1, V2, V3, V3A/B, V4 and V5/MT+. Thus, there is extensive binding of colour and motion information even early in processing.

Feldman (2013) argued that there are actually several binding problems. There is the problem of how visual features are bound together. Another problem is how we bind together information over successive eye movements to achieve the subjective perception of a stable visual world. Within the above broader context, it is clear that many different lines of research are relevant. For example, observers need to work out which parts of the visual information available at any given time belong to the same object. The Gestaltists put forward several laws to account for how observers do this (see [Chapter 3](#)). Research on selective attention, especially research on visual search (detecting target stimuli among distractors), is also relevant (see [Chapter 5](#)). This research shows the important role of selective attention in combining features close together in time and space.

One approach to solving the binding problem is the binding-by-synchrony hypothesis (e.g., Singer & Gray, 1995). According to this hypothesis, detectors responding to features of a single object fire in *synchrony* whereas detectors responding to features of separate objects do not. Of relevance, widespread synchronisation of neural activity is associated with conscious visual awareness (e.g., Melloni et al., 2007; Gaillard et al., 2009).

The synchrony hypothesis is oversimplified. Visual processing of an object occurs in widely distributed areas of the brain and proceeds through several stages. This makes it implausible precise synchrony could be achieved. Another problem is that two or more objects are often presented at the same time. On the synchrony hypothesis, it would seem hard to keep the processing of these objects separate.

Guttman et al. (2007) suggested an alternative hypothesis based on the notion that perception depends on *patterns* of neural activity over time rather than on precise synchrony.

In sum, there are several binding problems, most of which are hard to solve (Feldman, 2013). However, progress has been made. Selective attention undoubtedly plays an important role. Feature binding is typically associated with synchronised activity in different brain areas, but the association is often imprecise. There is also the issue of explaining *why* and *how* synchronised activity occurs.

Evaluation

Zeki's functional specialisation theory has deservedly been influential. It is an ambitious attempt to provide a simple theoretical framework within which to understand a remarkably complex reality. As is discussed later, Zeki's assumption that motion processing typically proceeds somewhat independently of other types of visual processing has received reasonable support.

There are three main limitations with Zeki's theoretical approach. First, the brain areas involved in visual processing are less specialised than implied by the theory. Heywood and Cowey (1999) considered the percentage of cells in each visual cortical area responding selectively to various stimulus characteristics (see [Figure 2.8](#)). Cells in several areas respond to orientation, disparity and colour. Specialisation was found only with respect to responsiveness to direction of stimulus motion in MT.

Second, early visual processing in areas V1 and V2 is more extensive than suggested by Zeki. As we saw earlier, Hegde and Van Essen (2000) found many V2 cells responded to complex shapes.

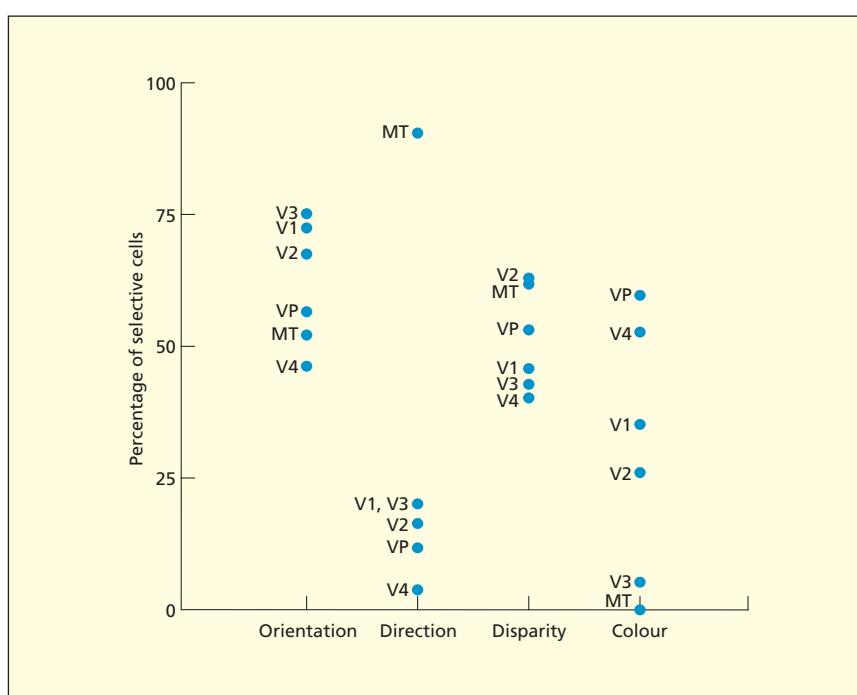


Figure 2.8

The percentage of cells in six different visual cortical areas responding selectively to orientation, direction of motion, disparity and colour.

From Heywood and Cowey (1999).

KEY TERMS

Ventral stream

The part of the visual processing system involved in object perception and recognition and the formation of perceptual representations.

Dorsal stream

The part of the visual processing system most involved in visually guided action.

Allocentric coding

Visual coding that is independent of the observer's perspective.

Egocentric coding

Visual coding that is dependent on the observer's perspective.

Third, Zeki and his colleagues have not as yet solved the binding problem. In fairness, there are probably several binding problems and no one has solved them. However, it appears that selective attention is of major importance (Feldman, 2013).

TWO VISUAL SYSTEMS: PERCEPTION AND ACTION

Here is a fundamental question in vision research: what are the major functions of the visual system? Historically, the most popular answer was that the visual system provides us with an internal (and typically conscious) representation of the world outside.

Milner and Goodale (e.g., 1995, 2008) argued that there are two visual systems, each fulfilling a different function or purpose. Their theoretical views represent the development of previous accounts (e.g., Bridgeman et al., 1979). First, there is the vision-for-perception (or “what”) system based on the **ventral stream** or pathway (see Figures 2.3 and 2.5). This is the one we immediately think of when considering visual perception. It is the system we use when deciding whether the object in front of us is a cat or a buffalo or when admiring a magnificent landscape. Thus, it is used to identify objects.

Second, there is the vision-for-action (or “how”) system based on the **dorsal stream** or pathway (see Figure 2.3), which is used for visually guided action. It is used when running to return a ball at tennis. It is also the system used when grasping an object. When we grasp an object, it is important we calculate its orientation and position with respect to ourselves. Since observers and objects often move relative to each other, orientation and position need to be worked out immediately prior to initiating a movement.

The key differences between these two systems were summarised by Milner (2012, p. 2289):

The dorsal stream’s principal role is to provide real-time “bottom-up” visual guidance of our movements online. In contrast, the ventral stream, in conjunction with top-down information from visual and semantic memory provides perceptual representations that can serve recognition, visual thought, planning and memory.

Schenk and McIntosh (2010) identified *four* core characteristics of the above two processing streams:

- 1 The ventral stream underlies vision-for-perception whereas the dorsal stream underlines vision-for-action.
- 2 Coding in the ventral stream is **allocentric** (object-centred; independent of the observer’s perspective), whereas dorsal coding is **egocentric** (body-centred; dependent on the observer’s perspective).
- 3 Representations in the ventral stream are sustained over time whereas those in the dorsal stream are short-lasting.
- 4 Processing in the ventral stream typically (but by no means always) leads to conscious awareness, whereas processing in the dorsal stream does not.

Finally, there are two other differences assumed theoretically between the two visual systems. First, processing in the dorsal stream is *faster* than in the ventral stream. Second, processing in the ventral stream depends more on input from the fovea (the central part of the retina used for detecting detail) than does dorsal processing.

Findings: brain-damaged patients

Milner and Goodale's theory can be tested by studying brain-damaged patients. Patients with damage to the dorsal pathway should have reasonably intact vision-for-perception but severely impaired vision-for-action. The opposite pattern of intact vision-for-action but very poor vision-for-perception should be found in patients with damage to the ventral pathway. Thus, there should be a double dissociation (see Glossary).

Of relevance to the theory are patients with **optic ataxia**, who have damage to the posterior parietal cortex (see Figure 2.9). Patients with optic ataxia are poor at making precise visually guided movements in spite of the fact that their vision and ability to move their arms are essentially intact. Perenin and Vighetto (1988) found patients with optic ataxia had great difficulty in rotating their hands appropriately when reaching towards (and into) a large oriented slot in front of them. These findings fit with the theory, because damage to the dorsal stream should impair visually guided action.

Patients with optic ataxia do not all conform to the simple picture described in the previous paragraph. First, somewhat different regions of posterior parietal cortex are associated with reaching and grasping movements (Vesia & Crawford, 2012) and some patients have greater problems with one type of movement than the other.

Second, some optic ataxia patients do not have severe problems with all aspects of visually guided actions. For example, Jakobson et al. (1991) studied a female patient, VK, who had difficulty in grasping objects even though her *initial* action planning was essentially intact.

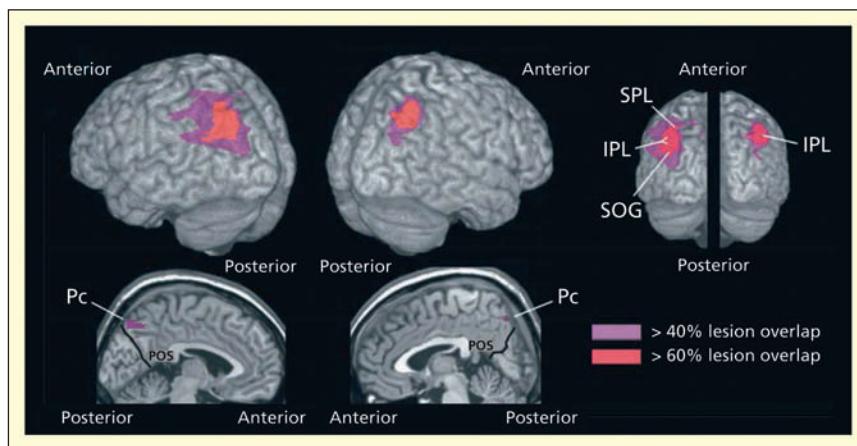


Figure 2.9

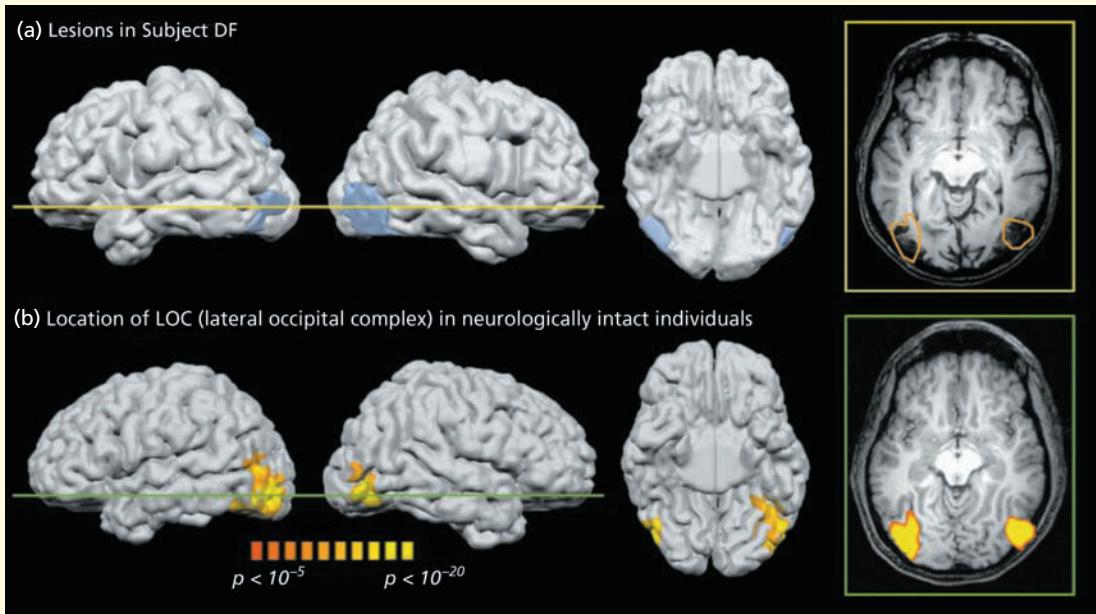
Lesion overlap (purple = > 40% overlap; orange = > 60% overlap) in patients with optic ataxia. SPL = superior parietal lobule; IPL = inferior parietal lobule; SOG = superior occipital gyrus; Pc = precuneus.

KEY TERM

Optic ataxia

A condition in which there are problems with making visually guided movements in spite of reasonably intact visual perception.

From Vesia and Crawford (2012). Reprinted with permission of Springer.

**Figure 2.10**

(a) damage to DF's lateral occipital complex within the ventral stream is shown in pale blue; (b) location of the lateral occipital complex in healthy individuals.

From James et al. (2003).
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Third, Pisella et al. (2009) argued that the notion that patients with optic ataxia have intact visual perception but impaired visually guided actions is oversimplified. When patients had access to visual feedback from their own hand, they only had severe problems with visually guided action in *peripheral* vision. There was much less evidence for impaired visually guided action in *central* vision, which is consistent with evidence indicating that many optic ataxics can drive effectively.

What about patients with damage to the ventral stream only? Of relevance here are some patients with **visual form agnosia**, a condition involving severe problems with object recognition even though visual information reaches the visual cortex (see Chapter 3). Probably the most-studied visual form agnosic is DF. James et al. (2003) found her brain damage was in the ventral pathway or stream (see Figure 2.10). DF showed no greater activation in the ventral stream when presented with drawings of objects than with scrambled line drawings. However, she showed high levels of activation in the dorsal stream when grasping for objects.

In spite of having reasonable visual acuity, DF could not identify any drawings of common objects. However, DF "could accurately reach out and grasp a pencil orientated at different angles" (Milner et al., 1991, p. 424).

In another study (Goodale & Milner, 1992), DF held a card in her hand and looked at a circular block into which a slot had been cut. She could not orient the card so it would fit into the slot, suggesting she had very poor perceptual skills. However, DF performed well when moving her hand forward and inserting the card into the slot.

Dijkerman et al. (1998) assessed DF's performance on various tasks when presented with several differently coloured objects. There were two main findings. First, DF could not distinguish accurately between the coloured objects, suggesting problems with object recognition due to damage to the ventral stream.

KEY TERM

Visual form agnosia

A condition in which there are severe problems in shape perception (what an object is) but reasonable ability to produce accurate visually guided actions.

Second, DF reached out and touched the objects as accurately as healthy individuals using information about their positions relative to her own body. This suggests her ability to use visual information to guide action using the dorsal stream was largely intact.

Goodale et al. (1994) gave DF two tasks. One involved distinguishing between two shapes with irregular contours and the other involved grasping these shapes firmly between thumb and index finger. DF performed very poorly on the former task that involved visual perception. However, Goodale et al. concluded that DF “had no difficulty in placing her fingers on appropriate opposition points during grasping” (p. 604).

Himmelbach et al. (2012) argued that this conclusion is unwarranted. They reanalysed DF’s performance based on the data in Goodale et al. (1994) and compared it against that of 20 healthy controls (see Figure 2.11). DF’s performance on the grasping task was substantially inferior to that of the controls. Similar findings were obtained when DF’s performance on other grasping and reaching tasks was compared against that of controls. Thus, DF has greater difficulties in visually guided action than was previously thought.

In sum, there are fascinating (and theoretically important) differences in visual perception and visually guided action between patients with visual form agnosia and those with optic ataxia. However, the picture is not neat and tidy. Both types of patients have problems with visual perception *and* with visually guided action. That complicates the task of making coherent sense of the findings.

Visual illusions

There have been hundreds of studies of visual illusions. The Müller–Lyer illusion (see Figure 2.12) is one of the most famous. The vertical line on the left looks longer than the one on the right. In fact, however, they are the same length as can be confirmed by using a ruler!

Another well-known illusion is the Ebbinghaus illusion (see Figure 2.13). In this illusion, the central circle surrounded by smaller circles looks smaller than a central circle of the same size surrounded by larger circles. In fact, the two central circles are the *same* size.

There are numerous other visual illusions. Their existence provides us with an intriguing paradox. How has the human species been so successful given that our visual perceptual processes are apparently very prone to error?

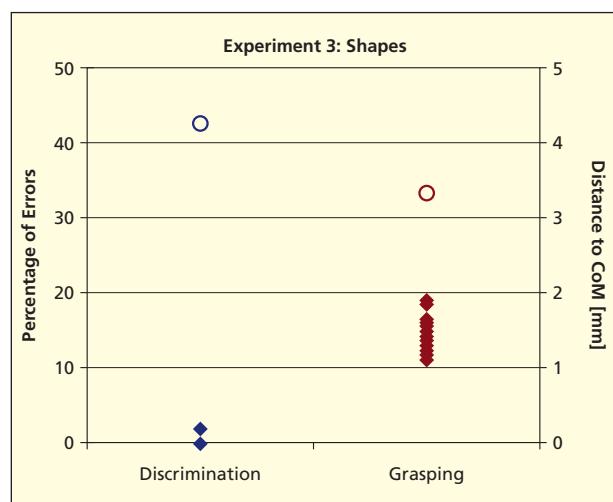


Figure 2.11

Percentage of errors made when discriminating and grasping irregular shapes by DF (open circles) and by healthy controls (filled diamonds).

From Himmelbach et al. (2012). Reprinted with permission of Elsevier.



Interactive exercise:
Müller-Lyer

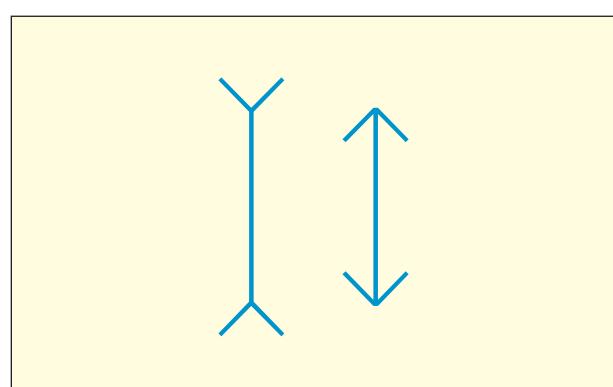
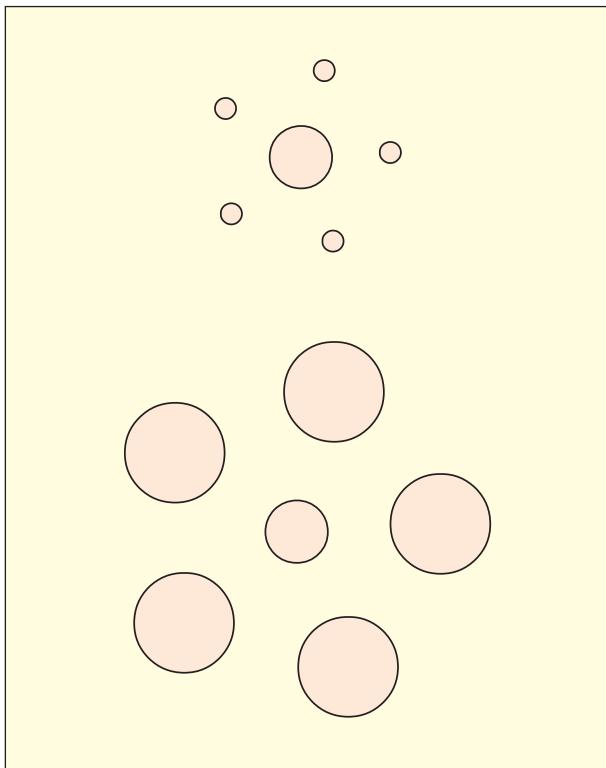


Figure 2.12

The Müller–Lyer illusion.

**Figure 2.13**

The Ebbinghaus illusion.

Milner and Goodale (1995) offered a neat explanation. They argued that most studies on visual illusions have involved the vision-for-perception system. However, we mostly use the vision-for-action system when walking close to a precipice or dodging cars. Milner and Goodale argued that the vision-for-action system provides accurate information about our position relative to objects. These ideas produce a dramatic prediction: actions (e.g., pointing, grasping) using the vision-for-action system should be unaffected by the Müller–Lyer, Ebbinghaus and many other visual illusions.

Findings

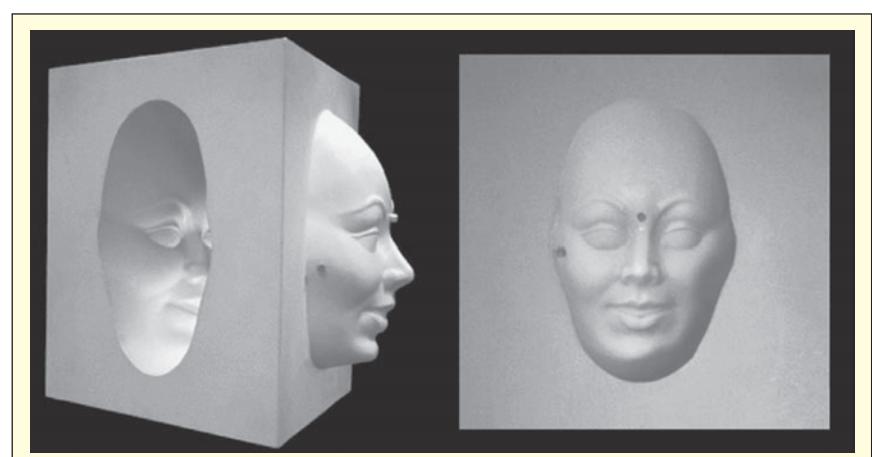
Bruno et al. (2008) carried out a meta-analysis (see Glossary) of 33 studies involving the Müller–Lyer illusion in which observers *pointed* rapidly at one of the figures. These studies were designed to involve the vision-for-action system and the mean illusion effect was 5.5%.

For comparison purposes, Bruno et al. (2008) considered 11 studies using standard procedures (e.g., verbal estimations of length) and involving

the vision-for-perception system. Here the mean illusion effect was 22.4%. The finding that the mean illusion effect was *four* times greater in the former studies clearly supports the perception–action model. However, the model seems to predict *no* illusion effect with rapid pointing.

**Weblink:**

Hollow face illusion

**Figure 2.14**

Left: normal and hollow faces with small target magnets on the forehead and cheek of the normal face; right: front view of the hollow mask that appears as an illusory face projecting forwards.

Króliczak et al. (2006). Reprinted with permission of Elsevier.

Support for the two-systems approach has also been reported with the hollow-face illusion. In this illusion, a realistic hollow mask looks like a normal face (see [Figure 2.14](#); visit the website: www.richardgregory.org/experiments). Króliczak et al. (2006) placed a target (a small magnet) on the face mask or on a normal face. Here are two of the tasks:

- 1 Draw the target position (using the vision-for-perception system).
- 2 Make a fast flicking finger movement to the target (using the vision-for-action system).

Króliczak et al. (2006) found there was a strong illusion effect when observers drew the target position. In contrast, observers' performance was very accurate (i.e., illusion-free) when they made a flicking movement. Both findings were as predicted theoretically.

In the above study, there was a third condition in which observers made a *slow* pointing finger movement to the target. Performance might have been expected to be accurate in this condition because it involved use of the vision-for-action system. However, the illusory effect was fairly strong. Why was this? According to Króliczak et al. (2006), actions may involve the vision-for-perception system as well as the vision-for-action system when preceded by conscious cognitive processes.

More serious problems for the original two-systems approach have accumulated in recent years. With three-dimensional versions of the visual illusions, actions made by observers include grasping as well as pointing. Evidence discussed earlier (Bruno et al., 2008) showed that *pointing* at the Müller–Lyer figure was associated with a greatly reduced illusory effect.

However, the situation is more complex with *grasping*. Franz and Gegenfurtner (2008) reviewed the evidence from studies focusing on the Müller–Lyer illusion. The mean illusory effect was 11.2% with perceptual tasks compared to 4.4% with full visual guidance of the hand movement. In contrast, grasping occurring without the observer being able to monitor his/her hand movement was associated with an illusory effect of 9.4%. These findings probably arose because the action programming involved in grasping requires the ventral stream.

Action: planning + motor responses

We have seen it is not entirely accurate to claim that vision-for-action depends almost entirely on the dorsal stream. Milner and Goodale (2008) argued that most tasks in which observers grasp an object involve some processing in the ventral stream as well as the dorsal stream. Involvement of the ventral stream is especially likely in the following circumstances:

- Memory is required (e.g., there is a time lag between the offset of the stimulus and the start of the grasping movement).
- Time is available to plan the forthcoming movement (e.g., Króliczak et al., 2006).
- Planning which movement to make is necessary.
- The action is unpractised or awkward.

Evidence that the involvement of memory can increase the involvement of the ventral stream in visually guided action was reported by Milner et al. (2003). Two patients with optic ataxia (involving damage to the dorsal stream) made reaching and grasping movements immediately (or a few seconds) after the offset of the target object. Surprisingly, the patients' performance was *better* when reliant on memory. According to Milner et al., the patients did better in the memory condition because they used their intact ventral stream.

As a rule of thumb, actions are most likely to involve the ventral stream when they involve conscious cognitive processes. This can be tested if we distinguish between *effective* and *appropriate* grasping (Creem & Proffitt, 2001). For example, we can grasp a toothbrush effectively by its bristles but appropriate grasping involves picking it up by the handle. Creem and Proffitt argued that appropriate grasping involves accessing stored knowledge about the object and so requires the ventral stream. As predicted, appropriate grasping was much more adversely affected than effective grasping by disrupting participants' ability to retrieve object knowledge.

Van Doorn et al. (2007) provided evidence that the ventral stream is involved in action planning. Participants were presented with a rod of various lengths forming part of a Müller–Lyer figure (see [Figure 2.12](#)). They decided whether to pick the rod up end-to-end using a one-handed or a two-handed grip (a decision involving planning). Participants chose a two-handed grip at shorter rod lengths more often when the fins pointed outwards than when they pointed inwards and so this aspect of their behaviour was influenced by the illusion. However, their maximal grip size was unaffected by the illusion. The visual processes guiding action selection (planning) seemed to involve the ventral stream, whereas those guiding motor programming did not.

Canal-Bruland et al. (2013) obtained evidence that some of the effects with visual illusions depend on apparently minor task changes. Participants in two experiments using a one-tailed version of the Müller–Lyer illusion estimated the distance to the endpoint of the shaft or threw a beanbag to that point. When participants stood at the base of the illusion, the usual effects were observed: there was an illusion effect on verbal estimates (perception) but not on throwing (action). However, there were comparable illusion effects on both measures when participants stood 1.5 metres behind the base of the illusion. The precise reasons for this difference in findings are unclear.

Dorsal stream: conscious awareness?

Remember the two systems approach includes the assumption that dorsal-stream processing is not accessible to consciousness. It is hard to test this assumption because of the difficulties in disentangling the relative contributions of the dorsal and ventral streams on most tasks involving visually guided action. Suppose, however, we used a very simple task such as reaching out for a target while avoiding obstacles (e.g., two rods). Milner (2012) reviewed research indicating this task can be performed by the dorsal stream alone and in the absence of conscious awareness. We will briefly discuss relevant evidence.

McIntosh et al. (2004) used an obstacle-avoidance task (see [Figure 2.15](#)). They tested a male patient, VE, who had suffered a stroke in the right hemisphere. As a result, he had extinction (see [Glossary](#)) involving greatly impaired conscious awareness of a stimulus presented to his left visual field in the presence of another

stimulus presented to his right visual field. VE took full account of a rod presented as an obstacle in his left visual field even when he claimed not to have seen it. Thus, his reaching behaviour was influenced by visual information of which he was not conscious.

Evidence that the dorsal stream is crucially important in reaching behaviour is supported by other research (reviewed by Milner, 2012). For example, Schindler et al. (2004) found two patients with optic ataxia (involving extensive dorsal stream damage) showed no ability to vary their reaching behaviour to avoid obstacles.

Roseboom and Arnold (2011) presented visual stimuli to healthy individuals followed by masking to prevent them from being seen. In spite of their total lack of conscious awareness of the orientation of the stimuli presented, they nevertheless learned to orient their grasp reasonably appropriately. Thus, visually guided action can occur in the absence of conscious awareness and with the probable use of the dorsal stream.

You may be feeling somewhat bewildered by now. After all, when you reach out to pick up an object, you typically have full conscious awareness of the object, of any obstacles and of the position of your hand. However, such conscious awareness is apparently not *essential* for visually guided action. Nevertheless, it may well be useful. For example, even though Roseboom and Arnold's (2011) participants performed well above chance, their performance was still markedly inferior to what it would have been if the stimuli had been visible.

Overall evaluation

Milner and Goodale's theoretical approach has been very influential. Their central assumption that there are two visual ("what" and "how") systems is probably broadly correct. This assumption has received support from two types of research. First, studies on patients with optic ataxia (damage to the dorsal stream) and visual agnosia (damage to the ventral stream) have produced the predicted double dissociation. Second, studies involving the visual illusions have often produced the surprising (but theoretically predicted) finding that action-based performance (e.g., pointing, sometimes grasping) is almost immune to illusory effects. Third, the assumption that processing in the dorsal stream is not accessible to consciousness has received reasonable support.

What are the limitations of the two systems approach? First, there is too much emphasis on the independence of the two systems rather than their interactions. Cloutman (2013, p. 251) reviewed the evidence and concluded that, "Information is transferred directly between the two pathways at multiple stages and locations along their trajectories".

Second, and related to the first point, there is the thorny issue of *how* these interactions occur given the very different nature of visual processing in the two streams. A possible explanation is provided by the "frame and fill" approach –

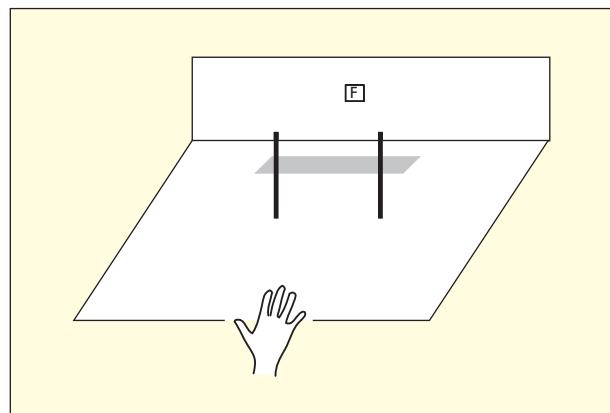


Figure 2.15

The obstacle-avoidance task, which required the participant to move his hand to reach the target zone (strip of grey tape). One or two rods were placed between the hand start position and the target zone to act as obstacles.

From McIntosh et al. (2004). © 2004 The Royal Society. Reprinted with permission.

rapid, coarse processing in the dorsal stream provides the “frame” for slower and more precise ventral stream processing (the “fill”) (Chen et al., 2007).

Third, the original notion (since abandoned by Milner and Goodale (2008)) that visually guided action depends almost entirely on the dorsal stream is incorrect. The dorsal stream is probably used on its own or with minimal ventral stream involvement only when someone performs rudimentary actions to simple targets (Schenk & McIntosh, 2010). The ventral stream seems to be involved whenever action planning and programming are required.

Fourth, the claimed double dissociation between optic ataxia and visual form agnosia is not clear-cut. Some patients with visual form agnosia have severe problems with visually guided action as well as vision for perception (Himmelbach et al., 2012). In addition, some patients with optic ataxia have impaired visual perception for stimuli presented to peripheral vision as well as impaired visually guided action (Pisella et al., 2009).

Fifth, it is often difficult to make firm predictions from the theory. This is because most visual tasks require the use of both processing streams, and subtle changes in the nature of the task can influence their relative use (e.g., Canal-Bruland et al., 2013).

COLOUR VISION

Why has colour vision developed? After all, if you see an old black-and-white movie on television, you can easily make sense of the moving images. One reason is that colour often makes an object stand out from its background, making it easier to distinguish figure from ground. Chameleons very sensibly can change colour to blend in with their immediate surroundings, thus reducing their chances of being detected by predators.

Another reason is that colour perception helps us to recognise and categorise objects. For example, it is useful when deciding whether a piece of fruit is under-ripe, ripe or over-ripe. Predictive coding (which involves processing the unpredicted components of sensory input) is also relevant (Huang & Rao, 2011). It allows us to focus rapidly on any aspects of the incoming visual signal (e.g., discolouring) discrepant with predictions based on ripe fruit.

Before proceeding, we must consider the meaning of the word “colour”. There are three main qualities associated with colour:

- 1 *Hue*: the colour itself and what distinguishes red from yellow or blue.
- 2 *Brightness*: the perceived intensity of light.
- 3 *Saturation*: this allows us to determine whether a colour is vivid or pale; it is influenced by the amount of white present.



Weblink:
Colour perception

Trichromacy theory

The cones in the retina are specialised for colour vision. Cone receptors contain light-sensitive photopigment allowing them to respond to light. According to trichromatic (three-coloured) theory, there are three different kinds of cone receptors. One type is especially sensitive to short-wavelength light and generally responds most to stimuli perceived as blue. A second type of cone receptor is most sensitive to medium-wavelength light and responds greatly to stimuli generally seen as yellow-green. The third type of cone receptor responds most to long-wavelength light such as that coming from stimuli perceived as orange-red.

How do we see other colours? According to the theory, most stimuli activate two or all three cone types. The colour we perceive is determined by the *relative* levels of stimulation of each cone type.

Many forms of colour deficiency are consistent with trichromacy theory. Most individuals with colour deficiency have **dichromacy**, in which one cone class is missing. In deutanopia, medium wavelength (green) cones are missing. In protanopia, long wavelength (red) cones are missing, and in tritanopia, short wavelength (blue) wavelength cones are missing.

Why has evolution equipped us with three types of cones? It is a very efficient system – we can discriminate millions of colours even with so few cone types. Note, however, that many animal species have more than three types of cones, so effective colour vision can be achieved in various ways.

Opponent processes

Trichromacy theory does not explain what happens *after* activation of the cone receptors. It also does not account for **negative afterimages**. If you stare at a square in a given colour for several seconds and then shift your gaze to a white surface, you will see a negative afterimage in the complementary colour (complementary colours produce white when combined). For example, a green square produces a red afterimage, whereas a blue square produces a yellow afterimage.

Hering (1878) explained negative afterimages. He argued that there are three types of opponent processes in the visual system. One opponent process (red–green channel) produces perception of green when responding one way and of red when responding the opposite way. A second opponent process (blue–yellow channel) produces perception of blue or yellow in the same way. The third opponent process (achromatic channel) produces the perception of white at one extreme and of black at the other.

What is the value of having these three opponent processes? There is evidence (e.g., Tailor et al., 2000; Lee et al., 2002) that the three dimensions associated with opponent processes provide maximally *independent* representations of colour information. As a result, the opponent processes provide very efficient encoding of chromatic stimuli.

Several lines of research support the notion of opponent processes. First, opponent cells have been identified in monkeys (DeValois & DeValois, 1975). Second, the theory accounts for negative afterimages. Prolonged viewing of a given colour (e.g., red) produces one extreme of activity in the relevant opponent process. When attention is then directed to a white surface, the opponent process moves to its other extreme, thus producing the negative afterimage.

The existence of opponent processes also explains some types of colour deficiency. Red–green deficiency occurs when the high- or medium-wavelength cones are damaged or missing, and so the red–green channel cannot be used. Blue–yellow deficiency occurs when individuals lacking the short-wavelength cones cannot make effective use of the blue–yellow channel.

Dual-process theory

Hurvich and Jameson (1957) proposed a dual-process theory combining the ideas discussed so far. Signals from the three cone types identified by trichromacy theory are sent to the opponent cells (see [Figure 2.16](#)). There are three channels.

KEY TERMS

Dichromacy

A deficiency in colour vision in which one of the three cone classes is missing.

Negative afterimage

The illusory perception of the complementary colour to the one that has just been fixated; green is the complementary colour to red and blue is complementary to yellow.



Weblink:

Colour blindness test

Weblink:

Colour afterimages

Weblink:

Opponent processes

KEY TERMS

Colour constancy

The tendency for an object to be perceived as having the same colour under widely varying viewing conditions.

Illuminant

A source of light illuminating a surface or object.

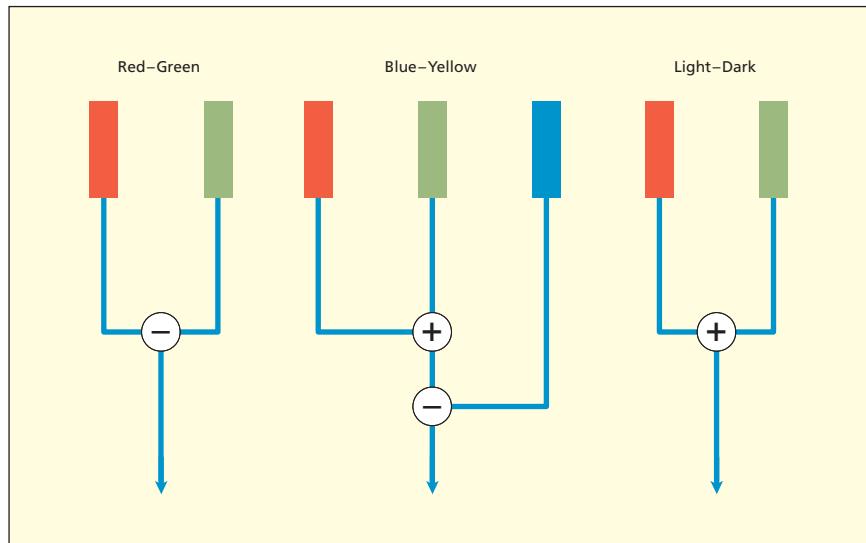


Figure 2.16

Schematic diagram of the early stages of neural colour processing. Three cone classes (red = long; green = medium; blue = short) supply three “channels”. The achromatic (light–dark) channel receives non-spectrally opponent input from long and medium cone classes. The two chromatic channels receive spectrally opponent inputs to create the red–green and blue–yellow channels.

From Mather (2009). Copyright © 2009 George Mather. Reproduced with permission.

The achromatic (non-colour) channel combines the activity of the medium- and long-wavelength cones. The blue–yellow channel represents the difference between the sum of the medium- and long-wavelength cones on the one hand and the short-wavelength cones on the other. The direction of difference determines whether blue or yellow is seen. Finally, the red–green channel represents the difference between activity levels in the medium- and long-wavelength cones. The direction of this difference determines whether red or green is perceived.

Evaluation

There is much experimental support for opponent-process theory. However, it is greatly oversimplified (Solomon & Lennie, 2007; Conway et al., 2010). For example, the proportions of different cone types vary considerably across individuals, but this has surprisingly little effect on colour perception. Second, the arrangement of cone types in the eye is fairly *random*. This seems odd because it presumably makes it hard for colour-opponent processes to work effectively. In sum, the processes involved in colour vision are much more complicated than previously believed.

Colour constancy

Colour constancy is the tendency for a surface or object to be perceived as having the same colour when the wavelengths contained in the **illuminant** (the light source illuminating the surface or object) change. The phenomenon of colour constancy indicates that colour vision does *not* depend solely on the wavelengths of the light

reflected from objects. Learn more about colour constancy on YouTube: This Is Only Red by Vsauce.

Why is colour constancy important? Suppose we lacked colour constancy. The apparent colour of familiar objects would change dramatically with changes in the lighting conditions. This would make it very hard to recognise objects rapidly and accurately.

It typically does not seem hard to achieve reasonable levels of colour constancy in our everyday lives. In fact, however, it is actually a very impressive achievement. Have a look at the object in [Figure 2.17](#). You probably immediately recognised it as a blue mug. If you look more closely, however, several other colours can also be identified in the mug. The wavelengths of light depend on the mug itself, the illuminant and reflections from other objects on to the mug's surface.

How good is colour constancy?

Granzier et al. (2009a) assessed colour constancy under natural conditions. Observers were initially presented with six uniformly coloured papers similar in colour and learned to name them. After that, they tried to identify individual papers presented at various indoor and outdoor locations differing substantially in terms of lighting conditions.

Granzier et al.'s (2009a) key finding was that 55% of the papers were identified correctly. This may sound unimpressive. However, it represents good performance given the similarities among the papers and the large differences in lighting conditions.

Reeves et al. (2008) argued that it is important to distinguish between our subjective experience and our judgements about the world. For example, as you walk towards a fire, it feels increasingly hot *subjectively*. However, how hot you *judge* the fire to be is unlikely to change. Reeves et al. found high levels of colour constancy when observers made judgements of the *objective* similarity of two stimuli seen under different illuminants. However, much lower levels of colour constancy were obtained when observers rated the *subjective* similarity of the hue and saturation of two stimuli. Thus, we can use our visual system *flexibly*.

It is often assumed colour constancy should be better when observers are presented with naturalistic three-dimensional stimuli rather than simple two-dimensional scenes. The former stimuli provide much richer information, which should enhance colour constancy. In practice, that is not the case (Foster, 2011). For example, de Almeida et al. (2010) found comparably high levels of colour constancy with two- and three-dimensional stimuli. This non-significant difference may have occurred because observers attended to only a small fraction of the information potentially available in three-dimensional stimuli.

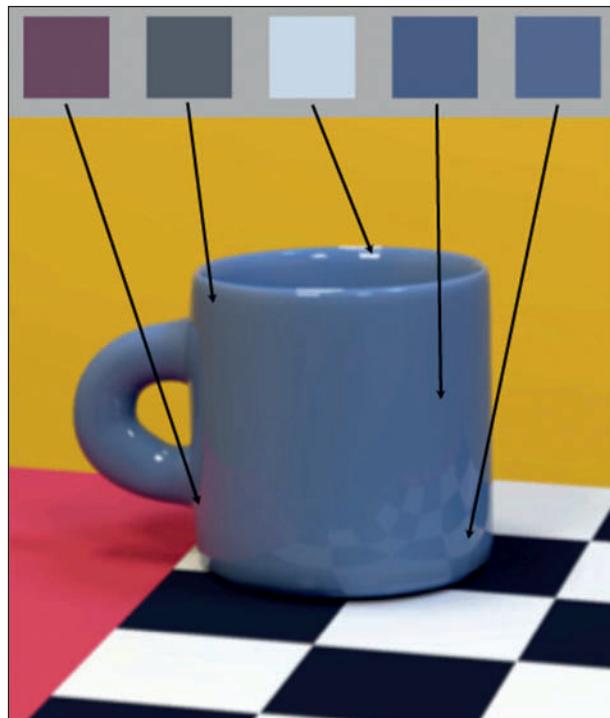


Figure 2.17

Photograph of a mug showing enormous variation in the properties of the reflected light across the mug's surface. The patches at the top of the figure show image values from the locations indicated by the arrows.

From Brainard and Maloney (2011). Reprinted with permission of the Association for Research in Vision and Ophthalmology.



Weblink:
Colour constancy

Estimating scene illumination

The wavelengths of light reflected from an object are greatly influenced by the nature of the illuminant (light source). If observers can make accurate illuminant estimates, this could lead to high levels of colour constancy. Observers do sometimes make effective use of information about the illuminant. However, they are typically very insensitive to changes in the illumination (Foster, 2011).

Evidence that observers often make limited use of illumination estimates was reported by Granzier et al. (2009b). Observers estimated a lamp's colour based on the light reflected from the scene it illuminated. They also judged the colour of a surface within the scene (to assess colour constancy). There were two main findings. First, observers' surface colour estimates were much more accurate than their estimates of the colour of the illuminant (i.e., the lamp). Second, there was no correlation between the accuracy of observers' estimates of the lamp's colour and that of the surface. These findings suggest colour constancy does *not* depend on illuminant estimates.

Local colour contrast

Land (e.g., 1986) put forward his retinex theory, according to which we perceive the colour of a surface by comparing its ability to reflect short, medium and long wavelengths of light against that of adjacent surfaces. In other words, we make use of local colour contrast.

Kraft and Brainard (1999) placed various objects (e.g., a tube wrapped in tin foil, a pyramid, a cube) in a box. Under full viewing conditions, colour constancy was 83% even with large changes in illumination. The most important factor was local contrast. When local contrast could not be used, colour constancy dropped to 53%.

Another important factor was global contrast, in which cone responses from the target surface are compared with those across the entire visual scene. When observers could not use global or local contrast, colour constancy dropped to 39%. When observers were also denied information in the form of reflected highlights from glossy surfaces, colour constancy dropped to 11%.

Foster and Nascimento (1994) developed Land's ideas into an influential theory based on local contrast and involving cone-excitation ratios. We can see the nature of their big discovery by considering a simple example. Suppose there were two illuminants and two surfaces. If surface 1 led to the long-wavelength or red cones responding *three* times as much with illuminant 1 as illuminant 2, then the same *threefold* difference was also found with surface 2. Thus, the *ratio* of cone responses was essentially invariant with different illuminants. As a result, we can use information about cone-excitation ratios to eliminate the illuminant's effects and so increase colour constancy.

There is much support for the notion that cone-excitation ratios are important (Foster, 2011). For example, Nascimento et al. (2004) obtained evidence suggesting the level of colour constancy shown in different conditions could be predicted on the basis of cone-excitation ratios.

Foster and Nascimento's (1994) theory provides an elegant account of how illumination-independent colour constancy works in relatively simple visual environments. However, it is of limited value when the visual environment is more complex (Brainard & Maloney, 2011). For example, colour constancy for a given

object can be made harder because of reflections from other objects (see Figure 2.17) or because there are multiple sources of illumination present at the same time. The theory does not provide a thorough account of how observers deal with such conditions.

Effects of familiarity

Colour constancy is influenced by our knowledge of the familiar colours of objects (e.g., bananas are yellow). In a study by Hansen et al. (2006), observers viewed photographs of fruits and adjusted their colour until they appeared grey. There was over-adjustment. For example, a banana still looked yellowish to observers when it was actually grey, leading them to adjust its colour to a slightly bluish hue. Thus, objects tend to be perceived in their typical colour even when the actual colour differs from the typical one.

KEY TERM

Chromatic adaptation

Changes in visual sensitivity to colour stimuli when the illumination alters.

Chromatic adaptation

One reason why we show reasonable colour constancy is because of **chromatic adaptation**, in which an observer's visual sensitivity to a given illuminant decreases over time. If you stand outside after dark, you may be struck by the yellowness of the artificial light in people's houses. However, if you spend some time in a room illuminated by artificial light, the light does not seem yellow.

R.J. Lee et al. (2012) exposed observers to sudden changes of illumination between sunlight and skylight conditions. The findings were complex, but some aspects of chromatic adaptation occurred in approximately six seconds. This fairly rapid decrease in the impact of a change in illumination increases colour constancy.

Invariant cell responses

Zeki (1983) found in monkeys that cells in area V4 (centrally involved in colour processing) responded strongly to a red patch illuminated by red light. However, these cells did not respond when the red patch was replaced by a green, blue or white patch even though the dominant reflected wavelength would generally be perceived as red. Thus, these cells responded to the *actual* colour of a surface rather than simply to the wavelengths reflected from it.

Kusunoki et al. (2006) reported similar findings to those of Zeki (1983). They measured the effects of changes in background illumination on neurons in monkey V4. They concluded these neurons "exhibit the property of colour constancy and their response properties are thus able to reflect colour perception" (Kusunoki et al., 2006, p. 3047).

Evaluation

Colour constancy is a complex achievement, and observers often fall well short of complete constancy. In view of its complexity, it is unsurprising the visual system adopts an "all hands on deck" approach in which several factors contribute to colour constancy. Of special importance are cone-excitation ratios that remain almost invariant across changes in illumination. In addition, top-down factors such as our memory of the familiar colours of common objects also play a role. Our

KEY TERMS

Monocular cues

Cues to depth that can be used by one eye, but can also be used by both eyes together.

Binocular cues

Cues to depth that require both eyes to be used together.

Oculomotor cues

Cues to depth produced by muscular contractions of the muscles around the eye; use of such cues involves kinaesthesia (also known as the muscle sense).

understanding of the brain mechanisms underlying colour constancy has been enhanced by the discovery of cells in V4 responsive to colour constancy.

What are the limitations of theory and research on colour constancy? First, we lack a comprehensive theory of how the various factors *combine* to produce colour constancy. Second, most research has focused on relatively simple visual environments and so the processes involved in trying to achieve colour constancy in more complex environments are poorly understood. Third, more research is needed to understand why the extent of colour constancy depends greatly on the precise instructions given to observers.

DEPTH PERCEPTION

A major accomplishment of visual perception is the transformation of the two-dimensional retinal image into perception of a three-dimensional (3-D) world seen in depth. It is crucially important to us to construct 3-D representations of the world around us if we are to pick up objects, decide whether it is safe to cross the road, avoid cliff edges and so on.

Depth perception depends heavily on numerous visual and other cues. We can define a cue as “any sensory information that gives rise to a sensory estimate” (Ernst & Bühlhoff, 2004, p. 163).

All cues provide *ambiguous* information, and so it would be unwise to place total reliance on any single cue. In addition, different cues often provide conflicting information. When you watch a movie at the cinema or on television, some cues (e.g., stereo ones) indicate everything you see is at the same distance. In contrast, other cues (e.g., perspective, shading) indicate some objects are closer than others.

In real life, cues to depth are often provided by movement of the observer or objects in the visual environment. Some cues are not visual (e.g., based on touch or hearing). However, the major focus here will be on visual depth cues available even if the observer and environmental objects are static. Such cues can conveniently be divided into monocular, binocular and oculomotor cues. **Monocular cues** are those requiring only one eye, although they can also be used readily when someone has both eyes open. Such cues clearly exist, because the world still retains a sense of depth with one eye closed. **Binocular cues** are those involving both eyes being used together. Finally, **oculomotor cues** depend on sensations of muscular contraction of the muscles around the eye. Use of these cues involves kinaesthesia (the muscle sense).

Monocular cues

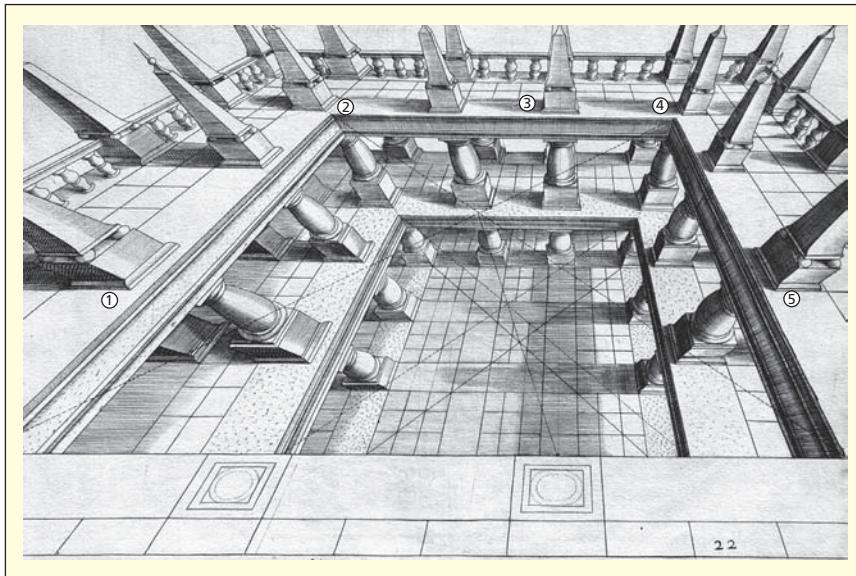
Monocular cues to depth are sometimes called *pictorial cues* because they are used by artists trying to create the impression of three-dimensional scenes when painting on two-dimensional canvases. One such cue is *linear perspective*. Parallel lines pointing directly away from us seem increasingly close to each other as they recede into the distance (e.g., the edges of a motorway). This convergence of lines creates a powerful impression of depth in a two-dimensional drawing.

The effectiveness of linear perspective in drawings varies as a function of viewing distance. We can see this clearly in a drawing by the Dutch artist Jan Vredeman de Vries (see Figure 2.18). As Todorović (2009) pointed out, this drawing looks distinctly odd when viewed from some distance but creates an effective 3-D effect when viewed from very close.



Weblink:

Cues to depth perception



KEY TERM

Texture gradient

The rate of change of texture density from the front to the back of a slanting object.

Figure 2.18

An engraving by de Vries (1604/1970) in which linear perspective creates an effective three-dimensional effect when viewed from very close but not from further away.

From Todorović (2009). Copyright © 1968 by Dover Publications. Reprinted with permission from Springer.

Another monocular cue is *texture*. Most objects (e.g., carpets, cobble-stoned roads) possess texture and textured objects slanting away from us have a **texture gradient** (Gibson, 1979; see Figure 2.19). This is a gradient (rate of change) of texture density as you look from the front to the back of a slanting object. Sinai et al. (1998) found observers were good at judging the distance of objects within seven metres when the ground in between was uniformly textured. However, distances were systematically overestimated when there was a gap (e.g., a ditch) in the texture pattern.

Shading provides another monocular cue to depth. Flat two-dimensional surfaces do *not* cast shadows and so shading indicates the presence of a 3-D object. Ramachandran (1988) presented observers with a visual display consisting of numerous very similar circular patches. Some were illuminated by one light source and the others by a different light source. Observers incorrectly assumed the visual display was lit by a single light source. This led them to assign different depths to different parts of the display (i.e., some “dents” were misperceived as “bumps”).

A further cue is *interposition*, in which a nearer object hides part of a more distant one. The strength of this cue can be seen in Kanizsa’s (1976) illusory square (see Figure 2.20). There is

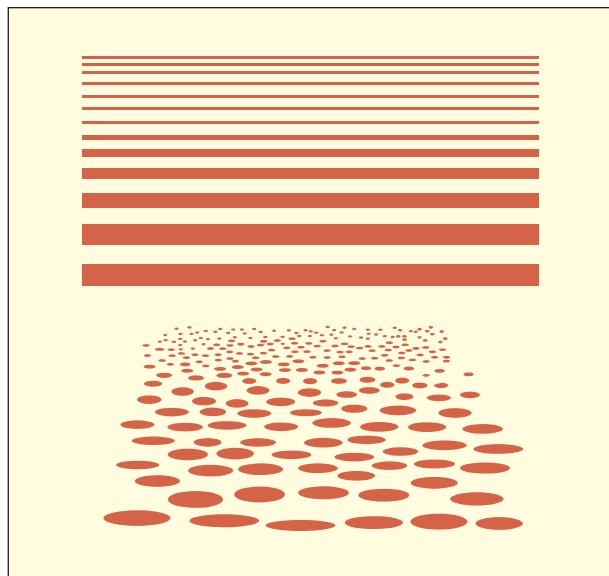


Figure 2.19

Examples of texture gradients that can be perceived as surfaces receding into the distance.

From Bruce et al. (2003).

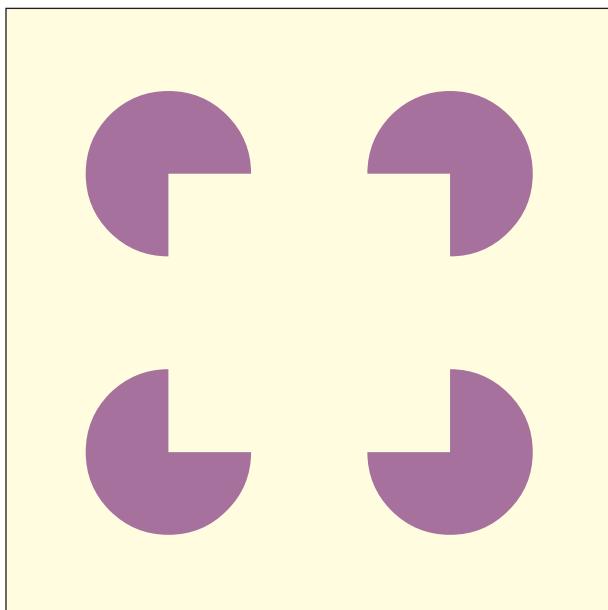


Figure 2.20
Kanizsa's (1976) illusory square.

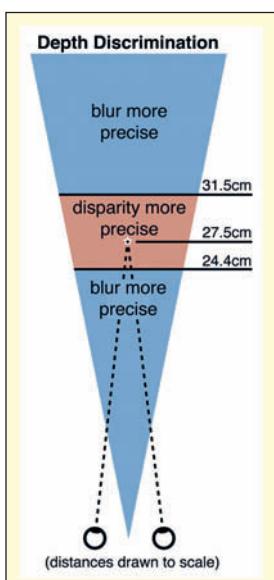


Figure 2.21
Effectiveness of blur and binocular disparity as cues to depth at different viewing distances.

From Held et al. (2012).
Reprinted with permission of Elsevier.

a strong impression of a yellow square in front of four purple circles even though many of the white square's contours are missing.

Another useful cue is *familiar size*. If we know the size of an object, we can use its retinal image size to provide an accurate estimate of its distance. However, we can be misled if an object is not in its familiar size. Ittelson (1951) had observers look at playing cards through a peephole restricting them to monocular vision. Playing cards of various sizes were presented at a distance of 2.28 metres. The perceived distances were determined almost entirely by familiar size – a half-size card was seen as 1.38 metres away and a double-size card as 4.56 metres away.

We turn now to a cue whose importance has been curiously underestimated: *blur*. There is no blur at the point of fixation, and it increases more rapidly at closer distances than at further ones. The role played by blur was clarified by Held et al.

(2012). They argued that **binocular disparity** (the slight difference in the two retinal images; discussed fully later) is a more useful depth cue close to the point of fixation. However, blur is more useful than binocular disparity further away from the fixation point. Held et al.'s findings were consistent with their assumptions (see Figure 2.21).

Finally, there is **motion parallax**, in which there is movement in one part of the retinal image relative to another. For example, consider what happens when an observer's head moves. This produces large apparent movement of nearby objects in the opposite direction but small apparent movement of distant objects in the same direction. Rogers and Graham (1979) found motion parallax can produce accurate depth judgements in the absence of all other cues.

Cues such as linear perspective, texture and interposition allow observers to perceive depth even in two-dimensional displays. However, much research with computer-generated two-dimensional displays has found depth is often underestimated (Domini et al., 2011). Two-dimensional displays provide cues to flatness (e.g., binocular disparity, accommodation and vergence, all discussed shortly). These flatness cues may reduce the impact of cues suggesting depth.

Oculomotor and binocular cues

The pictorial cues discussed so far can all be used as well by one-eyed individuals as by those with normal vision. Depth perception also depends on oculomotor cues based on perceiving muscle contractions around the eyes. One such cue is **vergence**. It is a depth cue that is based on the fact that the eyes turn inwards more to focus on a very close object than one further away.

Another oculomotor cue is **accommodation**. It refers to the variation in optical power produced by the thickening of the lens of the eye when someone focuses on a close object.

Vergence and accommodation are both very limited. First, they both provide only a single value in any situation. As a result, they can only provide information

about the distance of a *single* object at any one time. Second, they are both of value only when judging the distance of close objects, and even then the information they provide is not very accurate.

We turn now to a binocular cue that is dramatically more useful than accommodation or convergence. Binocular disparity is the slight difference or disparity in the images projected on the retinas of the two eyes when you view a scene. This produces **stereopsis**, which is the depth perception produced by binocular disparity.

Stereopsis is very powerful at short distances. However, the disparity or discrepancy in the retinal images of an object decreases by a factor of 100 as its distance from the observer increases from 2 to 20 metres. Thus, stereopsis rapidly becomes less effective at greater distances.

It has sometimes been assumed that stereoscopic information is available early in visual perception and is used in object recognition. However, contrary evidence was reported by Bülthoff et al. (1998). Observers' recognition of familiar objects was *not* adversely affected when stereoscopic information was scrambled. Indeed, the observers seemed unaware the depth information was scrambled! Observers' expectations about the structure of familiar objects were more important than the misleading stereoscopic information.

A key process in stereopsis is to *match* features in the input presented to the two eyes. Sometimes we make mistakes in doing this, which can produce various illusions and other effects. Consider, for example, the **autostereograms** found in the Magic Eye books. An autostereogram is a two-dimensional image containing depth information so it appears to be three-dimensional when viewed appropriately. You can see an autostereogram of a shark if you access the *Wikipedia* entry for autostereogram.

What happens with autostereograms is that the same repeating 2-D pattern is presented to each eye. If there is a dissociation of vergence and accommodation, two adjacent patterns will form an object that appears to be at a different depth from the background.

If you only glance at an autostereogram, you see a two-dimensional pattern. However, if you stare at it and strive *not* to bring it into focus, you can see a three-dimensional image. It often helps if you hold the autostereogram very close to your face and then move it very slowly away while preventing it from coming into focus.

Gómez et al. (2012) wondered why some individuals are much better than others at perceiving three-dimensional objects in autostereograms. They found individual differences in binocular disparity, vergence and accommodation all predicted success (or failure) with autostereograms.

Parker (2007) reviewed research on the brain areas associated with the processing of information relevant to binocular disparity. In general terms, processing of disparity information was more detailed and sophisticated in the ventral stream (see Glossary) than the dorsal stream (see Glossary).

Cue integration

So far we have considered depth cues one by one. However, we typically have access to several depth cues at once. This raises the question of how we *combine* these different sources of information to judge depth or distance. Two possibilities are *additivity* (adding together information from all cues) and *selection* (only using

KEY TERMS

Binocular disparity

A depth cue based on the slight disparity in the two retinal images when an observer views a scene; it is the basis for **stereopsis**.

Motion parallax

A depth cue based on movement in one part of the retinal image relative to another.

Vergence

A cue to depth based on the inward focus of the eyes with close objects.

Accommodation

A depth cue based on changes in optical power produced by thickening of the eye's lens when an observer focuses on close objects.

Stereopsis

Depth perception based on the small discrepancy in the two retinal images when a visual scene is observed (**binocular disparity**).

Autostereogram

A complex two-dimensional image perceived as three-dimensional when not focused on for a period of time.



Weblink:

Depth perception test

KEY TERM**Haptic**

Relating to the sense of touch.

**Weblink:**

Ambiguous depth cues

information from a single cue) (Bruno & Cutting, 1988). Cues may also be combined in more complex ways.

How should we integrate cue information to maximise the accuracy of our depth perception? Jacobs (2002) argued that we should assign more weight to reliable than to unreliable cues. Since cues reliable in one context may be less so in another context, we should be *flexible* in our assessments of cue reliability.

The above notions led Jacobs (2002) to put forward two hypotheses:

- 1 Less ambiguous cues (e.g., those providing consistent information) are regarded as more reliable than more ambiguous ones.
- 2 A cue is regarded as reliable if inferences based on it are consistent with those based on other available cues.

Experimentation in this area has benefited from advances in virtual reality technologies. These advances permit researchers to control visual cues very precisely and to provide observers with virtual environments permitting clear-cut tests of hypotheses.

Findings

Evidence supporting Jacobs' (2002) first hypothesis was reported by Triesch et al. (2002). They used a virtual reality situation in which observers tracked an object defined by colour, shape and size. On each trial, two attributes were unreliable or inconsistent (their values changed frequently). Observers attached increasing weight to the reliable or consistent cue and less to the unreliable cues during the course of each trial.

Evidence consistent with Jacobs' (2002) second hypothesis was reported by Atkins et al. (2001). They used a virtual reality environment in which observers viewed and grasped elliptical cylinders. There were three cues to cylinder depth: texture, motion and **haptic** (relating to the sense of touch).

When the haptic and texture cues indicated the same cylinder depth but the motion cue indicated a different depth, observers made increasing use of the texture cue and decreasing use of the motion cue. When the haptic and motion cues indicated the same cylinder depth but the texture cue did not, observers increasingly relied on the motion cue rather than the texture cue. Thus, whichever visual cue correlated with the haptic cue was preferred, and this preference increased with practice.

Most research suggests observers integrate cue information according to the additivity notion in that they take account of most or all cues (Landy et al., 2011). However, they attach additional weight to more reliable ones. These conclusions certainly apply to the numerous studies in which there were only small conflicts between the information provided by each cue.

What happens when two or more cues are in strong conflict? As we will see, observers typically rely heavily (or even exclusively) on only one cue. Thus, observers' depth perception is based on the selection strategy as defined by Bruno and Cutting (1988). This makes sense. Suppose one cue suggests an object is 10 metres away but another cue suggests it is 90 metres away. It is probably not sensible to split the difference and decide it is 50 metres away! We use the selection strategy at the movies – perspective and texture cues are used to produce a 3-D

effect, whereas we ignore cues (e.g., binocular disparity) indicating everything on the screen is the same distance from us.

Relevant evidence was reported by Girshick and Banks (2009) in a study on the effects of two cues (binocular disparity and texture gradients) on slant perception. When there was a small conflict between the information provided by the cues, observers used information from both. When there was a large conflict, however, perceived slant was determined exclusively by one cue (binocular disparity or texture gradient). Interestingly, the observers were not consciously aware of the large conflict between the cues.

We have discussed the ways in which observers combine information from different cues. To what extent does such cue combination produce *optimal* performance (i.e., accurate depth perception)? Lovell et al. (2012) addressed this issue. In their study, they explored the effects of binocular disparity and shading on depth perception. Overall, binocular disparity was the more informative cue to depth, but Lovell et al. tested the effects of making it less reliable over trials. Information from the cues was combined optimally, with observers consistently attaching more weight to reliable than unreliable cues.

Knill and Saunders (2003) studied the use of texture and stereo cues on judgements of surface slant. Texture information becomes increasingly useful as slant increases, and Knill and Saunders predicted that observers would make more use of texture cues at greater slants. Their prediction was confirmed. Knill and Saunders also found interesting individual differences in the weight attached to texture and stereo cues. Texture cues were heavily weighted by individuals best able to use such cues and the same was true with stereo cues. Overall, observers combined stereo and texture information in a fashion that was close to optimal.

Evaluation

Much has been learned about the numerous cues observers use to estimate depth or distance. Information from different depth cues is typically combined to produce accurate depth perception. This often happens in an additive fashion with information from all cues being combined. However, there are several situations (e.g., when different cues conflict strongly) in which one cue dominates the others.

As Jacobs (2002) argued, we attach more weight to cues that provide reliable information and are consistent with that provided by other cues. In addition, the weight we attach to any given cue is flexible – we sometimes learn a cue that was reliable in the past is no longer so. Overall, cues are generally weighted to produce accurate depth perception.

What are the limitations of research in this area? First, we spend most of our time estimating distance in settings in which numerous cues are present and there are no large conflicts between them. In contrast, laboratory settings often provide only a few cues, and those cues provide very discrepant information. The unfamiliarity of laboratory settings may sometimes cause suboptimal performance by observers and reduce generalisation to everyday life (Landy et al., 2011).

Second, it is generally assumed the information observers obtain from single cues is accurate. However, that assumption is rarely tested. Third, observers learn reasonably rapidly which cues are more and less reliable. Assessing cue reliability involves comparing the effectiveness of different cues and the complex processes involved are not well understood.