



THE PSYCHOLOGY OF LEARNING AND MOTIVATION

Volume 43

Brian H. Ross

**THE PSYCHOLOGY
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THE PSYCHOLOGY OF LEARNING AND MOTIVATION

Advances in Research and Theory

EDITED BY BRIAN H. ROSS

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CONTENTS

<i>Contributors</i>	ix
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ECOLOGICAL VALIDITY AND THE STUDY OF CONCEPTS

Gregory L. Murphy

I. Introduction.....	1
II. Three Disputes	2
III. What Is the Psychology of Concepts a Psychology of?	7
IV. Capacities versus Performance Models	14
V. What Should We Be Trying to Explain in the Psychology of Concepts?	16
VI. The Missing Piece to the Puzzle	19
VII. What Is the Real Category Structure?.....	26
VIII. Role Models	30
IX. Conclusion.....	36
References.....	37

SOCIAL EMBODIMENT

*Lawrence W. Barsalou, Paula M. Niedenthal, Aron K. Barbey,
and Jennifer A. Ruppert*

I. Introduction.....	43
II. Social Embodiment Effects	45
III. A Theory of Social Embodiment	63
IV. Explaining Social Embodiment Effects	77

V. Conclusion	83
References	85

THE BODY'S CONTRIBUTION TO LANGUAGE

Arthur M. Glenberg and Michael P. Kaschak

I. Introduction	93
II. Symbol Grounding and the Action-Sentence Compatibility Effect	94
III. How Language Becomes Embodied Meaning.....	100
IV. Perceptual Symbols in Language Comprehension	105
V. Grammatical Constructions in Language Comprehension	112
VI. Learning and the Indexical Hypothesis	118
VII. Conclusion	122
References	123

USING SPATIAL LANGUAGE

Laura A. Carlson

I. Introduction	127
II. Constituent Processes during Apprehension	129
III. Assigning Directions to Space: Setting the Parameters.....	138
IV. Generalizations and Conclusions.....	156
References	158

IN OPPOSITION TO INHIBITION

*Colin M. MacLeod, Michael D. Dodd, Erin D. Sheard,
Daryl E. Wilson, and Uri Bibi*

I. Introduction	163
II. A "Reader's Digest" History of Inhibition	166
III. The Attention Case Studies	170
IV. Memory Case Studies	185
V. The "Big Picture"	201
References	206

EVOLUTION OF HUMAN COGNITIVE ARCHITECTURE

John Sweller

I. How Information Structures Have Impelled the Evolution of Human Cognitive Architecture	216
II. Human Information Processing Recapitulates Evolution by Natural Selection	235
III. Instructional Consequences	244
IV. Conclusions	259
References	261

COGNITIVE PLASTICITY AND AGING

Arthur F. Kramer and Sherry L. Willis

I. Overview	267
II. Cognition across the Adult Life Span	267
III. Changes in Brain Function and Structure across the Adult Life Span	271
IV. Does Experience Reduce Age-Related Cognitive Decline?	275
V. Can Laboratory-Based Training Be Used to Reduce Age-Related Decline in Cognition, and If So, What are the Nature of These Training Benefits?	283
VI. Can Other Interventions Reduce Age-Related Decline in Cognition: Healthy Body, Healthy Mind?	291
VII. Conclusions and Future Directions	294
References	295
<i>Index</i>	303
<i>Contents of Previous Volumes</i>	313

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ECOLOGICAL VALIDITY AND THE STUDY OF CONCEPTS

Gregory L. Murphy

I. Introduction

The psychology of concepts has developed into a sophisticated and mature area of research since Eleanor Rosch's pioneering work in the 1970s (Mervis & Rosch, 1981). The main questions to be investigated are agreed upon, a number of empirical phenomena are widely accepted, and the lines separating different theoretical positions are well established. In a book reviewing this field (Murphy, 2002), I argued that we have indeed achieved considerable progress in the understanding of concepts. However, that understanding is largely empirical rather than theoretical. The main controversy of the 1980s, that of prototype versus exemplar representations of concepts, is still largely unresolved. The new question that was raised in the mid-1980s and extended through the 1990s, that of how background knowledge influences concepts, is also somewhat unsettled. Although there are numerous demonstrations showing that world knowledge influences concept learning and use, many researchers have not incorporated these effects into their theories or computational models. Finally, the study of concepts in children is now a major component of developmental psychology, but the topics and assumptions of that field often conflict with those of researchers in the adult literature.

As shown in this chapter, the problem is that conflicting approaches to concepts seem to have strong evidence in their favor. As a result, researchers

from each approach have tended to focus on their own favorite evidence and paradigms, paying little mind to those on the opposing side. One possible way to resolve some of these disputes is to switch from asking which side is correct to asking *when* each side is correct. Evidence for the different approaches suggests that there must be a grain of truth in most of them. However, that does not mean that every approach is equally worth pursuing. I think the field needs to take a step or two back and ask what precisely it is trying to explain. It is possible that some of the different approaches are indeed providing valid answers, but not to the same questions. And, some of these questions may not be the most interesting or general ones. Such arguments are difficult to make because they are not primarily empirical but are value judgments. However, they are value judgments that can be well informed and based on solid arguments, and I will attempt to make such arguments in the course of this chapter.

I begin by spelling out some of the conflicts that I alluded to earlier, and then I address more general questions of what the goals of the study of concepts should be and how that might help us resolve some of the conflicts.

II. Three Disputes

A. EXEMPLARS VERSUS PROTOTYPES

I will not attempt anything like a complete review of the exemplar–prototype debate here. In outline, the two positions are as follows. *Prototype theory* (Hampton, 1979, 1995; Rosch, 1975; Rosch & Mervis, 1975; Smith & Medin, 1981) argues that concepts are summary representations of the central tendency of a category. For example, I have a concept of telephones that includes information, such as their usual shapes, sizes, functions, inner workings, colors, and parts. This information is a summary representation in that it stands for the category¹ as a whole. This representation does not describe a specific object but rather sets out the likely properties of all the objects in the category (Rosch & Mervis, 1975). Thus, I might store the fact that telephones have buttons that you press or dials that you turn, even though no individual telephone (that I have seen) has both. *Exemplar theory* denies that such general representations are created. Instead, it argues that my concept of telephones is the set of memories I have of specific telephones.

¹ I generally use *category* to refer to the actual set of objects and *concept* to refer to the mental representation of those objects. Thus, one would pedantically say that I have a concept of dogs that picks out the category of dogs. However, I avoid such pedantry where possible and sometimes use *category* ambiguously when I want to refer to both the concept and category, as the two generally do go together.

So, if I am trying to decide if something is a telephone, I do not consult information about telephones in general but instead consult memories of past telephones I have known.

These theories differ greatly in the processes they posit for how concepts are learned, in how concepts are represented, and in how categorization and other conceptual processes take place. These differences are so great that one must imagine that the theories can readily be distinguished. In one sense, they can be. Studies by Medin, Nosofsky, Kruschke, and others have found that exemplar models generally do better than prototype models in carefully controlled category-learning experiments, in which mathematical instantiations of the models could be compared (for reviews, see Murphy, 2002; Nosofsky, 1992; Ross & Makin, 1999). In a number of comparisons, exemplar models fit the data as well as or just slightly better than prototype models; however, in other comparisons, prototype models were totally unable to explain the results. For example, prototypes are incompatible with nonlinearly separable categories, yet people are able to learn them (Estes, 1986; Medin & Schwanenflugel, 1981).

Despite this overall advantage of exemplar models in traditional category-learning experiments, a number of researchers in the field have been slow to adopt this type of model. In cognitive development, virtually all research seems to assume a summary representation of a category. Researchers who address the interaction of concepts with world knowledge almost all speak in terms of prototypes, perhaps because it is difficult to represent world knowledge in terms of exemplars (Murphy, 2002). Those who study the interaction of word meaning and concepts (e.g., conceptual combination, language production) all take a prototype view. Why haven't the experimental demonstrations of exemplar model superiority filtered down to these other domains?

B. KNOWLEDGE IN CATEGORY LEARNING

A major development in the study of concepts has been the attempt to integrate conceptual knowledge with more general knowledge of the concept's domain. For example, it has been argued that learning a concept of a new animal, perhaps seen at the zoo, involves knowledge of other animals and of biology in general. Such knowledge serves to aid the induction process so that a rich representation of the animal can be constructed based on relatively little experience. For example, when I see a new mammal in the African exhibit at the zoo, I might assume that it breathes, gives birth to live young, can stand high temperatures, and so on, even if I have not observed these properties directly. This use of background knowledge is found not only in category learning, but in induction,

conceptual combination, and other conceptual processes (Heit, 1997; Murphy, 1993, 2002).

Numerous demonstrations show that prior knowledge influences conceptual processes. Nonetheless, the main theories of concepts have not taken up this influence. For example, even recent comparisons of prototype and exemplar models use models that do not incorporate any knowledge, and they are tested on literally meaningless categories (e.g., Nosofsky & Johansen, 2000; Smith & Minda, 2000). The problem with this is that effects found with abstract, meaningless categories are often not found or are even reversed when the categories are meaningful. For example, nonlinearly separable (NLS) categories are much harder to learn than linearly separable (LS) categories when the categories' features are related to one another meaningfully (Murphy & Kaplan, 2000; Wattenmaker, Dewey, Murphy, & Medin, 1986), but this is not true for abstract categories. Categories formed by disjunctive rules are usually difficult to learn, but they are not if the rule is consistent with prior knowledge (Pazzani, 1991). When empirical factors have been pitted against consistency with knowledge in classification tests, knowledge has often been found to be more important (Keil, 1989; Wisniewski, 1995).

In short, demonstrations of the use of real-world knowledge might have been expected to change the nature of the experiments done in the concepts field. But rather than changing the direction of the field as a whole, the main effect has been to create two parallel tracks of research: one investigating structural effects in abstract categories and one exploring the influence of knowledge in meaningful categories. Although it is certainly possible that both will make contributions to our understanding of concepts, it also seems possible that one of the approaches is not right, or at least not as useful as the other. However, it is unclear on what basis that judgment should be made, as each tradition now has a set of empirical findings to point to as documenting the importance of its own questions.

C. STUDIES OF CHILDREN VERSUS STUDIES OF ADULTS

The final conflict in the field is more empirically oriented. As described elsewhere briefly (Murphy, 2001), researchers in cognitive development seem to have a very different idea of how concepts are structured than researchers in adult concepts. The typical experiment on concept learning in adults requires subjects to categorize items one at a time, over and over, until they get all the items correct. The difference in learning times for different concepts is often the critical data used to evaluate different theories. The concepts in such studies are often extremely difficult to learn. For example, Medin and Schwanenflugel (1981) constructed two categories

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with four items apiece, and subjects attempted to learn them over the course of 16 repetitions of the set of items. By the end of the learning, about a third of the subjects still had not mastered the categories. That is, they had not learned to say “category 1” to four items and “category 2” to the other four. Lamberts (2000) did not stop subjects after a set number of blocks but instead allowed them to continue until they had learned to categorize nine items perfectly. His subjects took an average of 38 blocks to do so, which seems extremely long. Once one starts looking for it, such poor performance in category-learning experiments is not unusual. Indeed, it occurs in some of my own studies (e.g., Murphy & Wisniewski, 1989). In some designs, the categories are probabilistic, and subjects *cannot* score more than 80% correct (e.g., Maddox, 1995).

The reason for this poor performance is not hard to find. Basically, the categories used in such experiments are poorly structured (Smith & Minda, 1998; Smith, Murray, & Minda, 1997). The categories have few features that are common to most members, and some of the members are very similar to members of the other categories. Such experiments seem to have an underlying assumption that the categories people learn are quite difficult and therefore that considerable experience is necessary to learn the detailed structure of the category.

However, studies of concept and word learning in children do not seem to share this assumption. This is best illustrated through the phenomenon of *fast mapping* (Carey, 1978; Markson & Bloom, 1997). In fast mapping, a child is shown one or two exemplars of a category, which are named two or three times. The naming may be overt (e.g., “Look at the koba”) or it may be indirect (e.g., “Can you hand me the chromium one?”). No further explanation or definition of the new name is given. The surprising aspect of this phenomenon is that children learn words under these circumstances and can remember them at least to some degree a month later, with no intervening exposure.

The memory for the word is of interest in its own right, but for the present purposes, the critical aspect of the fast mapping situation is its assumptions about the categories, underlying common words. In contrast to the adult literature, the notion of fast mapping seems to assume that the child can figure out the category picked out by the new word based on a single example. Clearly, these researchers do not believe that learning of real categories requires exposure to a large number of category exemplars, to be studied with great effort over the course of, say, 38 blocks. If they did, they would not show one exemplar and then test learning. (From now on, I will flout convention somewhat by using *fast mapping* to refer to the procedure of teaching a category by presenting one or two exemplars rather than to the learning process.)

The reason for the empirical discrepancy between adult and child studies is also not hard to find. In the fast-mapping study, the child views one or two exemplars and then is typically tested on the same exemplar or one that is extremely similar. There are no category members that are not similar to the learning item. The assumption is apparently that category members are generally uniform. But this assumption is completely different from that of many adult studies, which have very weak category structure. In some cases, the exact same stimulus can be in different categories (e.g., Gluck & Bower, 1988).

Two possible interpretations of the difference between adult and child studies suggest themselves. One interpretation is that children are very bright creatures who require minimal exposure to learn categories. Unfortunately, they grow up into very dull college sophomores who cannot learn categories without blocks and blocks of learning—a striking failure of our educational system. The other alternative is that one of these types of study is not right—its assumptions about category structure do not correspond to reality. Or, less optimistically, both are wrong.

D. SUMMARY OF THE THREE DISPUTES

What is surprising about these three cases is not that there are disagreements. Theoretical disagreements are part and parcel of science (although one might argue that psychologists have a tendency to prolong such disagreements beyond what is healthy). What is surprising is that very basic questions about the nature of concepts and the acquisition process remain unresolved. We have reached the 25th anniversary of the main proposal of the exemplar theory of concepts (Medin and Schaffer, 1978). After intensive research resulting in dozens of articles, however, the field does not seem any more in consensus than it was 25 years ago. Are concepts complex, poorly structured entities that take much experience and effort to learn, or are they simple things that you can get pretty well after a single example? That seems to me to be an extremely basic question about the topic we are studying. How can we go forward at all without knowing the answer to it? And if prior knowledge strongly influences learning and concept use, what are we to think of these models and theories that simply ignore it?

It would be easiest to attribute these conflicts to the shortsightedness of researchers who do not wish to address data that are problematic for their own approaches. No doubt this is part of the explanation. However, I will argue that these conflicts come about in large part because of a lack of agreement on what the basic questions are that the psychology of concepts should answer. Without some agreement on these questions, it will not be possible for researchers to have a basis on which to resolve their differences.

III. What Is the Psychology of Concepts a Psychology of?

There is a methodological pitfall masquerading as an advantage that accounts for some part of the problem I have described. In order to study concepts, all I have to do is to make up two sets of entities (which can be anything, although I will usually call them *objects* because that is usually what they are) and persuade subjects to give one response to one set and a different response to the other set. The problem with this is that I can make up any arbitrary sets, use any procedure to try to get subjects to learn, and use any response that is at all distinctive. Hull (1920), who was faced with the task of developing a methodology for studying concepts experimentally, listed a number of desiderata for studying concepts. The Desiderata included the use of distinct classes, each receiving different responses. However, they also included constraints on the concepts themselves, namely that each concept should contain an element that is unique to it. This desideratum reflected Hull's assumption about the structure of categories in the world, what has come to be known as the *classical view* of categories (Smith & Medin, 1981).

Let us imagine for a moment that Hull had been right about categories, that each category has a unique element or some set of defining features that determine category membership. What would we then think about the vast majority of modern experiments on concepts, which lack such defining features? These experiments might be interesting as studies of abstract learning, but they would simply not be *about* how people learn concepts. A study of how people learn nonlinearly separable categories might have some interest regarding the nature of memory and learning in general, but it would tell us little about how people learn real categories because nonlinearly separable categories by definition do not have definitions (sic). Studies of family resemblance concepts (Rosch & Mervis, 1975), in which category members tend to share features but have no feature common to the whole category, would also not be telling us how people learn real categories. These studies would be uninformative because the requirements involved in learning a well-defined category are different from those involved in learning family resemblance or NLS categories. Indeed, the study of logically defined concepts that was ushered in by Bruner, Goodnow, and Austin (1956) was essentially dropped when Rosch published her studies of the structure of natural categories (e.g., Rosch, 1973, 1975). The studies of concept attainment that Bruner et al. and many others carried out are now viewed as studies of a particular kind of reasoning or problem solving rather than studies of concept learning, precisely because we believe that real concepts are not like Bruner et al.'s concept.

In order to answer how people learn categories and form concepts, we cannot operate in a vacuum of knowledge about the real structure of

categories. For Hull, it would have been pointless to study how people learn family resemblance categories because this could not tell you how people learn “real” categories. We are less certain now, perhaps, what the real categories are and therefore are less willing to reject any particular experiment as being irrelevant. But perhaps we have erred on the side of liberality and acceptingness. Perhaps some of the categories we have studied do not tell us about how people learn real categories, just as the studies of Bruner et al. do not tell us how people learn family resemblance categories.

A. THE LOGIC OF HYPOTHESIS TESTING IN CATEGORIZATION RESEARCH

Although categorization experiments themselves form a family-resemblance category, there are some characteristics that are widespread throughout the domain. In particular, the experimental logic described in many articles is of the following sort: (a) Two or more theories of concepts are reviewed. (b) The theories turn out to make very similar predictions for simple categories. (c) However, there is a categorical structure that distinguishes the two theories. In particular, one theory says that the structure should be fairly easy, whereas the other says that it should be difficult. (More generally, there is a variable that one theory claims is important but the other does not.) (d) Therefore, the article presents experiments that test the critical structure or variable to see which theory is correct.

This logic, which seems perfectly straightforward as a form of scientific hypothesis testing, can be found in studies such as comparisons of exemplar and prototype theory, studies of feature frequency, examinations of knowledge effects and causal structure, and others. Clearly, if one theory predicts the structural effect (or the effect of the tested variable) correctly and the other does not, then strong support is given to the first theory.

The difficulty with this logic arises from the considerations raised in the previous section. What happens if the critical structure is one that is not present (or rarely present) in nature or if the variable is something that does not really vary in the domain of most concept learning? I call this *the problem of unconstrained concept construction*. The problem is that anyone can make up any old set of things and call it a concept. This concept can then serve as the critical test of one’s theory. For example, my theory, let us say, predicts that concept (1) below should be easier to learn than concept (2), whereas your theory makes no such prediction:

- (1) a horse, the Mona Lisa, Bill Clinton, a red telephone, and a pile of quartz
- (2) three roaches, a hair dryer, a postcard of Dayton, Ohio, and a retirement party

Suppose that I run the experiment and find that in fact (1) is easier to learn than (2). How likely are you to exchange your theory for mine? Unless you are remarkably easygoing, I would guess that my experiment will have little effect on your theorizing. And although I would take the opportunity to lambaste you and your theory in the usual outlets, I think you would be well justified in suggesting that this comparison is weird and unnatural and that its results simply cannot tell us much about how people learn concepts such as mammals, ball games, or pencils. The ability of a theory to distinguish these two categories simply does not give useful information about its ability to describe normal concepts.

This example is obviously exaggerated for purposes of illustration. However, the same question truly does arise in less exaggerated form in other cases. Suppose, for the sake of argument, that people almost always have some general knowledge of the domain of categorization when they learn a new concept. That is, after very early childhood, people seldom learn about an animal without already knowing some similar animals and some facts about animal behavior and biology; they seldom learn about a new sport without already knowing what sports are like; and they seldom learn about an electronic device without knowing a lot of consumer electronic products. If that is the case, then do studies of concept learning in which learners have no knowledge of the domain whatsoever tell us about real concept learning?

Or consider the linear separability debate. Medin and Schwanenflugel (1981) found no marked difference between people's learning of LS and NLS categories, which was contrary to the prediction of prototype theory. However, an examination of the categories used in their experiments (see Murphy, 2002; Smith et al., 1997) raises various concerns with them. For example, in every study of NLS categories that I know of, each category contains two objects that are exact opposites of one another. This is the simplest way to ensure that no independent weighting of features can correctly categorize all the items in the category. One category might have a single small blue triangle and another item with two large red circles. If each dimension has only two values (blue–red, circle–triangle, etc.), then these two items are true opposites. But what kind of category contains items that have *no* features in common whatsoever? It is as if we included trout in the category of birds and bluejays in the category of fish, keeping everything else the same. However, such opposites are put into NLS categories without apology. Smith et al. focus on the low degree of overall category differentiation in many experiments making these contrasts, arguing that the experimental categories are much less coherent than real categories. Furthermore, they claim that some subjects use prototypes when there is considerable category differentiation, even for NLS categories. Thus, past

findings strongly supporting exemplar theory may apply only to categories that are poorly structured.

A very similar problem comes about in interpreting the results of one of the most classic of all category-learning experiments, that of Shepard, Hovland, and Jenkins (1961). Shepard et al. developed six different categorization problems, each dividing eight stimuli into two categories of four items. These problems comprised all the logical possibilities of dividing up eight items based on three binary stimulus dimensions. The categories ranged from a simple single-dimensional categorization (e.g., separating large from small items) to a two-dimensional conjunctive rule to a categorization that used all three dimensions orthogonally. Figure 1 illustrates the easiest and hardest category structures. Shepard et al. and a large number of subsequent researchers (e.g., Kruschke, 1992) found a reliable ordering of learning difficulty of these six types, with type I easier than type II, types III–V being about the same, and type VI the hardest. A detailed analysis of their results led Shepard et al. (1961, p. 33) to the important conclusion that subjects were focusing attention on different stimulus dimensions, forming hypotheses about what rule separated the two categories.

I have no problem with Shepard et al.'s analysis (1961) of their experiment as a critique of stimulus-response (S-R) learning theories. Indeed, such theories make the claim that learning is an unconstrained process of S-R associations, and so testing them on arbitrarily constructed

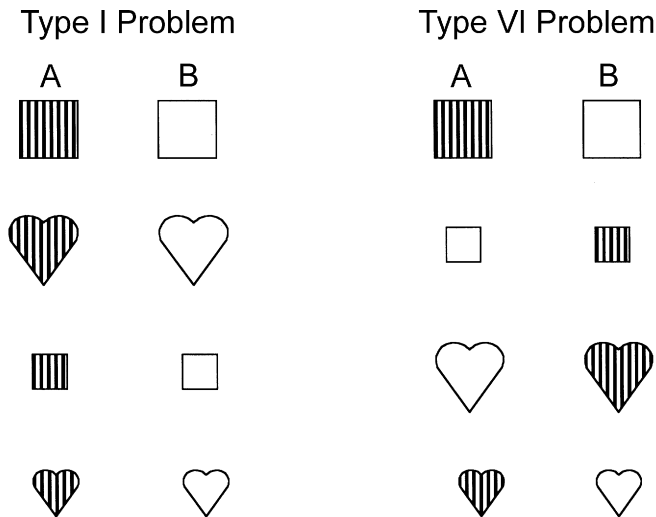


Fig. 1. Logical structures of Shepard et al.'s type I (easiest) category problem (left) and the type VI (hardest) problem (right).

categories is well within the rights of the investigator. The issue I would like to raise is the treatment of Shepard et al.'s data in the subsequent literature. It has become an important criterion in recent models of category learning that they reproduce the Shepard et al. data in some detail. For example, Kruschke (1992) contrasted the ability of his model, ALCOVE, to produce the correct ordering of Shepard et al.'s conditions compared to Gluck and Bower's (1988) configural cue model. Other researchers have also attempted to account for the relative difficulty of these six problems (e.g., Estes, 1994; Nosofsky, 1984).

The question raised by my earlier comments is what weight we should give to the ordering of Shepard et al.'s (1961) conditions. Compared to object and event categories, the type I category is grossly simplistic: There are no real object categories that are defined by a single stimulus value. (There are, of course, adjectival categories, such as red things or large things, although they are usually somewhat more complex than a single stimulus value. But I am talking about categories of whole objects or events, such as dog, funeral, zip disk drive, and movie.) Shepard et al.'s higher-level category types seem overly difficult and arbitrary. For example, the type VI problem contains a number of very different object pairs: A large black square and a small white square are in one category, and a large white square and a small black square are in the other. There is absolutely *no* family resemblance in the type VI categories—all the properties are equally frequent in the two categories (e.g., half the items are white and half are black in both categories). In the type V categories, two of the three dimensions are completely nondiagnostic and the other follows a three-out-of-four rule. For example, a large black heart, a small black heart, a large black square, and a small white square might all be in one category. Why the small white square (instead of the obvious small black square) is in the category is, of course, completely unclear to the subjects—it is just the arbitrary requirement of the experimental design.

Indeed, I think one could argue that only one of Shepard et al.'s (1961) rules is likely to correspond to the structure of natural categories: Bob Rehder pointed out to me that rule IV is essentially a family-resemblance category, in which each dimension is predictive of category membership. (Family-resemblance structure is actually a bit difficult to detect with only four items in a category.) The question, then, is to what degree we should use the differences in learning such categories as a criterion for evaluating theories of concepts. When I asked rhetorically whether the difference between categories (1) and (2) given earlier (the ones with the Mona Lisa, Bill Clinton, some quartz, etc.) should inform our theories of categorization, the reader answered rhetorically, "No, they are too weird." But why shouldn't the reader give the same answer for categories like the Shepard et al. set? If real-life categories are not orthogonal variations of stimulus dimensions,

or unidimensional splits, then why has the relative difficulty of learning such categories been of such importance to model testing in the field?

Note that I am not saying that Shepard et al.'s results are not important from a number of respects, such as telling us about selective attention and certain learning processes. What I am saying is that the ability of a theory to distinguish different category structures that do not actually exist in real life may not be an appropriate test of a model of concepts.

B. DEFENSIVE REPLIES

Let me quickly address three defensive replies to this sort of argument that I have heard from researchers, often after a drink or two at a conference poster session. One reply is something like, "That category structure [whichever one I am criticizing as unnatural] is extremely important. It has been studied in a dozen labs. How can you just ignore all those data?" However, the fact that something has been studied in the laboratory does not mean that it is relevant to a particular issue. If the problem (which I will expand on later) is how people learn and represent real categories, then the number of times a structure or paradigm is used in the laboratory simply does not speak to the question of whether the structure or paradigm tells us about real-life category learning.

A second reply is the same as the first, but with an emphasis on the fact that there are *data* out there, and every theory must account for published data. So, the finding that NLS and LS categories are learned equally easily (in certain circumstances) simply must be accounted for by any adequate theory of concepts because it is a documented finding. Although this reply is more reasonable than the first, I find it to be unconvincing as well. After all, my hypothetical finding that category (1) is easier to learn than category (2) is also a datum, and why shouldn't that be used to evaluate theories of concepts? If people's concepts do not include categories of the sort that are tested in these experiments, then it is simply hard to see how the theory's success within those unrealistic categories is a test of its account of *real* category learning. The question is not whether theories should have to account for data, but rather which data are relevant.

A third reply is to make a distinction between acquisition of everyday concepts and *perceptual classification*. I am not sure whether this distinction has been proposed explicitly, but a number of researchers working on mathematical models of categorization seem to be calling their topic "perceptual classification" (e.g., Cohen, Nosofsky, & Zaki, 2001; Lamberts, 2000; Maddox & Bohil, 2000; Nosofsky & Johansen, 2000). One could therefore interpret them as suggesting that there is a separate psychological process of perceptual classification, which may or may not be the same

process as that used to learn about real objects in knowledge-rich domains. Perhaps perceptual classification is a fairly low-level process by which items are associated to responses, which applies across a number of different domains, and which must be very flexible so that any possible distinction can be learned. Thus, criticisms of the sort I have been making based on word learning or the apparent structure of natural categories would not apply to the study of perceptual categorization because word meanings and object categories are not formed from (or only from) the perceptual classification process. In short, although this argument necessarily limits the interest of studies of perceptual classification (if they are not studying the mechanisms of real category learning), it also insulates it from ecological validity arguments.

To repeat, I am not sure that anyone has made this argument explicitly. However, it is certainly an option available to those who do experiments on very simple stimuli, with category structures that are far removed from those of everyday life. This reply has two problems, however. The first is that one cannot simply say, "I am studying perceptual classification and not object concepts," without some empirical evidence that there is a distinction between the two. By the same token, one could say, "I am working on dot patterns, whereas your categories are geometric shapes, and so my theory cannot be expected to explain your results." Is there evidence that object concepts do not involve perceptual associative learning? Unless the distinction between perceptual concepts and object concepts is proposed explicitly (not assumed) and supported empirically, use of the distinction to isolate perceptual classification from my criticisms is *ad hoc*. Second, if there is such a process of perceptual classification, it must receive its own justification as a topic of study. If it is not the process involved in children's learning of word meanings, of adults' learning of novel concepts in familiar domains, and so on, then why should one study this instead of real object learning? The reply to my objections seems to condemn the topic to irrelevance. A better strategy, in my opinion, would be to attempt to incorporate the perceptual learning processes into a broader theory of concept acquisition, which can apply to complex concepts, in knowledge-rich domains, and so on.

C. SUMMARY

Let me summarize the argument so far. The problem of unconstrained concept construction is that one can make up anything and call it a concept, test subjects on it, and then use the results to evaluate theories of concepts. This can lead (and in fact *has* led) to the construction of some very peculiar categories that are then used to discriminate theories of concepts. My

argument is that when these categories are outside the domain of natural categories, the logic of hypothesis testing breaks down. Yes, we want a critical test in which theories make different predictions. But if a theory is of behavior in a certain domain, then people's behavior in a different domain may not be an adequate test of it.

IV. Capacities versus Performance Models

One aspect of this argument (although not the only one) involves discriminating two different components of behavior. One we can call *capacities*, namely people's general abilities. For example, when we study memory capacity or language competence, we may be attempting to characterize people's knowledge or representational structure in a general way. The second component, which I have given the awkward name *performance models*, refers to what people actually do in specific circumstances. Performance models depend not only on the underlying abilities, but also on the situations that people find themselves in. Using a linguistic example, it is possible that I could figure out the meaning of a center-embedded sentence such as *The cat the dog the mouse chased feared ate*, but I would do so by trying to divide the sentence into clauses and match the subject with its verb, hopefully with pen and paper. However, in real life, no one ever says such sentences to me, and I never do process them. (If someone did slip one into a real conversation, the chance of my interpreting it correctly in real time would be slim.) Thus, a theory of my language understanding that does not provide for comprehension of doubly embedded sentences might correctly account for my use of language outside of experimental tasks—it would be a performance model of my actual language use.²

The study of language capacity would, on this definition, include basically anything that anyone could do with linguistic materials, from writing poetry to solving anagrams to cross-modal priming with a fast response deadline.

² This distinction sounds ominously like the competence/performance distinction in generative linguistics. However, that somewhat dubious distinction is usually intended to focus on underlying knowledge (competence) versus less interesting processes that filter the knowledge in external behavior. In contrast, I think that psychological studies of both capacities and performance models fall on the performance side of this distinction, because both are about mental representations and processes, and not just underlying knowledge. Also, whereas the competence/performance distinction is usually drawn to allow linguists to ignore performance data, I am suggesting that performance models are the more interesting topic of study. In short, despite the superficial similarity, try not to think of the competence/performance distinction when reading this section.

In contrast, a performance model of language would attempt to answer the question of how people deal with utterances of the sort they normally hear and how they produce the utterances they normally utter, in the contexts that they normally do these things. Clearly, the two are very related in most cases, but they also can deviate in others (e.g., the anagram case . . . and perhaps the cross-modal priming with the fast deadline?). In developing an explanation of how people actually comprehend ambiguous words, say, one is also a fortiori making claims about language capacity. If you argue that people consider all the different possible meanings of a word, you are making a claim about people's abilities. However, the reverse is not necessarily the case. One may find evidence of cognitive capacities that do not in fact participate in the normal behavior of that domain. The reason could be that the experimental task required use of a capacity that is normally not used due to its difficulty. If the anagram is really hard, you may have to engage in difficult strategies, such as consciously generating words, writing down letter combinations, and thinking about spelling rules. Another reason is that everyday life does not present a situation that would benefit from such a capacity. I understand normal English sentences well enough that I don't need pen and paper to figure them out. Thus, my ability to understand center-embedded sentences with pen and paper is simply not relevant to my normal language use.

There are arguments to be made for why we should try to understand cognitive capacities. I am not going to make those arguments. The next section argues at length for why we need a performance model of concepts. Here I will simply point out that if we want a theory of how people perceive and behave in their everyday lives, we must not be too hamstrung by data about their capacities. Clearly, any *limitation* on cognitive capacities will apply very broadly; if short-term memory has room for only three or four items even under favorable circumstances, we should not claim that people have a dozen items in short-term memory during our category-learning task. However, the fact that people *can* do something in certain laboratory settings does not mean that they do it in a particular, perhaps less demanding situation. To find out whether they do, we need evidence from within that setting and not from a very different one.

The implications of this argument to the psychology of concepts are clear. Because of the problem of unconstrained category construction, we can make up categories that are very difficult for subjects to learn or that are peculiar. Clearly, the results of such studies tell us about cognitive capacities—people's ability to learn, remember, and make decisions. What is not clear is whether these results are relevant to a performance model of actual category learning. The fact that people may memorize exemplars to learn some categories does not imply that they do so in real life unless the

real categories are like the experimental categories in certain respects. The fact that people can learn categories consisting of orthogonal items (as in Shepard et al.'s type VI task), and that this is harder than learning categories that are almost orthogonal (e.g., type V), is also a fact about human cognition. But it may or may not be a fact about human concept learning. Whether it depends on the nature of actual concepts, and that is something that an experiment using artificial materials cannot tell us.

Skeptics may question whether we should be trying to focus on performance models rather than capacities. Isn't it just as important to understand the basic processes of the mind as it is to understand whatever processes are used in most real behaviors? I address this question next.

V. What Should We Be Trying to Explain in the Psychology of Concepts?

Most of the long-standing questions psychologists explore are derived bottom-up. That is, they are an attempt to explain observed behavior and abilities. Different people do different things, giving rise to questions about individual differences. Human language is a unique activity, leading to the question of how people acquire and use it. Similarly, the psychology of concepts is derived to a large degree from questions about everyday human and animal behavior. Objects that are different are called by the same name; information learned about one object may be generalized to another in the same category; and children seem to learn names after one or two exposures.

The basic questions of the psychology of concepts arise from such common, everyday activities and abilities rather than being derived from prior theory of some kind. I am implicitly contrasting this with other kinds of scientific questions, such as those in physics in which researchers ask, "Why is there so little mass in the universe, given that our calculations suggest that there should be more?" (Physics can afford this because they have already answered the basic questions arising from everyday life, such as why apples fall from trees, what stars are, and the speed of light.) Psychology also has its share of theory-derived questions, such as the LS versus NLS category-learning issue discussed earlier. This arose through the theoretical insight of Medin and Schwanenflugel (1981) rather than being a basic observation that psychologists then attempted to explain.

What are the phenomena that we are trying to explain in the psychology of concepts? I would include the following in my list, which I do not claim is exhaustive by any means. I put on it the major behaviors related to concepts that take place in everyday life that we would like to explain. Readers should feel free to add their own phenomena to the list.

- Category members are generally similar to one another.
- Category members differ in their typicality.
- There is no apparent definition for most natural categories.
- Concepts are organized hierarchically.
- There is a clear preference for a middle level of categorization.
- Categories are important in explanations, both in science and in naive thinking.
- Categories can be learned without feedback.
- People draw inductions from one category member to others and from one category to related categories.
- Children can learn categories (and their associated labels) with little exposure or effort.

One might quibble over how much these phenomena derive from observation of behavior. It is true that some of them were identified explicitly only after the psychology of concepts began to be investigated in depth. However, these discoveries (e.g., the basic level of categorization: Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976) could have been made easily by anyone who happened to be looking for them [and indeed, Brown (1958) and Berlin, Breedlove, and Raven (1973) had come upon the basic-level phenomenon before Rosch et al. documented it more carefully]. These are descriptive rather than theoretical claims about categories, and therefore they form a core of empirical phenomena that we must try to explain.

The main argument I would like to make is that theories of concepts need to address the phenomena in this list and others like it, prior to other, less basic issues. Taking an extreme example, suppose that we had a theory of concepts that could explain how college students learn the six Shepard et al. (1961) categories, even going so far as to account for the learning curves of each group. However, suppose that we then “asked” this model how it is that children seem to learn categories based on a couple of examples. The model may not have a ready answer, as the learning of the Shepard categories it modeled takes many exposures of the stimuli, and learning is quite gradual.³ Suppose we ask the model about the hierarchical structure of categories, and why it is that one such level is preferred. If it is like most models, it does not contain any kind of relations between concepts, hierarchical or otherwise. Many models cannot simultaneously learn hierarchically organized concepts because an individual object has multiple “right answers” in a hierarchy (e.g., the object is a hatchback,

³ Perhaps there is a parameter in the model that can be adjusted to result in faster learning, but then the question arises as to why the children set that parameter to have faster learning and the college students set it to learn so slowly.

a car, a vehicle) and the learning algorithms are not set up for such a situation. The theory may or may not predict which level of categorization is easiest to learn. If the model learns with feedback, it probably cannot learn without feedback. In short, this hypothetical model (and many actual models) does not explain the phenomena on this list. In some cases, it may be that the model simply has not been extended to address all the phenomena. In others, it is very likely that the model cannot explain some of these phenomena.

To be fair to researchers in this field (since I am one of them), it is perfectly reasonable to try to bite off part of a complex phenomenon and to develop an account of it, which one hopes will be integrated into accounts of other phenomena. However, I believe it is also fair to make a value judgment about what aspects of the psychology of concepts are most critical. From the perspective of theory evaluation, if one theory can explain the ordering of the Shepard et al. categories and another can explain “fast mapping” in children, but not vice versa, the latter seems more promising as a theory. That is, a theory that seems to be capturing the natural structure and acquisition of categories should receive greater credit than one that captures an artificial task that can also be called “category learning.”

This is partly a matter of research priorities. We should be focusing on theories that seem to be addressing the basic phenomena in the field (as outlined earlier) rather than on theories that do not have clear implications for such phenomena. The question researchers must pose to themselves is, “What questions are the ones that I will spend my limited time and resources investigating?” As is well known there is tension in all of psychology between getting into the messy real world and staying in the laboratory, where one is usually better able to control and explain the phenomena. The motivation for being in the laboratory is that one hopes to explain the real-world phenomena through these careful studies. However, it is also well known that the phenomena of the laboratory sometimes turn into the topic of study themselves, and techniques that were supposed to tell us about important questions themselves turn into research questions, as people study what has gone on (or gone wrong) in the experimental paradigms. An example that is old enough not to embarrass any of us is the study of properties of consonant–vowel–consonant (CVC) trigrams in verbal learning experiments. Researchers first used CVC stimuli in memory studies to understand the basic properties of verbal memories. At some point, the trigrams and their properties began to be studied themselves, in some cases involving variables (e.g., meaningfulness) that would have been studied more easily in real stimuli. In retrospect, most of us would agree that many of the PhD students who did their dissertations on how familiarity, meaningfulness, pronounceability, practice, and test delay

influenced memory for CVCs could have spent their time more wisely looking at memory for real events or the processing of real words and sentences.

Obviously, I am suggesting that some of our present concerns may fall into the same category. Because hindsight is 20-20, it will be much easier for people to raise this question in the future, after more data have been collected and more theoretical development has taken place, than for us to see these obvious problems now. Nonetheless, I will argue that researchers should start thinking more seriously about just how well their research questions and paradigms are addressing the basic questions of how people in everyday life learn everyday concepts. The fact that there is no way to be sure that our work will answer these questions does not mean that we should not try, because if we do not try, then we are almost assured of future irrelevance.

VI. The Missing Piece to the Puzzle

If concept researchers generally accept what I have said so far (and I have no reason to think that they will), there is still one critical piece of information missing to guide them in designing their research, to wit: What is the nature of natural categories? If we are to try to understand how people learn real categories, we must have a pretty clear idea of what real categories are. Furthermore, we must also have a pretty clear idea of the ways in which people encounter category exemplars, the frequency of exemplars of different types, and the feedback they get about them. All of these are well known to influence concept learning. In the absence of this information, it is very difficult to criticize any experiment for using unnatural categories or learning procedures. Let me illustrate this problem by revisiting some of the controversies mentioned earlier.

A. FAST-MAPPING CHILDREN AND SLOW-MAPPING ADULTS

Children's extremely fast rate of vocabulary learning, with as little as a single exposure to a word, seems to imply an exceptionally fast ability to learn new concepts that underlie the words. (Or, if one assumes that children already knew most of the concepts prior to learning the word, that implies an even more amazing ability to form concepts without linguistic feedback from adults.) In contrast, as I have pointed out, dim-witted college students take many blocks to learn concepts in psychology experiments; exposure to a single exemplar is virtually never sufficient to learn such categories.

One might suggest that children have an innate inductive power that is lost later, perhaps during first-year orientation at college. However, in the few cases in which adults are tested in the same paradigm as children, they

actually turn out to be slightly better than the child subjects (Markson & Bloom, 1997). So, the difference is not in the superior ability of the children, but rather in the categories that must be learned and perhaps in the learning procedures.

In the fast-mapping task used in many different studies with a variety of goals, a child is introduced to one or two entities, which are named. Some time later, the child is tested. If the question is simply whether the child has “learned the name,” then he or she might be presented with an item at test that is virtually identical to the learning item, along with other items that are markedly different (Carey, 1978; Heibeck & Markman, 1987; Markman & Hutchinson, 1984; Markson & Bloom, 1997).⁴ Children correctly choose the very similar item as having the same name and reject the very different one. If we are to take this as a typical instance of word learning, then such studies imply that real-world categories of the sort that receive common nouns are extremely homogeneous. However, so far as I know, this assumption has not been verified in natural categories, and it conflicts with the apparent assumptions of weak structure in adult studies of concepts.

In a second kind of study, the child also learns on a single item but at test is shown other items that differ from the learning item in one or more critical respects. These studies investigate issues such as whether children pay attention to different stimulus dimensions and consider them relevant to category learning (e.g., Kemler Nelson, 1995; Jones, Smith, & Landau, 1991; Ward, Becker, Hass, & Vela, 1991; among many others). As such, they are investigating the child’s own assumptions about category structure (e.g., does the child assume that all category members will have the same shape as the learning item?). Nonetheless, the reasoning behind these questions also seems to assume quite strong category structure. That is, by asking if children expect the shape to be the same as the single item that has been taught, one is implicitly assuming that it is reasonable to test a child’s assumptions after viewing a single exemplar and therefore that children are not learning categories over the course of long repetitions of categorization trials with feedback. To put it the other way around, if one believed that the normal learning procedure required 38 blocks as in Lamberts’s (2000) study, then asking what hypotheses subjects formed after exposure to a single exemplar would be a bizarre research strategy. If that study is any indication, category learning requires massive exposure in which associations between properties and concepts are built up, or perhaps exemplars

⁴ Carey and Bartlett and Heibeck and Markman both studied adjective categories using contexts such as “Hand me the chromium tray.” In their testing, the object was not necessarily identical, but the adjective value (e.g., color or shape) was.

are memorized. Subjects' guesses about the category after one exemplar could not be having much effect, given the hundreds of exemplar exposures that are required for learning.

The question of which study is correct, that is, which study is actually telling us how people learn categories, requires us to answer the critical question of how natural categories are structured. If you really can see one example of a telephone or a bird or a zip drive and then reliably identify other members of these categories, then the fast-mapping study is telling us much about how people learn categories. If you need many, many exposures to different exemplars, preferably with feedback, before you can reliably identify category members, then the typical adult psychology experiment is probably telling us how people learn categories. If the answer is somewhere in between, then each is telling us something, but neither is very accurate.

B. KNOWLEDGE EFFECTS

It seems uncontroversial (finally) to say that our knowledge of categories is tied up with our other knowledge of the world. Our knowledge of dogs, their parts, appearance, behavior, internal properties, and functions in our society, is generally consistent with our knowledge of biology, psychology, physiology, and social relations. For example, dogs have four legs, which is related to the fact that most mammals have four limbs; dogs breathe, which is related to the fact that almost all animals breathe and that they need to do so in order to gain oxygen to fuel metabolic activity; and dogs form attachments to human families, which is related to the natural social behavior of canines and humans. Thus, our knowledge of dogs is not a list of unrelated facts, but instead has both internal coherence (e.g., dogs do not have wings and they don't fly; they are social and they protect their owners) and external coherence (e.g., dog physiology is very similar to that of other mammals).

In short, most of our concepts are *knowledge rich* in that they are intertwined with other, more general knowledge about whole domains (animal physiology; social behavior). In some sense, this interconnectedness is a true property of categories in the world. That is, dog physiology truly is related to mammal physiology more generally due to evolutionary relations among mammals—it is not just our perception that makes these concepts appear related. However, I am not sure that this fact by itself means that theories of concepts must incorporate these relations somehow. Instead, it must also be shown that people are sensitive to such relations. Fortunately, that has now been demonstrated quite well.

I can only summarize briefly the main results here. (See Murphy [2002]), Chapters 6 and 10, and Heit (1997). Having knowledge that relates the

properties of a concept vastly improves learning of that concept (e.g., Krascum & Andrews, 1998; Murphy & Allopenna, 1994; Pazzani, 1991), even when there is only a small amount of knowledge (Kaplan & Murphy, 2000). Unsupervised learning also benefits tremendously from knowledge that links features and helps distinguish categories (Spalding & Murphy, 1996). Children base category judgments on underlying theoretical bases when these are pitted against an item's appearance (Gelman & Wellman, 1991; Keil, 1989; Kemler Nelson, 1995). In categorization, adults are influenced greatly by the knowledge linking features (Lin & Murphy, 1997; Wisniewski, 1995). Category-based induction is influenced by relations among the category's properties and beliefs about the category (Lassaline, 1996; Proffitt, Coley, & Medin, 2000; Sloman, 1997). And so on.

Okay, knowledge is important: So what? We can apply to this issue the same reasoning that I raised earlier for category structure to this issue. Given that the large majority of studies of adult concepts look at people's learning of meaningless categories, with properties that are related only statistically, how much can they tell us about the learning of real concepts? They can tell us about real concept formation if (1) most real concepts are not knowledge rich or (2) the knowledge does not qualitatively influence the learning process. I think it is perfectly clear that the first is not true. Simply trying to write down everything one knows about a few common categories, such as dogs, murders, and dinners, will reveal that. The second possibility is more open to debate. Although I would not argue that knowledge always changes the learning process or changes it in every respect, there seem to be some important differences between learning with and without knowledge.

One difference is that learning is simply extremely fast when knowledge is present. Indeed, in my laboratory, subjects often learned a category in the first block of exposure to the stimuli (Murphy & Allopenna, 1994), whereas those without knowledge took four to nine blocks to acquire the category. In unsupervised category learning (i.e., without feedback), we have found in a number of studies that *no* subject learned the categories without helpful knowledge, but subjects did learn the categories when there was knowledge. In a particularly striking case (Spalding & Murphy, 1996, preview condition of Experiment 3), 78% of the subjects discovered the categories when knowledge was present, and 0% discovered the categories when there was no knowledge (see also Kaplan & Murphy, 2000). These very large differences in learning speed (with feedback) and category formation (without) are difficult to account for by a single learning mechanism that is just sped up when knowledge is present. I am not saying that a formal model with enough parameters could not reproduce this result, but I am saying that I do not believe that subjects are doing the same thing

when they learn with and without knowledge, given the enormous differences in performance.

Furthermore, purely structural effects of category learning can be eliminated or even reversed when knowledge is present. For example, Pazzani (1991) showed that the usual advantage of conjunctive rules over disjunctive rules could be eliminated when the category fit subjects' prior knowledge. Wattenmaker et al. (1986) showed that prior knowledge could create a preference for either LS or NLS categories, depending on the form of knowledge used. Wattenmaker (1995) has extended this result, showing that certain domains of knowledge seem to be better suited to different rules. Murphy and Kaplan (2000) also found striking reversals of category structure effects as a function of knowledge.

The importance of such findings is that they suggest that the results of studies of category learning in knowledge-free conditions, using dot patterns, geometric stimuli, color patches, or other stimuli popular in the field, will not generalize to real category learning. For example, most studies show that LS and NLS categories are not differentially difficult to learn when the categories are abstract (Medin & Schwanenflugel, 1981; Wattenmaker et al., 1986), but when knowledge suggests a theme connecting the features, the NLS categories can suffer greatly (Murphy & Kaplan, 2000; Wattenmaker et al., 1986). In a striking demonstration, Blair and Homa (2001) asked subjects to learn four categories instead of the usual two. They found that LS categories were much easier than NLS categories in this situation and that the difference was bigger when the categories were relatively large (nine exemplars) than when they were very small (three exemplars). The implication is that the results of the typical psychological experiment, with two categories and no knowledge, may not be extendable to the everyday situation in which one must learn multiple categories (there are many types of mammals, not just two) and one has knowledge about the domain.

The issue of knowledge may also relate to the previous case study, that of children's very fast acquisition of concepts. One way that children may be able to learn a category so quickly is by actively drawing inferences about the entire category based on a very small number of exemplars. For example, if children believe that an artifact is designed to perform a particular function, they assume that this aspect of the object is central to understanding it and that the observable parts and properties derive from the function. As a result, they focus on and learn some parts very quickly and ignore others (Kemler Nelson, 1995; Lin & Murphy, 1997). Although the children obviously have little empirical basis to decide that a given part is critical to category membership, since they have observed it in only one exemplar, they do so because the part is highly related to the object's function.

My claim is that such reasoning and attentional processes cannot be captured by the usual mechanisms of associative learning or exemplar memory that seem to account for most experimental category learning. I would not argue that the results of artificial category learning have no relevance to realistic learning. However, we have no way of knowing which principles or findings of the artificial situation will apply to realistic situations. In short, to understand exactly how knowledge is used and how category structure and empirical variables affect learning in a knowledge-rich situation, we must study those variables (even the empirical ones) in a knowledge-rich situation. Simple generalizations from the abstract literature on category learning (e.g., that LS and NLS categories are equally easy to learn, that disjunctive rules are harder, and that people do not discover family resemblance categories in unsupervised learning) have not turned out to be true when they were tested in the knowledge-rich situation. As mentioned earlier, this argument only applies if real categories are indeed knowledge rich. I think that this claim is clearly true, but we need more descriptive evidence of real categories to establish this more comprehensively.

C. LEARNING SETTING AND TIME COURSE

As discussed previously, Carey (1978) and Markson and Bloom (1997) found that children (and adults) can learn a new word based on a few exposures and recognize it a month later, having at least some idea of what it means. In real life, it might not be very common to hear a new category name and then go a month without encountering or talking about the category, but it no doubt does happen. Encounters with some new categories are sporadic. If you learn what a lynx is at the zoo at age 6, you may talk about lynxes for a few minutes until a more attractive animal comes along. You might encounter lynxes in a picture book a few months later. On the next trip to the zoo a year later, you might see a lynx again. You may encounter lynxes in a discussion of the ecology of South America in third grade and so on. Although there are some categories that children encounter constantly (spoon, cookie, car, chair), there are others that are low frequency and are encountered in widely spaced spurts.

Typical psychology experiments, in fact *all* category-learning experiments that I know of, teach new categories in a concentrated series of exposures, usually in a single session. Starting with Hull (1920), we have presented items over and over again, requiring subjects to respond to each one and measuring how long it took subjects to learn the category. Clearly, the memory requirements, and perhaps the learning strategy, could be very different in this situation than in the case of the lynxes. The memory

differences require little comment. Seeing lynxes one after the other in quick succession in order to learn them is different from seeing them once every 6 months. One would imagine that the difficulty of remembering all the details of exemplars would influence what concept is formed. [See Wattenmaker (1993) for one perspective on this issue.]

The possible effects on learning strategies are perhaps less apparent. When category members appear every few seconds, one can try out different hypotheses about what the category is. For example, one can try to find out whether a single dimension distinguishes the categories to be learned, sampling the different stimulus dimensions in turn. Evidence shows that people do attempt to classify items in just this way, especially at the beginning of a category-learning study (Nosofsky, Palmeri, & McKinley, 1994), which is clearly what subjects prefer to do in category construction tasks (Ahn & Medin, 1994; Medin, Wattenmaker, & Hampson, 1986; Spalding & Murphy, 1996). However, if one views a single exemplar of a category and does not see another one for a few months, this strategy would be grossly inefficient. Instead, one would be well advised to try to learn as much as possible from the first few exemplars so that one can then notice what seems to be common to them.⁵ Smith and Minda (1998) found that subjects' learning strategies can change over the course of the learning phase, even within the usual category-learning experiment. Thus, it seems even more likely that learning processes may vary over time in real category learning taking place over days or years.

A related procedural detail is that most adult experiments require subjects to learn to distinguish two categories. For example, category A tends to be two blue circles, and category B to be one red diamond. Subjects do not just learn category A but learn to distinguish it from category B. This likely has a number of effects. First, as Blair and Homa (2001) pointed out, one can simply not learn one category. Everything that is not in category A must be in category B, so one does not need to learn both categories to perform perfectly in the task. Second, a number of papers have pointed out that what one learns to distinguish two categories is not neutral: One learns to focus on the features that are most discriminative, which are not necessarily the features that are most common or important in the category (Chin-Parker & Ross, 2002; Goldstone, 1996; Yamauchi & Markman, 2000). If the same

⁵ Indeed, I believe that people are much more likely to look for a single defining dimension in experiments, as such problems are often found in academic testing situations such as the SATs or various reasoning tests. I doubt that anyone of any age ever thought that a lynx was an object with fur, or a four-legged object, or a growling object, or any other single-dimensional category. So, this tendency is probably due to both the artificiality of the stimuli and subjects' beliefs about experimental categories.

exemplars are presented in a different task, such as using them to solve some problem or making an inference, what subjects learn can be quite different (Ross, 1997, 2000).

In the category-learning experiment, the only interaction subjects have with exemplars is to categorize them, and the only interaction subjects have with the categories is simply to provide a category name and accept the feedback. In real life, we obviously interact with the objects (sit on chairs, use the telephone, feed the dog) and also use the categories in reasoning and planning (e.g., I must rent a car on my trip; I must avoid that dog, which might bite me).

This is one area in which the more ecologically valid situation is finally getting attention. Because there is a good summary of this issue and the work arising from it (Markman & Ross, in press), I will not review it here. However, I can certainly say that the nature of learning and the result of the category representation both seem to be different when the items are used or interacted with in some way other than the typical categorization setting. For example, cue validity (which is important for discriminating categories) influences learning much more in the traditional task than in the category use tasks (Chin-Parker & Ross, 2002). I am not claiming that people do not ever learn objects in the way they do in the typical experiment. What I am saying, however, is that some learning situations are clearly different, and their results in turn differ. In short, this is another example in which one must be careful in generalizing from the experimental situation to the more naturalistic one. Furthermore, without knowing more about the typical learning tasks and situations, we cannot know what experimental paradigms are more appropriate.

VII. What Is the Real Category Structure?

To summarize the argument so far, I have pointed out that the psychology of concepts has largely studied category learning in a rather sterile and simplified setting. I have argued that results from this setting, with arbitrarily constructed categories, cannot be generalized easily to real category learning, if real categories and learning situations are different. The perhaps obvious issue now is to say whether the situations really *are* different. The problem is that this is not really known.

The very first studies of concept learning in experimental psychology suffered from this problem. Smoke (1932) criticized Hull's (1920) study because he believed that the rules defining categories were much more complex than those Hull used. He ridiculed the idea that there is a single property that is common to all cats or dogs, as there was in Hull's stimuli.

However, Smoke's own categories were much like the logically defined categories of Bruner et al. (1956), which later were criticized by Eleanor Rosch and many others.

A. FEATURE LISTINGS

In the 1970s, Rosch and her collaborators collected feature listings of natural categories in order to identify their structure (e.g., Rosch & Mervis, 1975; Rosch et al., 1976). This very time-consuming and difficult process was also done by some other researchers afterward (e.g., Hampton, 1979; Malt & Smith, 1984; Tversky & Hemenway, 1984) but seems to be much less common today, which is perhaps not surprising given the large numbers of subjects needed and the large amount of processing necessary to arrive at reasonable lists of features (for discussion, see Tversky & Hemenway, 1984).

If one looks at the resulting feature lists, one often finds that the tested concepts are well structured. That is, there are a lot of features listed as common to the categories—not just one or two. Rosch and Mervis (1975) collected features of superordinate categories, such as furniture, vegetable, and clothing, which are the level of natural categories that have the weakest within-category structure. For each of these categories, they sampled 20 items, ranging in typicality from prototypical items to atypical items that many people might not actually judge as being in the category (e.g., telephone for furniture; elevator for vehicle; foot for weapon). They found that there was sometimes a feature common to all category members, but more generally there was “a large number of attributes true of some, but not all, category members” (p. 581). For example, there was at least one property true of 18, 17, 16, and 15 members of the categories. In short, there were many commonalities among category members. This was especially true for the 5 most typical items in each category. Here Rosch and Mervis found an average of 16 properties that were true of all 5 items. The 5 least typical items had hardly any properties in common, but these were in some cases dubious category members anyway.

It is well established that the most common categories that we use, basic-level categories, have an even stronger category structure—that is, their exemplars have more features in common and share fewer features with exemplars of other categories—than do the superordinates just described (Markman & Wisniewski, 1997; Mervis & Crisafi, 1982; Rosch et al., 1976; for a review, see Murphy, 2002, Chapter 7). This strong category structure is exactly why we establish and use categories, because they provide us with a lot of information in an efficient manner. When I say “I bought a dog yesterday,” the listener knows that I bought a four-legged animal that

barks, has fur, drools, eats meat, has a liver, is probably a pet, has better hearing than humans, and so on. Although I did not say any of these things, they are all typical properties of dogs, and so just giving the category name communicates this information.

In contrast, the typical category in an adult study of category learning does not have this commonality. Certainly, researchers do not attempt to teach subjects categories in which there are features shared by 18, 17, 16, and 15 out of 20 exemplars, and in which the most typical members share 16 features. Thus, evidence from feature listing provides a *prima facie* case that the adult studies are not testing categories of the sort that people usually form.

Unfortunately, this case is still *prima facie* and is not by any means closed. Although the feature-listing studies have provided the best information we have so far on the structure of natural categories, that information is extremely limited. Here are some of the problems with it.

1. Use of Verbal Features

Because subjects give single words or short phrases to describe the features, only features that are easily verbalizable are listed. Omitted are complex perceptual properties, such as overall similarity of shape or texture. For example, I believe that felines all have a similar shaped head, but it is impossible to describe this shape in a few words, and I very much doubt that subjects will write “feline-shaped head” when listing features of cats or tigers because it sounds vacuous.⁶ Similarly, very abstract properties may not be easy to describe and so these may not get written down either. Rosch et al.’s (1976) subjects could not list a single feature common to most furniture, and I suspect that the abstractness of their common function is the problem there. A final limitation of verbal features has been found by Solomon and Barsalou (2001), who showed that the features that are referred to by the same name in different concepts may not be represented identically. A bee’s wing is not the same part as a bird’s or an airplane’s.

2. Conscious Access

Related to the first problem is the fact that people only write down features that they consciously and explicitly know. Linda Smith (Smith & Heise, 1992; and personal communication) has suggested that artifacts and

⁶ Indeed, Quinn, Palmer, and Slater (1999) have shown that people can learn to distinguish male and female cats based on a subtle difference in their facial proportions. This difference is not easily verbalizable and probably was not consciously known (see next point).

natural objects differ in textural properties of the sort that are seldom found in feature lists. For example, fur and feathers are complex texturally and have a lot of high spatial frequency information. In contrast, a manufactured metal or plastic part is extremely smooth with no such texture or variation. Although people may in fact *use* this difference in categorizing objects, they may not consciously know the distinction. A similar property is differences in locomotion of different animals or artifacts (see Massey & Gelman, 1988). People can tell whether it is a dog or cat running away, but they may not think of that difference in the context of writing down features and may not know how to describe it (the first issue) if they do.

3. Listing of Category Features Rather Than Object Features

When subjects are asked to list features, they are told to write down properties of dogs, chairs, plants, and so on—namely categories. They are not usually asked to write the properties of Pepe, the miniature poodle–chihuahua mix, or of the grape vine that I have been unable to exterminate from my garden, or of my left shoe, and so on. As a result, the features people list are the most typical and representative features of the category, which may create a bias. By listing a typical feature of dogs, such as their having hair, I do not take into account the existence of hairless dogs such as chihuahuas. This makes the dog category seem more distinctive than it is. It is not clear how significant this bias is because atypical members by definition do not have the properties of most items and so omitting their properties is only slightly distorting the picture of the entire category. However, it is distorting it nonrandomly because it omits the features of items that are likely to cause the most trouble in categorization. If we had feature lists for a few thousand dogs, rather than people's summaries of what dogs are generally like, we would have a far more accurate picture of the structure of this category.

4. Mind versus Matter

A severe problem with feature listings is that they are people's interpretations of the environment rather than an objective measure of environmental structure (Murphy, 1982). In particular, they are usually measures of a category's features *after* the category has been learned. It is well known that differences between categories tend to be exaggerated (see Homa, Rhoads, & Chambliss, 1979; Smith & Minda, 2001) and that people omit features that seem too obvious (e.g., that birds breathe). Asking people to list features simply cannot be a complete measure of the actual structure of the domain as it presents itself to be learned.

B. CONCLUSION

Where do these problems leave us? I do not want to overemphasize them because that would encourage researchers to ignore the need to measure category structures. It is possible to overcome some of the concerns by having judges amend the lists (e.g., noticing that “breathes” was mentioned for animals but not for birds), by using some automated procedures that are not subject to these concerns (visual pattern abstractors, text analyzers), by consulting expert sources (encyclopedias, field guides, etc.), or by better sampling of category exemplars (randomly choosing pictures to get listings of). However, the problems do suggest that we need to return our attention to questions of the structure of real categories and to attempt to derive better measures. The next section briefly describes four research projects that have made some inroads in accomplishing this, albeit not through feature listings. They may serve as role models for future work in this area.

VIII. Role Models

A. PSYCHOANTHROPOLOGICAL STUDIES OF CONCEPTS

One of the most important research programs in the recent psychology of concepts was that carried out by Douglas Medin, Scott Atran (an anthropologist), John Coley, and their collaborators on the effects of expertise and cultural knowledge on concepts. They have investigated the concepts of the Itzaj Indians in Guatemala, Native Americans in northern Wisconsin and Michigan, and tree experts living in the Chicago area, among others. Their comparative analyses have allowed them to investigate questions such as the universality of category structure (Medin, Lynch, Coley, & Atran, 1997), the use of categories in induction (Coley, Medin, & Atran, 1997; López, Atran, Coley, Medin, & Smith, 1997), the basis of the basic level of categorization (Coley et al., 1997), and, more generally, the connection between conceptual processes and knowledge (Lynch, Coley, & Medin, 2000; Medin et al., 1997; Proffitt et al., 2000).

To pick just one aspect of their research program, I will summarize their work on expertise and category-based induction (Proffitt et al., 2000). Most research on induction has taken a formalist approach, based on the similarity of categories. The influential model of Osherson, Smith, Wilkie, López, and Shafir (1990) has had considerable success in explaining how people reason about problems, such as the following:

Robins are susceptible to disease X.

Geese are susceptible to disease X.

Therefore, ostriches are susceptible to disease X.

The model predicted people's reasoning about such problems by taking into account the similarity of robins and geese to birds in general and to the item mentioned in the argument conclusion (here ostriches). Given that similar items tend to share properties (almost by definition), it is not surprising that similarity can predict the induction of a new property.

Proffitt et al. (2000) looked at tree experts of various kinds to see how they would make inductions of diseases from one kind of tree to another (a standard property in this task). Perhaps surprisingly, they found that their tree experts did not generally use similarity among categories in making these decisions. Instead, they engaged in causal reasoning of various sorts, attempting to decide how a disease present in one kind of tree might be communicated to another kind of tree. The rationales they gave for their answers included factors such as the specific mechanism of disease transmission, the geographic distribution of the trees involved, and the susceptibility of each tree type to disease.

Lest one think that this pattern is restricted to scientists, López et al. (1997) found that the Itzaj Mayan Indians also engaged in such reasoning practices, failing to show some of the critical patterns of induction that have consistently supported the Osherson et al. (1990) model of induction. However, the Itzaj are similar to the tree experts in that both know a great deal about the domain in question. The Itzaj are highly familiar with their natural environment, unlike most American undergraduates. The picture that one gets is that similarity is used when one knows little about the domain of induction, but that it is preempted when the subject can reason about the categories involved.

Not to dwell on the obvious, I will just point out that this is a clear case in which the results found in the context-free, knowledge-deprived domain of the laboratory may have simply given the wrong answer to the question of, "How do people usually make category-based inductions?" Given that people typically do have background knowledge about the categories they interact with the most, and given that inductive reasoning is apparently different for knowledge-related categories with familiar predicates than for other categories with "blank" predicates, we simply cannot generalize the results from most of the category-based induction literature to many real-life inductions.

B. CATEGORIES AND NAMING

Barbara Malt and Steven Sloman have carried out a series of studies on how everyday objects are named. They have studied simple object domains such as containers and dishes, so these are certainly not exotic domains chosen for their peculiar characteristics. Furthermore, they have investigated the

patterns of names in different languages (English, Spanish, and Chinese) so that they could ascertain the importance of the categories' intrinsic structures in determining naming. These investigators make the important distinction between the underlying concepts of a domain and the names that are applied to it (e.g., Malt, Sloman, Gennari, Shi, & Wang, 1999; Malt & Sloman, in press). Although the two are related, names do not always directly reflect conceptual differences. For example, a category of objects could consist of two fairly clear subcategories that are distinguished conceptually, but the entire category might receive a single name.

Malt et al. (1999) found that subjects from three different cultures agreed on the conceptual measures of the container domain (i.e., correlations of greater than .90 in their similarity judgments). However, the names subjects used for objects did not agree as much (correlations of .35 to .55). Furthermore, although the names used in each language correlated positively with the speakers' similarity judgments (an estimate of conceptual structure), the correlations were not always high (most notably a .46 correlation for Chinese speakers).

Finally, an examination of the multidimensional scaling solutions shows that objects could not be named solely on the basis of the underlying similarity structure. That is, the names did not form prototype categories in which all the *bottles* were clustered together separate from the *containers* and *jars*. Objects called *container* were strewn through a large portion of the similarity space, mixed in with objects having other names. Items called *jar* tended to be grouped together, but a number of items called *bottle* were closer to the jars than they were to the other things called *bottle*. In short, the name categories were not linearly separable (at least based on the similarity scaling). However, none of these categories contained "opposite" items as the experimentally constructed NLS categories do.

An example may explain how this pattern of naming could come about. Consider a plastic squeeze-type bottle for ketchup. Not too long ago, ketchup bottles were made out of clear glass, which one poured the ketchup out of, not very dissimilar from wine or milk bottles (remember them?). Like many other glass products, ketchup bottles eventually were made out of plastic. Because of the proverbial difficulty of pouring ketchup out of bottles, these bottles were eventually made out of a squeezable material and, in some cases, were opaque. The result is something that is in fact more similar to a tube of toothpaste than it is to a prototypical glass bottle (e.g., a wine bottle): plastic, squeezable, and opaque, with a snap-off top. However, because the original ketchup container was a *bottle*, and perhaps because the changes from it were gradual, the present container is also called a *bottle*. This *chaining* from older versions of artifacts to newer ones create name categories that are not necessarily very coherent (Lakoff, 1987; Malt et al.,

1999). That is, although previous bottles may have all been made out of glass and had a similar tapered shape, new bottles can be made out of plastic and have a variety of peculiar shapes. Thus, the previous bottle prototype may no longer represent the category as a whole. The notion of chained or radial categories (Lakoff, 1987) may create structures that are quite different from the usual assumptions of category structure as studied in categorization experiments. Through work such as Malt and Sloman's, we may discover even more unusual or unexpected structures.

C. THOUGHT FOR FOOD

Brian Ross and I investigated a single domain in some detail, that of foods (Ross & Murphy, 1999). We first derived a list of foods that college undergraduates would be familiar with, attempting to sample a variety of different types. We focused on "basic" foods such as steak or broccoli rather than dishes combining foods such as beef stew or lasagna. Subjects' sortings of the foods revealed two different types of organization. First, they formed the expected taxonomic categories, grouping items as meats, breads and grains, vegetables, etc. Second, they formed what we called *script-based* categories, such as snacks, breakfast foods, and dinner entrees—foods that are eaten at the same time or in the same setting. Script categories sometimes include very diverse foods, such as eggs, bagels, bacon, and cereal as breakfast foods.

This result was surprising because of a well-known argument in the cognitive development literature that adults eschew categories based on scripts and thematic relations in favor of taxonomic categories (see Markman, 1989). In contrast to this prediction, we found that most foods were rated as being in two or more script-based categories. Later experiments showed that subjects readily accessed the script categories in speeded tasks and that they used both categories in category-based induction. For example, if subjects were told of a novel property of one kind of food (e.g., bagel), they would extend it to both members of the food's taxonomic category (e.g., cracker) and its script-based categories (e.g., egg).

This work is relevant to the present discussion because the category structures that it found are not the typical ones investigated in experimental tasks. Exploratory work discovered that most foods were classified into multiple categories and into multiple *kinds* of categories. Both those kinds were efficacious in various tasks. In contrast, in the usual experiment, each item is in just one category, and the categories are mutually exclusive. Usually, the categories have contrasting features, such that if one is associated with small items, the other will be associated with large items.

None of this was found in the food categories that we explored. Items were in multiple categories, and the different categories were associated with very different properties, for example, “high in protein” for meats versus “served hot” for dinner foods. Once one learns that meats are high in protein, it does not follow that dinner foods are probably low in protein.

These results demonstrate that people simultaneously have different categorization schemes of the same domain. That is, they know that eggs are often eaten at breakfast but also that they are protein rich and a dairy food. Exactly how these cross-cutting conceptualizations influence one another is not known, and it is not known in part because this richer and more complex situation is simply not investigated in experimental studies.

D. LANGUAGE DIARIES

A final example refers to the practice in studies of language acquisition to keep a diary of a child’s utterances, and sometimes other language interactions. Most relevant to the present discussion is the work of Carolyn Mervis (1987; see also Clark, 1973), who tracked her son’s use of category terms. She determined that his use of such names overlapped with the adult usage: It included some items that adults would not include and excluded some items that adults would have included. Mervis also engaged in focused testing of a few category names, collecting possible referents to see what her son called them so as to identify the properties that he must have been relying on. She pointed out that children rely on shape and perceptual features in general more than adults do because of their relative lack of knowledge and that their limited experience with unusual items can reduce their accuracy in using the category name correctly. If you never heard an ostrich called a bird, there would be very little reason for you to so label it the first time you saw one.

Mervis (1987) reported detailed results for just a few categories. It would be very helpful to have such studies with more children and more categories. In particular, it would be very useful to have a description of what kinds of exemplars children encounter when they are learning category terms, and it would also be very helpful to test children (without feedback) on real categories in order to document their level of understanding of different categories. Such data could help resolve the conflict I have raised between the typical fast-mapping experiment and the typical adult category-learning experiment. I pointed out that researchers on adult concepts usually require subjects to learn all of the exemplars in their categories, whereas children in many studies are tested on only one or two items that are very similar to the learning item. By studying the actual extent of children’s productive use and comprehension of category names, we can come to a better understanding of

how closely children approximate the ideal espoused by the adult studies. Indeed, as Mervis pointed out, adults are by no means perfect in their categorization of real objects, in some cases systematically misclassifying items due to ignorance. Thus, the perfect classification criterion used in adult studies may not be realistic even for adults.

Finally, it would be helpful to have more information on the procedures and time course of learning category names. To what degree do children acquire words after a brief, intensive exposure to one or a few objects (as in many word-learning studies) and to what degree do they encounter them spread across diverse settings over the course of months (as in no experimental study)?

E. SUMMARY

These four examples provide possible role models for future research on real categorization and category structure. I have argued throughout the chapter that experimental categories are often more arbitrary and poorly structured than real-life categories. However, some of the aforementioned examples suggest that category structures may be more complex or richer than those of some experiments. Malt and Sloman's work shows that some lexical categories may be strangely structured relative to the underlying similarity structure—nonlinearly separable, to say the least. However, these structures are not arbitrary or randomly determined—they derive from historical processes of naming and technological development. Similarly, Ross and Murphy's foods were cross-classified rather than being in a single salient category, as in most studies. My point, then, is not that experimental categories have always been more difficult than real categories that people learn [cf. my point about Shepard et al.'s type I categories (1961), but that we simply do not know the relation between tested and actual categories.

From such examples, someone might argue, "Apparently, some natural categories are not well structured, so I can just make up my experimental categories with whatever structure I need to test the theories I am studying." That argument is wrong on two counts. First, not all complexity is the same, and we cannot know whether the particular form of complexity in an experimental category is realistic until we examine real categories. Second, the complexity of real categories may also come with added information that is not present in the traditional experiment. The jar and bottle categories may seem poorly structured and overlapping, but the distinction may reflect historical relations (ketchup used to come in glass bottles) or abstract functional properties that language users are sensitive to. There may be rich perceptual or functional information in the experience of using objects that is not present in a category-learning task with dot

patterns. Without a detailed study of the structures and learning situations of everyday categories, we cannot ever discover these variables, and therefore we cannot know to what degree our data are generalizable.

IX. Conclusion

I have harped on my main points enough so that they do not require much summary. One point I would like to make clear is that I am not suggesting that researchers on concepts need to abandon the laboratory and go into the wild world of natural concepts and people's unconstrained behavior. The laboratory has provided the best setting for testing hypotheses in psychology, and I expect that it will continue to do so in the future. However, the question of what variables we should be manipulating, what conceptual structures we should use, and what learning problems we should be investigating cannot be answered from within the laboratory. The questions must to some degree come from an analysis (or best guess) about what the categories and learning situations are like outside the laboratory. If our research questions do not come from such an analysis, we may answer them, but we will not be answering the question of how people normally learn concepts.

At the beginning of this chapter, I raised a number of apparently intractable disputes in the field, such as the prototype-exemplar debate and the role of knowledge. I suggested that the chapter might point a way out of these disputes. Well, the *chapter* has not, but if its recommendations are followed, I believe that the field may find a way out of them.

First, it is possible that an analysis of real-world categories and learning may show that evidence favoring one theory is predominantly from situations that are not realistic. In such a case, I have argued that the "unrealistic" theory may be right, but it is not right about normal category learning. I would expect that researchers in the field would then shift their attention to the theory that does better in the realistic settings.

The second way that an ecological analysis might help resolve disputes is if systematically different category structures or learning situations are identified. For example, it is possible that simple object concepts do generally have strong family-resemblance structures, but certain other concepts (e.g., legal, aesthetic, social) are poorly structured. It is possible, then, that people use different learning strategies (e.g., looking for rules, learning exemplars, forming prototypes) depending on the category structure to be learned. In such a case, the analysis of real categories would not reject a theory but would specify the domains in which it is likely to apply. Similarly, perhaps the search for defining features often found in

category-learning experiments is not found in different situations when exemplars are sparse and encountered at long intervals or when there is significant background knowledge.

In short, as I suggested earlier, the question would change from which theory is correct to *when* each theory is correct. I think that such an outcome is likely, as there is already evidence that people may use multiple strategies in learning experimental categories (Malt, 1989; Nosofsky et al., 1994; Smith & Minda, 1998). If we could establish the existence of such strategies, along with some idea about when they are used, we would be much better off than in the present situation, in which different parts of the field do different experiments to provide support for different theories, and there is no clear way to decide between them.

No doubt engaging in an ecological analysis will not by itself lead to a quick and easy solution to all the problems facing the field of concepts. However, I believe that it might help us solve some of the persistent problems or at least reframe them into issues that have more tractable solutions. Furthermore, such an analysis may bring to the fore new and interesting issues that are not currently addressed in our present paradigms, which is perhaps the most exciting possible consequence of all.

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SOCIAL EMBODIMENT

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I. Introduction

Please adopt the following positions while reading this chapter. First, sit upright in your chair—do not slump. Second, place a hand beneath the table top and press upward with your palm. Third, hold a pen in your teeth with the tip pointing forward. If you adopt these positions while reading this chapter, the optimal result will be achieved. We will explain later.

Over the years, numerous findings have implicated embodiment in social cognition. By *embodiment* we will simply mean that states of the body, such as postures, arm movements, and facial expressions, arise during social interaction and play central roles in social information processing. Across diverse paradigms, social psychologists have reported four types of embodiment effects. First, perceived social stimuli do not just produce cognitive states, they produce bodily states as well. Second, perceiving bodily states in others produces bodily mimicry in the self. Third, bodily states in the self produce affective states. Fourth, the compatibility of bodily states and cognitive states modulates performance effectiveness.

Although these four findings have been well known for many years, they have remained relatively disparate. No single theory has integrated them, nor explained them in a unified manner. Recent research on embodiment in cognitive psychology, cognitive science, and cognitive neuroscience offers a framework for doing so. Increasingly these researchers are developing

embodied theories of cognition (e.g., Barsalou, 1999a,b, 2000a; Damasio, 1989, 1994, 1999; Glenberg, 1997; Lakoff & Johnson, 1980, 1999; Mandler, 1992; Newton, 1996; Simmons & Barsalou, 2003b; Wilson, 2003). Furthermore, empirical evidence is accumulating for these theories (a few examples include Barsalou, Solomon, & Wu, 1999; Glenberg & Kaschak, 2002; Martin, 2001; Spivey, Tyler, Richardson, & Young, 2000; Stanfield & Zwaan, 2001; Zwaan, Stanfield, & Yaxley, 2003). For a more extensive review of relevant empirical findings, see Barsalou (2003).

Embodied theories of cognition depart from traditional theories in their assumptions about knowledge representation. In traditional theories, knowledge consists of amodal symbols that *redescribe* sensory, motor, and introspective states.¹ On seeing a smiling infant, for example, a parent has sensory experiences of the infant (e.g., visual, auditory, tactile, olfactory). The parent may also initiate motor actions (e.g., cuddling) and experience introspective states as a result (e.g., happiness). Traditional theories assume that *knowledge* of such experiences does not consist of the sensory, motor, and introspective states that constituted the experiences originally. Instead these theories assume that a symbolic system redescribes these states, producing amodal descriptions that reside separately from sensory, motor, and introspective systems and that operate according to different principles. For example, sensory, motor, and introspective states could be redescribed as feature lists, networks of propositions, fired sets of productions, instantiated schemata, statistical vectors, and so forth. In all cases, knowledge of the original experience is a redescription in an amodal representation language. Furthermore, later processing of the event operates on these redescriptions—not on the sensory, motor, and introspective states that produced them. In memory, recalling an episode activates an amodal redescription of the episode. In language, comprehending a text produces amodal propositions that represent its meaning. In thought, reasoning proceeds via symbolic operations over amodal redescriptions of a situation or problem.

Conversely, embodied theories represent knowledge as partial simulations of sensory, motor, and introspective states (e.g., Barsalou, 1999a,b; 2002, in press; 2003; Damasio, 1989; Simmons & Barsalou, 2003b). When an event is experienced originally, the underlying sensory, motor, and introspective states are partially stored. Later, when knowledge of the event becomes relevant in memory, language, or thought, these original states are partially simulated. Thus, remembering an event arises from partially simulating the sensory, motor, and introspective states active at the time. Similarly,

¹ Introspective states include events perceived inside the mind and body that typically lack counterparts in the external world, such as emotions, affects, appetitive states, cognitive operations, and beliefs (Barsalou, 1999b).

understanding a text about an event induces a simulation of the experience. Finally, reasoning about an event proceeds by simulating it and then transforming the simulation.

As described later, this approach does not entail that actual bodily states are executed obligatorily, as in James' (1890) ideomotor theory. Instead *simulations* of bodily states in modality-specific brain areas may often be the extent to which embodiment is realized. Depending on the situation, embodiment may range from simulation, to traces of execution, to full-blown execution. As we will also see, these embodiments are not merely peripheral appendages or epiphenomena of social information processing—they constitute the core of it.

The theme of this chapter is that embodied theories of knowledge have the potential to explain and integrate social embodiment effects. The remaining sections first review these effects and then sketch a theory of social embodiment based on the assumption that simulations represent knowledge of social situations. Finally, we illustrate how this theory explains and unifies social embodiment effects.

II. Social Embodiment Effects

Four types of embodiment effects have been reported in the social psychology literatures: (1) perceived social stimuli produce bodily states; (2) perceiving bodily states in others produces bodily mimicry in the self; (3) bodily states in the self produce affective states; and (4) the compatibility of bodily and cognitive states modulates performance effectiveness. We do not review the literatures for these effects exhaustively. Instead we simply present examples to illustrate the phenomena and motivate theoretical integration later.

A. SOCIAL STIMULI ELICIT EMBODIED RESPONSES IN THE SELF

In this first embodiment effect, people perceive a social stimulus, or receive language that describes a social stimulus. For example, a person might perceive an elderly person, or receive a description of one. Clearly social stimuli produce cognitive responses such as trait inferences, causal attributions, stereotypes, and so forth. Notably, however, social stimuli also produce bodily responses. In most of the studies to follow, actual social stimuli are rarely presented. Instead subjects mostly receive words that describe social stimuli; occasionally they receive pictures. While this might lead to some concern about ecological validity, the fact that words consistently produce embodied responses is impressive. Presumably the effects of actual social stimuli would be stronger.

1. *Bodily Responses*²

Wiesfeld and Beresford (1982) reported a bodily response to a social stimulus that any student or former student will recognize. On receiving their grades for a midterm exam, high school students adopted a more erect posture after receiving good grades, but adopted a less erect posture after receiving poor grades. The grades did not merely produce cognitive and affective responses in the students—they produced bodily responses as well.

A central issue is whether social events, such as receiving a grade, trigger bodily reactions directly or whether mediating mechanisms exist. For example, receiving a grade might trigger an emotional state, which in turn produces a bodily state. Throughout our review of embodiment effects, this issue will not concern us—our goal will simply be to document the ubiquitous presence of bodily states in social phenomena. Later, after presenting a theory of these phenomena, we will return to this issue.

In seminal studies, Bargh, Chen, and Burrows (1996) brought the social elicitation of bodily responses under experimental control. Using a paradigm that many researchers have since adopted, Bargh and colleagues had subjects form sentences from short word lists. In the critical conditions, a subset of words was related to a social stereotype or trait (e.g., “gray,” “Florida,” and “bingo” for the *elderly* stereotype).³ In the control conditions, subjects received all neutral words. Of interest was whether the critical words primed the stereotypes relative to the neutral words, and if so, whether this priming produced embodiment effects.

When Bargh et al. (1996) primed subjects with the *elderly* stereotype, an embodied effect did indeed occur. Once the experiment was over, critical subjects took longer to walk from the laboratory to the elevator than control subjects. Processing words about a social stimulus—the *elderly* population—induced a related embodiment effect. Because the *elderly* stereotype specifies that the elderly tend to move slowly, this knowledge about movement became active and affected subjects’ actual movements.

Many subsequent experiments have demonstrated similar effects (for a review, see Dijksterhuis & Bargh, 2001). In the same basic paradigm, Aarts and Dijksterhuis (2002) primed subjects with the names of either fast or slow

² As will be seen, we distinguish among bodily, facial, and communicative forms of embodiment for each of the four embodiment effects. Clearly, facial and communicative actions occur on the body, and thus could potentially be included under *bodily* effects. For lack of a better term, however, we will use “bodily” in referring to embodiment effects that largely occur with the arms, legs, and torso, thereby contrasting these effects with facial and communicative ones.

³ Italics are used to indicate concepts, and quotes are used to indicate linguistic forms (words, sentences). Thus, *elderliness* in this sentence indicates a concept, whereas “gray” indicates a word.

animals (e.g., “cheetah” versus “snail”). Subjects primed with fast animals subsequently took less time walking to another room than subjects primed with slow animals. Again words about a stimulus activated knowledge about movement, which in turn produced an embodiment effect.

Dijksterhuis, Spears, and Lepinasse (2001) showed that the speed effect occurs for actions besides walking. Their subjects first viewed photographs and later performed a lexical decision task (i.e., judging whether letter strings form words or not). When subjects first viewed pictures of the elderly, their later lexical decision responses were slower than those of subjects who had viewed nonelderly photographs instead. Again a social stimulus activated knowledge that produced an embodied effect.

Even subliminal social stimuli trigger embodied responses. In Winkielman, Berridge, and Wilbarger (2002), happy or angry faces were presented to subjects subliminally as they judged visible faces for gender. When subjects were later offered a flavored drink, subjects who saw happy faces poured and drank more than subjects who saw angry faces. Even though the subliminal faces were not recognized above chance on a later test, they affected subjects’ drinking behavior.

Because of the cover stories and indirect measures in these experiments, subjects were probably unaware that social stimuli affected the speed of their actions. In the Winkielman et al. (2002) study, subjects could not even see the stimuli that modulated their behavior. This suggests that the priming in these studies occurred automatically, a conclusion reached by Dijksterhuis and Bargh (2001) in their review of the literature. Since the advent of modern psychology, theorists have argued that much action arises automatically (e.g., James, 1890; Jeannerod, 1997; LaBerge & Samuels, 1974; Schneider & Shiffrin, 1977; Stroop, 1935). Many embodiment phenomena appear to arise largely in this manner.

2. *Facial Responses*

It is well known that perceived stimuli produce facial responses. In Cacioppo, Petty, Losch, and Kim (1986), subjects viewed visual scenes that were either pleasant or unpleasant while electromyography (EMG) monitored their facial musculature. A cover story and bogus electrodes led subjects to believe that the experiment addressed brain responses to perceptual stimuli. As predicted, pleasant scenes tended to produce positive facial expressions on subjects’ faces, whereas negative scenes tended to produce negative expressions. The perceived scenes modulated facial reactions.

Pictures of people have similar effects. In Vanman and Miller (1993), subjects viewed pictures of people from the same versus a different fraternity, sorority, university, or race. EMG showed that the pictures

modulated subjects' facial expressions. When a picture depicted a person from a subject's fraternity, sorority, university, or race, the subject's facial expression tended to be positive. Conversely, when a picture depicted a person from a different fraternity, sorority, university, or race, the subject's facial expression tended to be negative.

Just imagining a person produces facial responses—actually seeing a person is not necessary. In further experiments, Vanman, Paul, Ito, and Miller (1997) had subjects imagine various people who might later work with them to solve problems. A variety of variables moderated subjects' facial expressions, as measured by EMG. In particular, subjects were most likely to produce positive facial expressions when their imagined partners were competent on the task, exerted high effort, or belonged to the same race. Conversely, subjects were most likely to produce negative facial expressions when their imagined partners were incompetent, exerted low effort, or belonged to a different race.

Simply having subjects read about a fictional character produces facial responses. Andersen, Reznik, and Manzella (1996) obtained personality descriptions about significant others in a subject's life and then developed fictional characters who partially resembled them. On a later occasion, subjects read about these fictional characters, not realizing that they were related to their significant others. Most importantly for our purposes here, these fictional characters modulated the facial expressions on subjects' faces, as coded by a naive judge. When subjects read about characters based on significant others they liked, they tended to adopt positive facial expressions. Conversely, when subjects read about characters based on significant others they disliked, they tended to adopt negative facial expressions. Simply reading about social stimuli modulated facial responses.

As these studies illustrate, social stimuli do not just produce bodily responses, they also produce facial ones. Again these effects are likely to be relatively automatic and unconscious. In the Vanman studies, subjects typically claimed that they had no racial prejudice on explicit questionnaires, yet exhibited subtle racial bias in their facial musculature (cf. Greenwald, Banaji, Rudman, Farnham, Nosek, & Mellott, 2002). In the Andersen studies, subjects did not know that the fictional characters were related to their significant others. Furthermore, these subjects probably were not aware that they were even producing facial responses to the characters. Under such experimental conditions, it is likely that facial responses to social stimuli result automatically, at least to some extent.

3. Communicative Responses

Social stimuli also affect embodied aspects of communication. For example, Bargh et al. (1996) manipulated whether subjects were primed with words

related to rudeness (e.g., “aggressively”) or with words related to politeness (e.g., “patiently”). A control group received words unrelated to rudeness and politeness. After constructing sentences from the word lists, subjects were supposed to meet with an experimenter in another room, whom they found engaged in a contrived conversation with a confederate. The critical measure was whether subjects interrupted the conversation. Subjects receiving rude words were more likely to interrupt than subjects receiving neutral words, whereas subjects receiving polite words were less likely to interrupt. As in previous studies, words activated social knowledge that culminated in an embodied effect, this time one associated with communication.

Dijksterhuis and van Knippenberg (2000) reported a similar communicative effect. In the critical conditions, subjects were primed with words related to the *politician* stereotype. Subsequently subjects wrote essays on nuclear testing. Subjects primed with the *politician* stereotype wrote longer essays than subjects primed with neutral words. Because politicians are associated with long windedness (as Dijksterhuis and van Knippenberg established in previous work), activation of this knowledge produced corresponding embodied effects.

Again such effects are likely to result from automatic processing. Subjects probably were not aware that stereotypes were being primed and affecting their behavior.

4. *Related Nonsocial Effects*

The adult cognitive literature similarly demonstrates that nonsocial stimuli produce embodied responses. Chao and Martin (2000) had subjects name objects implicitly while lying passively in an fMRI scanner (i.e., functional magnetic resonance imaging). When subjects saw manipulable objects, such as a hammer, a grasping circuit in the brain became active (e.g., Rizzolatti, Fadiga, Fogassi, & Gallese, 2002). Although subjects were instructed to lie still and simply perform visual categorization, a motor circuit nevertheless became active, preparing subjects for functional use of the object (e.g., grasp and swing a hammer). Similar to the findings just reviewed, visual categorization of a functional artifact produced an implicit embodied response.

In an eye movement study, Spivey et al. (2000) also observed this effect. Subjects listened to vignettes about the top of a skyscraper, the bottom of a canyon, etc. As subjects listened to a vignette, their eyes tended to look in the direction of the focal entity, as if they were actually in the setting. For vignettes about the top of a skyscraper, subjects tended to look up; for vignettes about the bottom of a canyon, subjects tended to look down. Simple descriptions of a physical setting produced an embodied

effect, causing subjects to orient perceptually as if present in it. Barsalou and Barbey (2003) similarly found that subjects look up while describing the properties of birds, but look down while describing the properties of worms.

B. EMBODIMENT IN OTHERS ELICITS EMBODIED MIMICRY IN THE SELF

In the studies just reviewed, social stimuli produced embodied responses in the perceiver. Social stimuli similarly produce embodied responses in this next embodiment effect. The following studies differ, however, in that the embodied responses mimic perceived social stimuli. In the previous section, embodied responses were not mimicry—typically they went beyond the social stimulus in some way. For example, when subjects received words that primed *rudeness*, or a picture that depicted a member of a social group, the stimulus did not literally contain an embodied action. For example, words about *rudeness* did not directly demonstrate interrupting behavior, nor did a picture about a fraternity member depict frowning. Rather these stimuli triggered knowledge that contained embodied responses, which then played out in behavior.

In contrast, these next embodiment effects mimic embodied states perceived in social stimuli. For example, an emotional expression on another person's face produces the same expression on the perceiver's face. Increasingly, theorists believe that these effects arise from brain circuits specialized for mimicry. For example, Rizzolatti and his colleagues have identified a mirror neuron circuit that produces motor mimicry in response to perceived actions (e.g., Rizzolatti et al., 2002; also see Chao & Martin, 2000). Such circuits could play two important roles in intelligent organisms. First, they provide a fast learning mechanism, whereby an organism learns new actions through imitation (e.g., Meltzoff, 2002). Second, these circuits produce social contagion, inducing similar emotional states in conspecifics, as well as empathy and cooperation (e.g., Dijksterhuis & Bargh, 2001; Hatfield, Cacioppo, & Rapson, 1992; Neumann & Strack, 2000). Later we return to the theoretical implications of these effects. First, however, we review the specific forms they take.

1. Bodily Mimicry

When two people interact, their bodily actions often become entrained. Although the literature reports much anecdotal evidence for bodily mimicry, controlled laboratory demonstrations exist as well. In Bernieri (1988), judges coded the postural synchrony of two people interacting. In the control condition, the same two target individuals were judged, but as each interacted with another person (to the judges, it appeared that the two target individuals had actually interacted with each other). Bernieri

found that postural synchrony was higher for two individuals engaged in an actual interaction than for two individuals in a contrived interaction. As each individual perceived the other performing bodily actions, mimicry resulted to some extent. Bernieri, Reznick, and Rosenthal (1988) reported related results for mother–child interactions (also see Bernieri & Rosenthal, 1991).

Subsequent research has continued to demonstrate bodily mimicry in dyadic interactions. In Chartrand and Bargh (1999), the experimenter either rubbed her nose or shook her foot while interacting with subjects. As predicted, subjects mimicked the experimenter. When the experimenter scratched her nose, subjects were more likely to scratch their nose than to shake a foot. Conversely, when the experimenter shook her foot, subjects were more likely to shake a foot than to scratch their nose. Watching a social stimulus produce an action tended to induce the same action in the perceiver.

2. *Facial Mimicry*

As people interact, their facial expressions become entrained as well. In Bavelas, Black, Lemery, and Mullett (1986), a confederate experienced a fake injury and winced. As subjects viewed the wince, they often winced in response, with the size of their wince increasing with how clearly they could see it on the confederate's face. In Provine (1986), subjects yawned more often when the people they were watching yawned than when they did not. In O'Toole and Dubin (1968), mothers tended to open their mouths after their infants opened their mouths to feed. The inclination to mimic perceived facial expressions is a powerful force in human interaction that has been documented widely (also see Bush, Barr, McHugo, & Lanzetta, 1989; Dimberg, 1982). People even mimic faces presented subliminally (Dimberg, Thunberg, & Elmhed, 2000).

Indeed this force is so powerful that it leaves permanent records on people. Zajonc, Adelman, Murphy, and Niedenthal (1987) studied the facial similarity of couples married 25 years or more. Zajonc and his colleagues predicted that facial mimicry should cause married partners' faces to become increasingly similar over time. Because establishing empathy with each other is important, married partners should frequently mimic each other's facial expressions, such that their facial musculatures settle into similar entrenched states. After 25 years, the similarity of their faces should be greater than at the time of their marriage, and also more similar than random people of the same age. Zajonc et al. (1987) indeed found that facial similarity increased within couples over time, implicating the constant presence of facial mimicry.

3. *Communicative Mimicry*

Embodied mimicry also occurs during communication. During conversations, partners tend to match each other on latency to speak, speech rate, utterance duration, and so forth (e.g., Cappella & Planalp, 1981; Matarazzo & Wiens, 1972; Webb, 1972). Listeners similarly attempt to match emotional tone in the voices of the speakers they hear (e.g., Neumann & Strack, 2000). Listeners also mimic speakers' manual gestures (e.g., Bavelas, Black, Chovil, Lemery, & Mullett, 1988; Maxwell, Cook, & Burr, 1985) and even their syntactic constructions (e.g., Bock, 1986). Across many levels of analysis, mimicry helps speakers and listeners achieve synchrony during communication. Many theorists further argue that such synchrony helps conversational partners establish rapport, empathy, and cooperation (e.g., Bernieri, 1988; LaFrance, 1985; LaFrance & Ickes, 1981; Neumann & Strack, 2000; Semin, 2000).⁴

C. EMBODIMENT IN THE SELF ELICITS AFFECTIVE PROCESSING

The previous two sections showed that social stimuli produce embodied responses. In this next section, we see that embodiment is not just a response to social stimuli, but in turn constitutes a potent stimulus. Embodied states in the self trigger a wide variety of affective states. At least since James (1890), researchers have reported such phenomena and developed theories of them. In reviewing these phenomena, we do not commit to any particular account, such as the importance of the autonomic nervous system in James' view. Instead our goal is simply to illustrate that bodily states constitute a powerful trigger for affective states.⁵

⁴ Gesture in communication constitutes another important area of social embodiment. Communicative gestures appear to play important roles in language use, such as helping speakers retrieve words (e.g., Krauss, Chen, & Chawla, 1996) and helping speakers convey ideas (e.g., McNeill, 1992). Because embodiment in language lies beyond the scope of our review, we do not address it further. Nevertheless embodiment plays diverse roles in language that we do not address here (also see Lakoff & Johnson, 1980, 1999).

⁵ We further assume that bodily states induce cognitive states, not just affective ones. For example, performing the action of dancing might activate knowledge of associated settings, entities, and events (e.g., nightclubs, bands, and drinking). Because work in social psychology has focused primarily on how bodily states produce affective states, we do not focus on how bodily states produce cognitive states. Nevertheless we assume that the latter effects are ubiquitous and constitute an important topic for future study. The final paper in this section, Strack and Neumann (2000), addresses embodied effects in fame judgment, which could be construed as a cognitive task, although it clearly has an evaluative component as well.

1. Bodily Elicitation

When people adopt a particular posture, it influences their affective state. In Duclos, Laird, Schneider, Sexter, Stern, and Van Lighten (1989), subjects were led to believe that the study addressed whether performing multiple tasks simultaneously produced unilateral or bilateral brain activity, as measured by bogus electrodes. One of the multiple tasks was to adopt various bodily positions, which subjects did not realize were associated with fear, anger, or sadness. As predicted, the postural states modulated affect. When subjects were induced to hold postures associated with fear, their rated fear was higher than when they adopted other postures. Analogous results occurred for postures associated with sadness and anger.

Many additional studies demonstrate that embodiment not only produces affect per se, but propagates this affect to other cognitive processes. In Riskind and Gotay (1982), subjects were induced into an upright or slumped posture under the cover story that galvanic skin responses to different muscle positions were of interest. After resuming normal posture, subjects attempted to solve puzzles in a “separate experiment.” Subjects who were earlier induced into an upright posture persisted longer on the puzzles than subjects induced into a slumped posture. Riskind and Gotay (1982) concluded that subjects’ posture modulated their confidence, thereby affecting task performance.

In Stepper and Strack (1993), subjects were induced into an upright or slumped posture under the cover story that task performance under different ergonomic conditions was of interest. While upright or slumped, subjects performed an achievement test and received bogus feedback that they had done well. Later subjects rated their feeling of pride at the time. Subjects who had been upright while receiving task feedback experienced more pride than subjects who had been slumped. As in Riskind and Gotay (1982), subjects’ posture affected their affective state.

Arm motions can similarly induce affective states. Typically, when people encounter a desirable object, they use their arms to pull it toward themselves (approach behavior). Conversely, when people encounter an undesirable object, they push it away (avoidance behavior). Cacioppo, Priester, and Bernston (1993) explored the relation between such arm motions and affective evaluation. While viewing neutral Chinese ideographs, subjects either pushed upward on the table surface (approach) or downward on the table (avoidance). Later subjects rated how much they liked the ideographs. Consistent with the embodiment hypothesis, ideographs seen during the approach movement received higher ratings than ideographs seen during the avoidance movement. Another experiment showed that the approach movement made subjects’ overall attitude more positive, relative to

performing no action, whereas the avoidance movement made their overall attitude more negative. Similar to posture, arm motion induced affective states.

Finally, head movements induce affective states as well. In Wells and Petty (1980), subjects were induced to nod their heads vertically or to shake their heads horizontally under the cover story that the experiment assessed the ability of headphones to stay on the head while bopping to music. While wearing the headphones, performing a head movement, and listening to music, subjects also heard a message about a university issue. Later, when subjects rated how much they agreed with the message, their earlier head movements moderated their judgments. Subjects who had nodded vertically while hearing the message were more favorable than subjects who had shaken their heads horizontally. Although subjects believed that these actions were testing headphone use, the effect associated with these actions nevertheless influenced message evaluation.

Tom, Pettersen, Lau, Burton, and Cooke (1991) replicated Wells and Petty's finding. Again subjects were induced to nod their heads vertically or to shake their heads horizontally under the cover story about headphones falling off while listening to music. While subjects performed the action and listened to music, a pen lay on the table before them. Afterward a naive experimenter offered the subject either the pen they had seen or one they had not seen. Subjects who had nodded vertically were more likely to take the original pen, whereas subjects who had shaken their heads were more likely to take the new pen. When subjects had seen the original pen earlier, their head movement affected their evaluation of it.

2. *Facial Elicitation*

A large literature demonstrates that adopting facial expressions produces affective responses, what has often been referred to as *facial feedback* (for a review, see Adelman & Zajonc, 1987). Although accounts of these effects differ (e.g., Buck, 1980; Kraut, 1982; Laird, 1984; Winton, 1986), many studies show that configuring the face into an emotional expression tends to produce the corresponding affective state.

Consider another study from the Duclos et al. (1989) work described earlier. Again, subjects believed that the study addressed whether performing multiple tasks simultaneously produces unilateral or bilateral brain activity, where one of the tasks was to adopt various bodily states. Under this cover story, subjects were induced indirectly to adopt facial expressions associated with fear, anger, disgust, or sadness. As predicted, subjects experienced each emotion most strongly while holding the respective facial expression.

Again such effects go beyond the production of affective states per se, propagating to other cognitive processes. Strack, Martin, and Stepper (1988) provided a particularly compelling demonstration. Subjects held a pen either in their teeth or lips, with the writing tip pointing out (similar to smoking a cigar). Subjects were led to believe that the study assessed methods for teaching paraplegics to write with their mouth. Unbeknownst to subjects, holding a pen with one's teeth tends to trigger the musculature associated with smiling, whereas holding a pen with one's lips tends to trigger the frowning musculature. During the study, subjects were asked to actually use the pen as a paraplegic might for drawing lines, underlining items in a search task, and so forth. In the critical task, subjects viewed cartoons and rated how funny they were, again writing with the pen held in their teeth or lips. Consistent with the embodiment hypothesis, subjects holding the pen with their teeth rated the cartoons as funnier than subjects holding the pen with their lips. Although subjects were not aware that their musculature had been manipulated into an emotional expression, the expression associated with the musculature affected evaluation.

In Strack and Neumann (2000), subjects believed that the experiment addressed whether computer work causes forehead tension. While sitting in front of a computer, subjects received photos of famous and nonfamous people and judged how famous each one was. Subjects were further told that EMG would be used to monitor their forehead tension. The key manipulation was whether subjects were asked to furrow or raise their eyebrows, with both groups being told that this action produces forehead tension. In previous work, furrowing the brow has been shown to occur while exerting effort, whereas raising the eyebrows has not. Of primary interest was the effect of this manipulation on fame judgments. In classic work, Jacoby, Kelley, Brown, and Jasechko (1989) showed that subjects attribute fame to a name they process effortlessly. Strack and Neumann (2000) reasoned analogously that if furrowing the brow induces the affect of exerting effort, then subjects who furrow their brows should perceive the faces as less famous than subjects who raise their brows (which does not occur while exerting effort). Strack and Neumann (2000) obtained this finding. Fame judgments were significantly lower while furrowing the brow than while raising it.

D. THE COMPATIBILITY OF EMBODIMENT AND COGNITION MODULATES PERFORMANCE EFFECTIVENESS

We have seen thus far that embodiment can function both as a response and as a stimulus. A wide variety of social stimuli produce embodied responses in the self, with a subset of these responses constituting mimicry.

Conversely, an embodied state in the self can induce a variety of affective states. We next see how these three previous types of embodiment effects enter into more complex relationships with cognitive processing. In general, when embodied and cognitive states are compatible, processing proceeds smoothly. When embodied and cognitive states are incompatible, less efficient processing results.

Not only do these relationships demonstrate important interactions between the body and higher cognition, they further suggest that higher cognition utilizes embodied representations. If higher cognition used disembodied representations, interference between incompatible bodily and cognitive states would not be expected. Previous research on modality-specific interference shows that when working memory content and response mode utilize different representational formats, no interference occurs between them (e.g., Brooks, 1968; Segal & Fusella, 1970). Conversely, when working memory content and response mode share a common representational format, interference occurs. It follows that if higher cognition uses embodied representations, then interference should often be expected between embodiment and higher cognition. Compatibility effects between embodiment and cognition should be widespread.

Before reviewing these studies on embodiment–cognition compatibility, it is first worth making a preliminary point. All of the studies to follow further demonstrate the phenomena in the preceding three sections. Each finding could have been included for a previous embodiment effect, given that it illustrates either an embodied response to a social stimulus or an embodied state that triggers an affective state. We have held off describing most of these findings until now, given that they also demonstrate embodiment–cognition compatibility. It is important to remember that they demonstrate the earlier embodiment effects as well.⁶

1. Motor Performance

Further results from the Wells and Petty (1980) study discussed earlier demonstrate an embodiment–cognition compatibility effect. In that study, some subjects received an agreeable message, whereas other subjects received a disagreeable one. This manipulation was crossed with whether subjects nodded their head vertically or shook it horizontally while attempting to test whether headphones fall off. Of interest here is that head movements were faster when compatible with the message than when

⁶ As will become evident, some compatibility effects result from interactions between bodily and *affective* states, whereas others result from interactions between bodily and *nonaffective* states. We use “cognition” in referring inclusively to both affective and nonaffective states, as we review “embodiment–*cognition* compatibility effects.”

incompatible. While nodding vertically, subjects nodded faster for the agreeable message than for the disagreeable one. Conversely, while shaking horizontally, subjects shook faster for the disagreeable message. This result demonstrates that bodily states interacted with cognitive processing. When the agreeableness of the message was compatible with the head action, subjects were able to perform the action faster than when the message was incompatible. Embodiment–cognition compatibility affected performance efficiency.

Chen and Bargh (1999) reported a similar result [as did Neumann and Strack (2000) and Wentura, Rothermund, and Bak (2000)]. In Experiment 1, Chen and Bargh's subjects received positively or negatively valenced words (e.g., "love," "hate") and had to indicate each word's valence. Subjects responded either by pulling a lever toward them or pushing it away. If embodiment and cognition interact, then positively valenced stimuli should be associated with pulling things toward oneself, whereas negatively valenced stimuli should be associated with pushing things away. Thus subjects should respond fastest to positive words when pulling the lever toward them, but should respond fastest to negative words when pushing the lever away. Consistent with the embodiment prediction, Chen and Bargh (1999) obtained this result.

In Experiment 2, Chen and Bargh (1999) obtained a similar result when subjects simply had to indicate when a word appeared on the screen—subjects made the same response to all words regardless of their affective valence. When subjects indicated a word's appearance by pulling the lever toward them, they responded faster to positive words than to negative ones. When subjects indicated a word's appearance by pushing the lever away, they responded faster to negative words. Automatic activation of a word's meaning implicitly affected subjects' ability to simply indicate stimulus presentation. Most importantly, embodiment—as realized in drawing positive things closer and pushing negative things away—interacted with the cognitive task that subjects performed. In general, all of these results show that motor performance is optimal when compatible with cognitive processing.

2. Memory Performance

Similar interactions occur between embodiment and memory. In Laird, Wagener, Halal, and Szegda (1982), subjects read both anger-provoking passages and humorous passages. Subsequently, under the guise of a cover story, subjects' smiling or frowning musculature was activated while they attempted to recall the earlier material. Consistent with the embodiment prediction, facial expression modulated recall. Whereas humorous passages were recalled better while smiling than frowning, anger-provoking passages were recalled better while frowning. Interestingly, this effect only occurred

when subjects' facial expressions influenced their mood, indicating that mood moderated the relation between embodiment and memory. Most importantly, though, when embodiment, mood, and memory were compatible, performance was optimal.

A study described by Zajonc, Pietromonaco, and Bargh (1982) illustrates a similar effect in face recognition (cf. Graziano, Smith, Tassinary, Sun, & Pilkington, 1996). Subjects were asked to perform various motor actions while viewing pictures of faces. Whereas some subjects had to mimic the head orientations and facial expressions of the faces, other subjects had to chew gum or squeeze a sponge (i.e., motor controls). A fourth group had to judge the head orientations and facial expressions of the faces (i.e., nonmotor controls). After studying the pictures, subjects received a recognition test. As the embodiment view predicts, picture memory was best when subjects' embodiment was compatible with the pictures—the group mimicking the pictures scored highest. The worst performance occurred for subjects who performed the most competitive motor response—chewing gum. Subjects who squeezed a sponge or judged the faces fell in between. As in the Laird et al. (1982) study, performance was optimal when embodiment and memory were compatible.

Förster and Strack (1996) demonstrated a similar compatibility effect in word recognition. Subjects were induced either to nod their heads vertically (as in agreement) or to shake their heads horizontally (as in disagreement) while studying a list of positively valenced and negatively valenced adjectives. To disguise the study's intent, subjects were told that its purpose was to assess whether headphones fall off under various head movements. On a later recognition test, memory sensitivity was higher for compatible movement–adjective pairings than for incompatible pairings. Specifically, when subjects nodded their heads vertically, their memory for positive adjectives was better than their memory for negative ones. Conversely, when subjects shook their heads horizontally, their memory for negative adjectives was better. Again memory performance was optimal under conditions of embodiment–cognition compatibility.

Embodiment also affects memory for real-life events, not just laboratory ones. In Riskind (1984), subjects recalled past experiences from their life that were pleasant or unpleasant. While recalling memories, embodiment was manipulated by having subjects adopt different postures and facial expressions. Whereas subjects in the positive embodiment condition adopted an expansive posture and a smiling expression, subjects in the negative embodiment condition slumped and frowned. As predicted, this manipulation affected memory, modulating the latencies to retrieve positive versus negative life experiences. Adopting an expansive posture and smiling increased the speed of recalling positive experiences relative to recalling negative ones.

Finally, Förster and Strack (1997, 1998) demonstrated a compatibility effect in retrieval from long-term knowledge. Subjects were instructed to generate the names of famous people and to write them in one of three columns labeled “like,” “dislike,” and “neutral.” While retrieving these names from memory and writing them down, subjects either pulled up on the table surface (approach) or pushed down on it (avoidance). The intent of the study was disguised by telling subjects that optimizing the writing behavior of disabled people was of interest. As the embodiment hypothesis predicts, subjects who performed the approach action retrieved more names of people they liked, whereas subjects who performed the avoidance action retrieved more names of people they disliked. Again memory performance was optimal when motor and cognitive factors were compatible.

3. Facial Categorization Performance

Interactions between embodiment and cognition also occur during face processing. Wallbott (1991) asked subjects to categorize the emotional expressions of pictured individuals (i.e., whether an individual was happy, sad, angry, etc.). As subjects judged emotional expressions, their own faces were videotaped. Judges later found that subjects tended to mimic the facial expressions they were judging. Even more interestingly, subjects’ accuracy in judging facial expressions increased as their mimicry increased. Although subjects were not required to produce facial expressions and simply had to perform visual categorizations, perceiving a facial expression tended to induce the same expression in the perceiver. Presumably this effect would even be stronger in the presence of an actual individual as opposed to a picture. Regardless, compatibility between embodiment and visual categorization optimized performance.

Adolphs, Damasio, Tranel, Cooper, and Damasio (2000) reported a related finding. When clinical patients have lesions in somatosensory cortex, they are deficient in judging the facial expressions of others. Although it might seem surprising that a lesion in the somatosensory cortex affects visual categorization, Adolphs et al. (2000) argued that simulating emotional expressions on one’s own face and experiencing the somatosensory feedback facilitate this process. Similar to Wallbott (1991), facial mimicry arises spontaneously while perceiving faces, with the resultant feedback enhancing the ability to categorize emotional expressions.

Niedenthal and her colleagues demonstrated the compatibility effect for face processing under controlled laboratory conditions (Niedenthal, Halberstadt, Margolis & Innes-Ker, 2000; Niedenthal, Brauer, Halberstadt, & Innes-Ker, 2001). In these studies, subjects watched one facial expression morph into another and had to detect when the expression changed. In some

studies, subjects were simultaneously under a mood induction, where the mood was compatible or incompatible with the initial expression. For example, subjects might watch a happy face morph into a sad or neutral face while in a happy mood (compatible). Alternatively, subjects might watch a happy face morph into a sad or neutral face while sad (incompatible). Across experiments, Niedenthal et al. (2000, 2001) found that compatibility between judged expressions and mood speeded the detection of changed expressions.

In a final study, Niedenthal et al. (2001) demonstrated that embodiment underlies this effect. Whereas some subjects were free to move their mouth, others had their mouth frozen by having to hold a pen in it. Consistent with the embodiment hypothesis, subjects detected change faster when their mouth was free to move than when it was frozen. Similar to Wallbott (1980) and Adolphs et al. (2000), compatibility between visual categorization and embodiment optimized visual categorization.

4. Reasoning Performance

Embodiment–cognition compatibility also affects reasoning. In Riskind (1984), subjects first performed a spatial reasoning test that was either easy or difficult and then predicted how well they would perform on a similar test later. Subjects who received easy tests predicted success on the future task, whereas subjects who received difficult tests predicted failure. Subsequently subjects participated in a bogus biofeedback experiment that involved taking either an upright or a slumped posture while hooked up to electrodes. Most importantly, initial success or failure on the reasoning test was crossed with the subsequent upright or slumped posture, thereby implementing compatibility. Of interest was whether compatibility between initial reasoning performance and embodiment affected performance on the subsequent reasoning task. Compatibility was defined as subjects succeeding and then having to take an upright posture or failing and having to take a slumping posture. Incompatibility was defined as either success/slumping or failure/upright. Consistent with the embodiment view, subjects persisted longer at trying to solve the later puzzles when reasoning performance and embodiment had been compatible earlier. Riskind (1984) concluded that compatibility helps subjects strategize about the reasoning task effectively, such that they are more likely to persist in solving problems.

5. Secondary Task Performance

Thus far we have seen that compatibility between embodiment and cognition optimizes performance. These next studies point toward one possible explanation of compatibility effects. Specifically, these studies show that

compatibility minimizes the amount of processing resources needed to manage embodied and cognitive tasks performed simultaneously. Conversely, when embodiment and cognition are incompatible, more processing resources are necessary. To assess processing resources, the following studies measure secondary task performance while embodiment and cognition are either compatible or incompatible. If compatibility modulates the availability of processing resources, performance on the secondary task should be worse under incompatible task conditions than under compatible ones.

Förster and Strack (1996) were the first to assess this hypothesis. As described earlier, they manipulated whether head movements (nodding versus shaking) were performed while studying positive versus negative adjectives. As also described, Förster and Strack found that compatibility between the head movements and the adjectives optimized later recognition memory. In Experiment 3, they used a secondary task—placing pegs into holes on a board—to assess the availability of processing resources. As subjects moved their heads and studied adjectives, their performance on the secondary task indexed the remaining capacity available and, inversely, the capacity used by the primary tasks.

As predicted, subjects were poorer at the secondary task when their head movements were incompatible with the adjectives than when they were compatible. For example, when subjects nodded their heads and studied negative adjectives, their secondary task performance was lower than when they nodded their heads and studied positive adjectives. This finding suggests that processing resources moderated the memory compatibility effect. When embodiment and word valence were compatible, more processing resources were available to encode the adjectives into memory. When embodiment and word valence were incompatible, fewer resources were available for learning.

Förster and Stepper (2000) offered further evidence for this conclusion. In one study, subjects stood upright (positive posture) or knelt (negative posture) while learning positive and negative words. As subjects studied the words, they performed the same secondary task of placing pegs in holes. Similar to Förster and Strack (1996), compatibility between posture and word valence modulated secondary task performance. The minimal processing resources were required for compatibility, whereas more were required for incompatibility.

In another experiment, Förster and Stepper (2000) replaced the upright versus kneeling manipulation with the experience of a sweet versus a bitter taste, respectively. When both the taste and the words were positive or both negative, secondary task performance was higher than when one was positive and the other negative. Again more processing resources were free when embodiment and cognition were compatible.

6. *Related Nonsocial Effects*

A variety of embodiment–cognition compatibility effects have been reported for nonsocial stimuli. In Tucker and Ellis (1998), subjects were instructed to detect whether a cup was right side up versus upside down. Although the handle of the cup was irrelevant to the decision, it nevertheless interacted with the motor response that indicated the vertical orientation of the cup. Specifically, subjects responded faster when the handle was on the same side of the display as the response hand than when the handle was on the opposite side. For example, right-handed responses were faster when the handle of the cup was on the right side of the screen than when the handle was on the left. On perceiving the cup, the cognitive system immediately detected the embodied implication of the handle, namely whether the handle would be easily graspable by the response hand or not. Although grasping the handle was irrelevant, its embodied implications were computed automatically and immediately. As for the social phenomena just reviewed, embodiment–cognition compatibility optimized performance. Tucker and Ellis (2000, 2001) reported similar compatibility results for other types of embodied responses.

Glenberg and Kaschak (2002) reported a similar phenomenon in language comprehension. When subjects judged the sensibility of a sentence that described a forward hand movement (e.g., “close the drawer”), they responded faster when using a forward hand movement than a backward one. Conversely, when subjects judged the sensibility of a sentence that described a backward hand movement (e.g., “open the drawer”), they responded faster when using a backward hand movement.

Finally, Simmons and Barsalou (2003a) found that compatible embodiment facilitates the visual categorization of artifacts. When subjects performed an arm movement that was compatible with a visually presented object, they categorized the object faster than when they performed an incompatible action. For example, subjects categorized a picture of a faucet faster when performing the action of turning a faucet than when making a comparable but unrelated movement.

In summary, the embodiment–cognition compatibility that we saw for social stimuli also occurs for nonsocial stimuli. This broader pattern suggests two general conclusions: First, a common mechanism appears to produce compatibility effects across diverse domains. Second, embodiment appears to enter centrally into cognitive processing, given that bodily states interact widely with cognitive ones. As described earlier, if cognitive states were amodal and disembodied, they should not interact with bodily states. Given embodiment’s ubiquitous interactions with cognition, it can hardly be viewed as peripheral, as in most current theories.

III. A Theory of Social Embodiment

Although the phenomena just reviewed all involve embodiment, no unified account of them exists. Furthermore, embodiment is often viewed as peripheral to these phenomena, namely as an appendage that accompanies more central representations of social entities and events. This next section presents a theory in which embodiment resides at the heart of social representations, contributing directly to their meaning. The subsequent section shows how this account explains social embodiment phenomena.

According to most theories, knowledge consists of amodal symbols that *redescribe* modality-specific states. On interacting with a person in a social event, an amodal redescription of the perceptions, actions, and introspections in the event becomes established in memory to support social processing. Nearly all accounts of social cognition represent knowledge this way, using feature lists, propositions, productions, schemata, statistical vectors, and so forth to redescribe perceptual, motor, and introspective states. Many examples of such theories can be found in the edited volumes of Wyer and Srull (1984a,b,c). According to these views, amodal redescrptions of social experience constitute social knowledge.

A few notable exceptions have stressed the importance of embodied representations in social cognition. Early accounts of attitudes proposed that motor movements are central components of attitudes (for a review, see Fleming, 1967). Darwin (1872/1904) used *attitude* to mean the collection of motor behaviors, especially posture, that conveys an organism's affective response toward an object. Subsequent accounts similarly stressed the importance of motor behavior in attitudes (e.g., Sherrington, 1906; Washburn, 1926). More recently, Zajonc and Markus (1984) have argued that motor behavior and affect represent themselves in higher cognition rather than amodal symbols standing in for them. Similarly, Damasio (1994, 1999) argued that somatic markers are central to higher cognition and that without them, rationality is compromised. All of these views are closely related to the theory we propose.

A. MODAL REENACTMENTS OF PERCEPTION, ACTION, AND INTROSPECTION

The modal reenactment of perceptual, motor, and introspective states constitutes the central mechanism in our theory (e.g., Barsalou, 1999a,b; in press; Damasio, 1989). Rather than amodal redescrptions of perceptual, motor, and introspective states representing knowledge, reenactments of these states do. We further assume that the reenactment process underlying knowledge is roughly the same as the reenactment process underlying mental imagery (e.g., Deschaumes-Molinaro, Dittmar, & Vernet-Maury, 1992;

Farah, 2000; Finke, 1989; Grezes & Decety, 2001; Jeannerod, 1995; Kosslyn, 1994; Shepard & Cooper, 1982; Zatorre, Halpern, Perry, Meyer, & Evans, 1996). Damasio (1989) sketched a preliminary account of the reenactment process. Simmons and Barsalou (2003b) offered a more developed account, although full-fledged computational models remain to be built.

As Figure 1 illustrates in a highly simplified and schematic manner, the reenactment process has two phases: (1) the storage of modality specific states and (2) the partial reenactment of these states on later occasions. Each phase is addressed in turn.

1. Storage of Modality-Specific States That Arise in Feature Maps

When a physical entity is experienced, it activates feature detectors in the relevant feature maps (Fig. 1a). During visual processing of a face, for example, some neurons fire for edges and planar surfaces, whereas others fire for color, configural properties, and movement. The global pattern of activation across this hierarchically organized distributed system represents the entity in vision (e.g., Palmer, 1999; Zeki, 1993). Analogous patterns of activation on other sensory modalities represent how the face might sound and feel. Activation in the motor system similarly represents embodied responses to the face, such as the formation of a facial expression, and approach/avoidance behavior. A similar mechanism underlies the introspective states that arise while interacting with an entity. For example, activation patterns in the amygdala and orbitofrontal areas represent emotional reactions to social stimuli. Much neuroscience research documents the structure of feature maps across modalities and the states that arise in them.

In the simplified and schematic illustration of a visual feature map in Fig. 1a, the neural activation resembles a face. This might seem naïve. In vision, however, feature maps are often organized topographically. The visual system alone contains many topographically mapped feature areas. The motor, somatosensory, and auditory modalities analogously contain somatotopic and tonotopic maps organized according to external physical structure. Motor and somatosensory maps follow bodily structure to a considerable extent, and auditory maps are laid out according to pitch. Thus it is quite reasonable to assume that modality-specific representations take topographic forms, at least to some extent. Nevertheless, *nothing* in the account to follow depends on topographically mapped representations. If these representations were completely arbitrary, having nothing to do with topography, the account would work the same. The critical assumptions are that modality-specific states arise to represent experience, regardless of whether they are topographical, and that higher cognitive processes reenact them to represent knowledge.

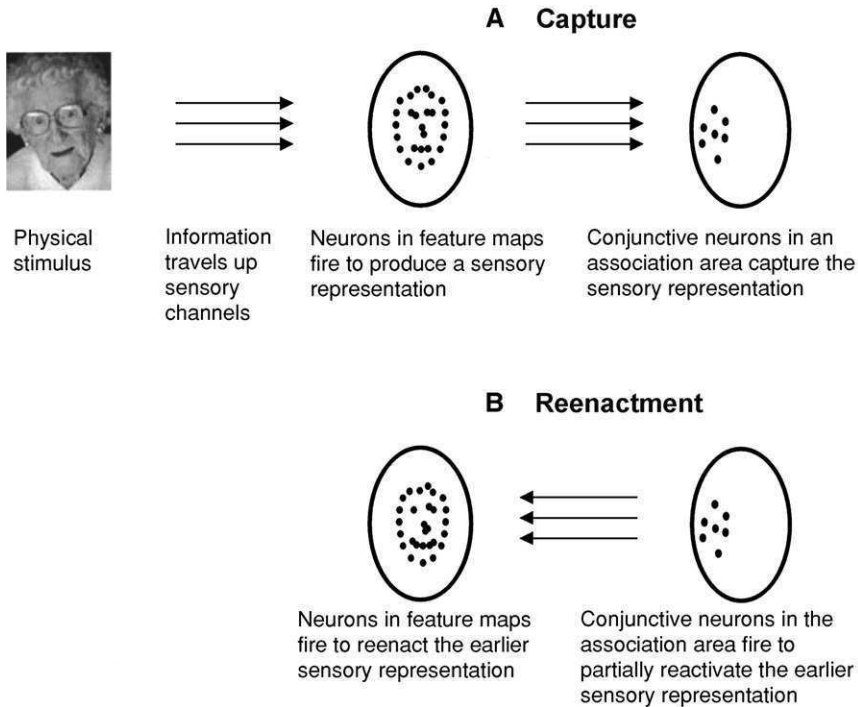


Fig. 1. Illustration of how modality-specific information is captured (A) and reenacted (B) in Damasio (1989) and Barsalou (1999b).

When a pattern becomes active in a feature map during perception or action, conjunctive neurons in an association area capture the pattern for later cognitive use. As Fig. 1a illustrates, conjunctive neurons in the visual system capture the pattern active for a particular face. A population of conjunctive neurons together codes a particular pattern, with each individual neuron participating in the coding of many different patterns (i.e., coarse coding; Hinton, McClelland, & Rumelhart, 1986). Damasio (1989) called these association areas *convergence zones* and proposed that they exist at multiple hierarchical levels in the brain, ranging from posterior to anterior (for a specific proposal, see Simmons & Barsalou, 2003b). Most locally, convergence zones near a modality capture activation patterns within it. Association areas near the visual system, for example, capture patterns there, whereas association areas near the motor system capture patterns there. Downstream in more anterior regions, higher association areas, including the temporal and frontal lobes, integrate activation *across* modalities.

2. *Reenactments of Modality-Specific States*

The convergence zone architecture has the functional capability to produce modality-specific reenactments. As Fig. 1b illustrates, once a set of conjunctive neurons captures a feature map pattern, the set can later activate the pattern in the absence of bottom-up stimulation. When retrieving the memory of a person's face, for example, conjunctive neurons can partially reactivate the visual state active while perceiving it. Similarly, when retrieving an action, conjunctive neurons partially activate the motor state that produced it. A given reenactment is never a complete reinstatement of an original modality-specific experience. Furthermore, biases may enter into the reenactment process. Thus all reenactments are partial and potentially inaccurate. At least some semblance of the original state, however, is partially activated—it is not represented as an amodal redescription.

The reenactment process is not necessarily conscious. Although conscious reenactment is viewed widely as the process that underlies mental imagery, reenactments need not always reach awareness. *Unconscious* reenactments may often underlie memory, conceptualization, comprehension, and reasoning (Barsalou, 1999b, 2003). Although explicit attempts to construct mental imagery may create vivid reenactments, many other cognitive processes may rely on less conscious reenactments or reenactments that are largely unconscious (e.g., Solomon & Barsalou, 2003; Wu & Barsalou, 2003).

In the account of social embodiment to follow, the neural reenactment of modality-specific states is the critical mechanism, *not* the experience of conscious mental images. Many of the social embodiment effects reviewed here appear to result from relatively unconscious simulations for two reasons. First, experimental cover stories tend to minimize conscious strategic processing, drawing subjects' attention away from the critical processes under study. Second, much evidence exists that embodiment effects result from automatic processes (e.g., Bargh & Chartrand, 1999; Dijksterhuis & Bargh, 2001; Hatfield et al., 1992). Both factors suggest that the reenactments underlying social embodiment phenomena may often be relatively unconscious.

B. SIMULATORS AND SIMULATIONS

Barsalou (1999b) developed a theory of knowledge based on the neural reenactment of modality-specific states (also see Barsalou, in press). These articles show that a fully functional conceptual system can be built on the reenactment mechanism just presented. Using this mechanism, it is possible to implement the type-token distinction, categorical inference, productivity,

propositions, and abstract concepts. Contrary to previous arguments, amodal symbols are not necessary for implementing these classical conceptual functions.

The two central constructs in this theory are *simulators* and *simulations*. Whereas simulators integrate information across a category's instances, simulations are specific conceptualizations of the category. Each is addressed in turn.

1. *Simulators*

Much work has shown that categories tend to have statistically correlated features (e.g., Chin-Parker & Ross, 2000; McRae, de Sa, & Siedenberg, 1997; Rosch & Mervis, 1975). Thus, when multiple instances of the same category are encountered, they tend to activate similar neural patterns in feature maps (cf. Farah & McClelland, 1991; McRae & Cree, 2002). As a result, similar populations of conjunctive neurons in convergence zones—tuned to these specific conjunctions of features—tend to capture these patterns (Damasio, 1989; Simmons & Barsalou, 2003b). Over time, this population of conjunctive neurons integrates modality-specific features across category instances and settings, establishing a multimodal representation of the category. Figure 2a provides a highly simplified and schematic illustration of the resultant distributed system. Barsalou (1999b) referred to these distributed systems as *simulators*. Conceptually, a simulator functions as a type, integrating the content of a category across instances and providing the ability to interpret later individuals as tokens of the type (Barsalou, in press).

Consider the simulator for the social category *face*. Over time, visual information about how faces look becomes integrated in the simulator, along with auditory information for how they sound, somatosensory information for how they feel, motor programs for interacting with them, emotional responses to experiencing them, and so forth. The result is a distributed system throughout the brain's association and modality-specific areas that establishes conceptual content for the general category of *face*.

2. *Simulations*

Once a simulator becomes established for a category, it can reenact small subsets of its content as specific *simulations* (Fig. 2b). All of the content in a simulator never becomes active at once. Instead only a small subset becomes active to represent the category on a given occasion (cf. Barsalou, 1987, 1989, 1993). For example, the *face* simulator might simulate a smiling face on one occasion, whereas on others it might simulate an angry face, a yelling face, or a kissing face. Although all the experienced content for faces resides

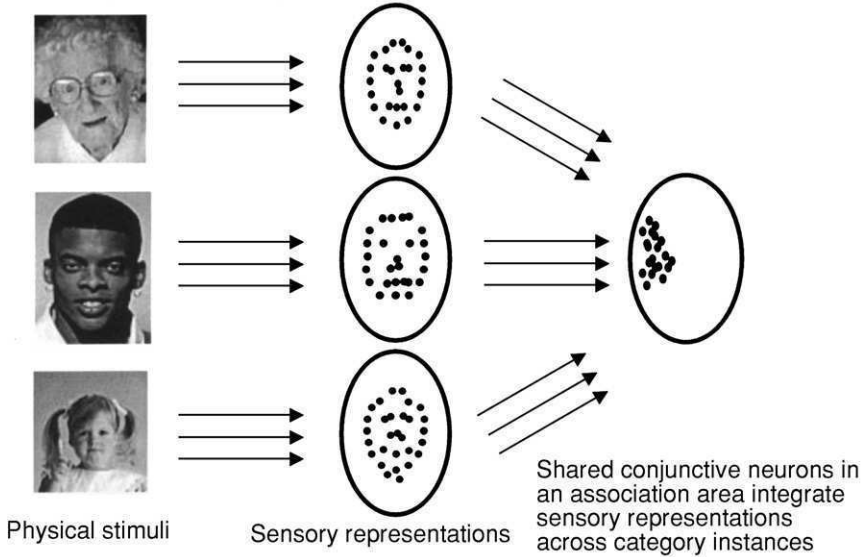
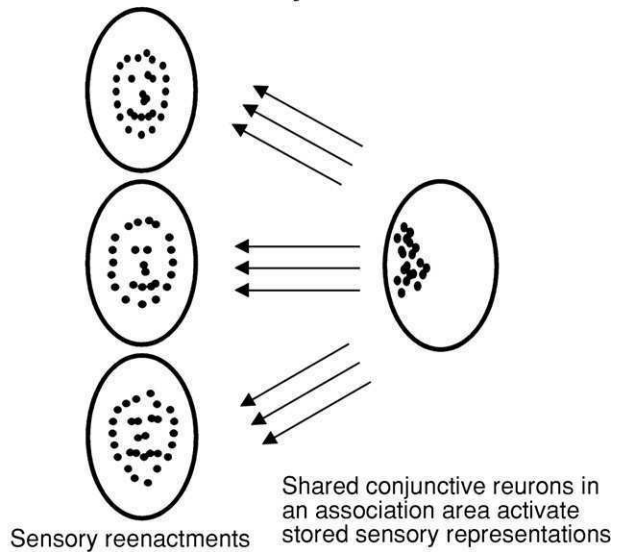
A Capture of Multiple Instances in a Simulator**B Reenactment of Different Instances by a Simulator**

Fig. 2. Illustration of simulators (A) and simulations (B) in perceptual symbol systems (Barsalou, 1999b).

implicitly in the *face* simulator, only a specific subset is reenacted on a given occasion.

Once a simulation becomes active, it serves a wide variety of cognitive functions (Barsalou, 1999b). Of particular interest later, simulations can be used to draw inferences about a category's perceived instances. Additionally, simulations can represent a category's instances in their absence during memory, language, and thought.

Simulations can go considerably beyond the information stored originally in a simulator—they are not mere reenactments of previously experienced events. Information stored on different occasions in a simulator may merge together at retrieval, thereby producing reconstructive and averaging effects. Remembering a face seen once, for example, may be distorted toward a similar face seen many times. Furthermore, intentional attempts to combine simulations from different simulators productively can produce infinite simulations never experienced (Barsalou, 1999b, *in press*). For example, people can simulate a rug and then systematically simulate its color and pattern to represent a wide variety of novel rugs (e.g., a blue shingle-patterned rug, a red hardwood floor-patterned rug).

3. *Types of Simulators*

In principle, an infinite number of simulators can be established in memory and can develop for all forms of knowledge, including objects, properties, settings, events, actions, introspections, and so forth. According to Barsalou (1999b, *in press*), a simulator develops for any component of experience that attention selects repeatedly. Thus, if attention focuses repeatedly on a type of object in experience, such as *face*, a simulator develops for it. Analogously, if attention focuses on a type of action (*kissing*) or a type of introspection (*happiness*), simulators develop to represent them as well. Such flexibility is consistent with Schyns, Goldstone, and Thibaut's (1998) argument that the cognitive system learns new features as they become relevant for higher categorization. Because selective attention is so flexible and open-ended, a simulator can develop for any component of experience selected repeatedly.

A key issue concerns which components of experience develop simulators and why attention focuses on them and not others. Many factors potentially influence this process, including genetics, language development, culture, and goal achievement. A complex set of factors determines where attention focuses consistently, such that simulators develop for those components of experience. A further account of these mechanisms lies beyond the scope of this chapter. Essentially this is the problem of what constrains knowledge (e.g., Goodman, 1972; Murphy & Medin, 1985), and any theory—not just an embodied one—must resolve it.

Another key issue concerns simulators for abstract concepts. Barsalou (1999b) proposed that these simulators generally construct complex multimodal simulations of temporally extended situations, with simulated introspective states being central. What distinguishes abstract from concrete concepts is that abstract concepts tend to contain more situational and introspective state information than concrete concepts (Wiemer-Hastings, Krug, & Xu, 2001). For example, one sense of *truth* refers to a speaker making a claim about a situation, followed by a listener representing the claim, comparing it to the actual situation, and deciding if the claim interprets the situation accurately (e.g., the claim that it is snowing outside). This sense of *truth* can be represented as a simulation of the temporally extended situation, including the relevant introspective states (e.g., representing, comparing, deciding). Many abstract social concepts, such as *love*, *cooperation*, and *aggression*, can similarly be viewed as complex simulations of social situations, with simulated introspective states being central.

C. SITUATED CONCEPTUALIZATIONS: MULTIMODAL SIMULATIONS OF SOCIAL SITUATIONS

Barsalou (2003) contrasted two ways of thinking about concepts. Nearly all theories view concepts as *detached databases*. As a category is experienced, its properties and/or exemplars are encoded and stored into a global database for the category, along the lines of an encyclopedia entry. As a result, a global description develops for a category that is relatively detached from the goals of specific agents.

Alternatively, a concept can be viewed as an *agent-dependent instruction manual*. According to this view, knowledge of a category is not a global description of its members. Instead a concept is more like an ability or skill that delivers specialized packages of inferences to guide an agent's interactions with specific category members in specific situations. Across situations, a concept delivers different packages of inferences, each tailored to current goals and constraints.

1. *Situated Conceptualizations*

Barsalou (2003) referred to a package of situation-specific inferences as a *situated conceptualization*. Consider the concept of *anger*. According to traditional views, *anger* is represented as a detached collection of amodal facts that become active as a whole every time the category is processed. Alternatively, a simulator for *anger* produces many different situated

conceptualizations, each tailored to helping an agent handle anger in a specific context—no global description of the category exists. For example, one situated conceptualization for *anger* might support interacting with an angry child, whereas others might support interacting with an angry spouse, an angry colleague, or one's own anger. On this view, the concept for *anger* is not a detached global description of the category. Instead the concept is the ability to produce a wide variety of situated conceptualizations that support goal achievement in specific contexts.

2. *Multimodal Simulations Implement Situated Conceptualizations*

Following Barsalou (2003), we assume that an integrated simulation becomes active across modalities to implement a situated conceptualization. Consider a situated conceptualization of *anger* for interacting with an angry child. One thing that this conceptualization must simulate is how the child might appear perceptually. When children are angry, their faces and bodies take particular forms, they execute certain actions, and they make distinctive sounds. All these perceptual aspects can be represented as modal simulations in knowledge about the situation. Rather than amodal descriptions representing these perceptions, simulations of them do.

A situated conceptualization about an angry child is also likely to represent actions that the agent could take in handling the situation, such as consoling and restraining. Modal simulations, too, can represent these actions. Knowledge of what an agent can do is represented by simulations of the actions themselves rather than as amodal redescriptions of them.

A situated conceptualization about an angry child is also likely to include introspective states of both the child and the parent. Because the parent knows what anger feels like, she can run simulations of her own anger to project what the child is feeling. The situated conceptualization for this situation might further include simulations of what the parent might be feeling, such as compassion, frustration, or annoyance. Again, modal simulations of these states represent knowledge of them in the situated conceptualization.

Finally, this situated conceptualization for *anger* in a child specifies a setting where the event is taking place—the event is not simulated in a vacuum. Thus the event might be simulated in a bedroom, classroom, toy store, etc. Again such knowledge is represented as simulations, this time as reenactments of particular settings.

According to Barsalou (2003), a situated conceptualization typically contains simulations of the four basic components just described: (1) people and objects, (2) agentive actions and other bodily states (embodiment!), (3)

introspective states, such as emotions and cognitive operations, and (4) settings. Putting it all together, a situated conceptualization is essentially a multimodal simulation of a multicomponent situation, with each modality-specific component being simulated in the respective brain area.

Furthermore, such simulations place the agent directly in them, creating the experience of “being there” (Barsalou, 2002, 2003). Because these simulations reenact agentive actions and introspective states, they create the experience of the conceptualizer being in the situation—the situation is not represented as something detached from the conceptualizer.

Finally, a given situated conceptualization typically consists of simulations from many different simulators. For example, a situated conceptualization for handling an angry child is likely to include simulations from simulators for people, objects, actions, introspections, and settings. Rather than a single simulator producing a situated conceptualization, many simulators contribute to the broad spectrum of components that a situated conceptualization contains.

3. Entrenched Situated Conceptualizations for Repeated Social Situations

For decades, social theorists have argued that entrenched situations play central roles in personality and social interaction (e.g., Andersen & Glassman, 1996; Sullivan, 1953). Over the course of life, people experience many social situations repeatedly, such as those involving significant others. As a result, knowledge of these situations becomes entrenched in memory, thereby supporting skilled performance. Entrenched knowledge can also guide interactions with novel people who are similar to known individuals in entrenched situations. Even though entrenched knowledge may not always provide a perfect fit, it may often fit well enough to provide useful inferences.

We assume that situated conceptualizations represent the entrenched knowledge in these theories. As a situation is experienced repeatedly, multimodal knowledge accrues in the respective simulators for the people, objects, actions, introspections, and settings experienced in it. The components of the conceptualization become entrenched in their respective simulators, as do the connections between these components. Eventually the situated conceptualization becomes so well established that it comes to mind automatically and immediately as a unit when the situation arises. After a parent frequently experiences an angry child, for example, the situated conceptualization for this situation becomes entrenched in memory, with minimal cuing bringing it all to mind on subsequent occasions. Thus an entrenched situated conceptualization can be viewed as a frequently associated configuration of modality-specific representations, distributed

across a diverse collection of simulators for people, objects, actions, introspections, and settings.⁷

Over time, a wide variety of situated conceptualizations becomes entrenched, reflecting the many social situations a person experiences frequently. Together this collection of situated conceptualizations constitutes a form of social expertise.

4. *Simulation as Meaning*

In the papers reviewed earlier, researchers often view embodiment as separate from social knowledge. Often researchers assume that bodily states are *associated* with traits and stereotypes rather than *constituting* their core conceptual content. Often researchers seem to assume that traits and stereotypes contain distilled amodal information that constitutes the core concepts, with embodiment being peripheral.

In contrast, we propose that multimodal simulations constitute the core knowledge of traits and stereotypes. Rather than amodal redescription of embodied states constituting traits and stereotypes, embodied states represent themselves in these constructs. Consider the trait of *slow movement* in the *elderly* stereotype. On the embodied view, *slow movement* is not represented by an amodal redescription, which in turn implements associated movements in the motor system. Instead knowledge of *slow movement* resides in simulations of seeing and executing slow movements—no further amodal descriptions exist or are necessary. Similarly, knowledge about *anger* resides in simulations of what anger looks like, how one acts, and how one feels introspectively. On this view, simulations of perception, action, and introspection directly constitute the conceptual content of social knowledge. Knowledge is not a redescription of these states in an amodal language, but is the ability to partially reenact them.

D. INFERENCE VIA PATTERN COMPLETION

Once situated conceptualizations become entrenched in memory, they play important roles in social processing. Of particular interest here is their support of social inference through pattern completion. As we will see, social inference via pattern completion plays the central role in our account of the social embodiment phenomena described earlier. This account can also be viewed as one way to implement priming, a ubiquitous phenomenon

⁷ As described later, we do not assume that just a single situated conceptualization represents a repeated situation. Instead we assume that an entrenched attractor in a dynamic system develops to produce related but different conceptualizations (Barsalou, in press). Thus the conceptualizations for interacting with an angry child are likely to be similar in many ways but also to be different, at least subtly.

in social cognition (e.g., Bargh & Pietromonaco, 1982; Devine, 1989; Higgins, Rholes, & Jones, 1977; Srull & Wyer, 1979).

1. Pattern Completion with Entrenched Situated Conceptualizations

Situated conceptualizations that become entrenched in memory support successful social interaction through pattern completion. On entering a familiar situation and recognizing it, an entrenched situated conceptualization that represents the situation becomes active. Typically not all of the situation is perceived initially. A relevant person, setting, or event may be perceived, which then suggests that a particular situation is about to play out. It is in the agent's interests to anticipate what will happen next so that optimal actions can be executed. The agent must draw social inferences that go beyond the information given (e.g., Griffin & Ross, 1991).

The situated conceptualization that becomes active constitutes a rich source of social inference. The conceptualization can be viewed as a pattern (i.e., as a complex configuration of multimodal components that represent the situation). Because part of this pattern matched the current situation initially, the larger pattern became active in memory. The remaining parts of the pattern—not yet observed in the situation—constitute inferences, namely educated guesses about what might occur next. Because the remaining parts cooccurred frequently with the perceived parts in previous situations, inferring the remaining parts from the perceived parts is reasonable. As a partially viewed situation activates a situated conceptualization, the conceptualization completes the pattern that the situation suggests.

To the extent that a situated conceptualization is entrenched in memory, pattern completion is likely to occur at least somewhat automatically. As a situation is experienced repeatedly, its simulated components and the associations linking them increase in potency. Thus when one component is perceived initially, these strong associations complete the pattern automatically.

Consider the example of seeing a friend. His face, clothing, and bodily mannerisms initially match modality-specific simulations in one or more situated conceptualizations that have become entrenched in memory. Once one of these wins the activation process, it provides inferences via pattern completion, such as actions that the friend is likely to take, actions that the perceiver typically takes, affective states that are likely to result, and so forth. The unfolding of such inferences—realized as simulations—produces social prediction.

2. Pattern Completion with Biologically Based Mechanisms

Thus far we have assumed that pattern completion proceeds largely through situated conceptualizations that have become entrenched through learning.

We further assume, however, that pattern completion can also occur with minimal learning via mechanisms that arise biologically. One modality-specific component of a situated conceptualization may activate another, even when they have not been associated through extensive learning.

Such inferences could arise in at least two ways. In some cases, perceptual information triggers emotional reactions and/or motor responses automatically—a releasing stimulus elicits a fixed action pattern. In humans, emotional states may follow from perceiving particular facial expressions, as may approach/avoidance behavior, sexual arousal, and so forth. On seeing an angry adult face, for example, biologically based circuitry may produce fear and retreat. Similarly, when an angry face is simulated in a situated conceptualization, it may trigger simulations of fear and retreat through the same mechanism. Although learning may play a role in establishing and strengthening these circuits (e.g., Elman, Bates, Johnson, Karmiloff-Smith, Parisi, & Plunkett, 1996), biologically based mechanisms appear to at least anticipate them. Most importantly for our purposes, the activation of a fixed action pattern to a releasing stimulus can be viewed as an inference. Given initial information, an organism infers a likely outcome and takes the appropriate action.

Another likely candidate for such inferencing is biologically based imitation. At birth, human infants imitate adults, suggesting that a nonlearned mechanism is responsible (Meltzoff, 2002). Much recent work in neuroscience suggests the mirror-neuron circuit as a likely candidate for this mechanism (Rizzolatti et al., 2002). As the visual system processes another person's action, the brain automatically simulates an analogous action in the perceiver's motor system. Such simulations, too, can be viewed as inferences, namely the brain perceives a person performing an action and infers what it would be like for the perceiver to perform it.

Both types of biologically based responses can be viewed as inferences via pattern completion. Certain social situations become so important over evolution that the brain evolves to represent them with minimal learning. For example, a releasing stimulus and its fixed action sequence form a larger pattern. When the releasing stimulus is perceived, the pattern completes itself by running the fixed-action sequence. Imitation can be viewed similarly. When an action is perceived, the pattern completes itself by running the action in the perceiver's motor system. In both cases, the patterns are multimodal, where one modal component triggers another via biologically based circuits. In both cases, responses can be viewed as inferences to perceived information via pattern completion.

3. *The Statistical Character of Representation and Inference*

We assume that everything about the production of inferences via pattern completion has a statistical character (e.g., Barsalou, 1987, 1989, 1993; Smith & Samuelson, 1997). A simulator is essentially a dynamical system capable of producing infinite simulations (Barsalou, in press). On a given occasion, the simulation constructed reflects the current state of the simulator, its current inputs, and its past history. An entrenched situated conceptualization is an attractor in this system, namely a state that is easy to settle on, because the associations representing it have become strong through frequent use. Furthermore, infinitely many states near the attractor offer different versions of the same conceptualization, each a different adaptation to the situation. Thus the entrenched conceptualization for interacting with an angry child is not a single simulation but rather the ability to produce many related simulations. Across different instances of the same situation, the situated conceptualizations that guide an agent vary dynamically, depending on all relevant factors that influence the system.

As a result, the inferences that arise via pattern completion vary as well. Because the conceptualizations that represent a situation vary across occasions, so do the completions that follow from them. In different instances of the same situation, somewhat different inferences may result from completing somewhat different patterns.

Finally, the individual inferences that arise from pattern completion vary statistically in strength. Whereas some inferences may appear highly likely, others may seem tentative. Many factors probably affect inferential strength, including how automatically an inference is produced, how connected it is to other information, and whether competing inferences exist. In this spirit, Dijksterhuis, Aarts, Bargh, and van Knippenberg (2000) showed that the strength of an embodied inference increases as it co-occurs more often with a social stimulus. Specifically, words about the elderly prime elderly behavior in young subjects when their contact with the elderly has been frequent but not when their contact has been infrequent.

4. *Simulation versus Execution of Inferences*

Thus far we have assumed that inferences are realized via simulation. When perception triggers a situated conceptualization, nonperceived components of the situation are simulated, thereby providing inferences about it. Seeing one's infant, for example, might activate a situated conceptualization that simulates cuddling, without any actual cuddling movements occurring. On many other occasions, however, once motor simulations become active, they may initiate actual actions. Thus the simulation of cuddling one's infant

might eventually trigger actual cuddling. In these cases, the motor inferences that arise during pattern completion eventually become realized as behaviors.

The literature on motor imagery demonstrates that the distinction between motor imagery and motor behavior is far from discrete. When people imagine simple actions, such as finger tapping, not only does the motor cortex become active, so do spinal neurons and the peripheral musculature (e.g., Jeannerod, 1995, 1997). When expert marksmen imagine shooting a gun, their heart rate and breathing fluctuate as if they were actually shooting one (Deschaumes-Molinario et al., 1992). As such findings illustrate, simulated movements are close to being realized as actual movements, thereby readying agents for action.

Thus when the pattern completion process provides motor inferences, it may realize them in a variety of ways. On some occasions, actions may only be simulated. On others, actions may be simulated with only traces appearing in behavior—not full-blown execution. On still other occasions, simulations may trigger full execution of the respective actions. As the literature on the motor system illustrates, a complex set of mechanisms represents, gates, executes, and monitors action at multiple levels. As a result, action takes many forms, both in representation and in execution. We assume that all these different realizations constitute possible inferences via the pattern completion process.

IV. Explaining Social Embodiment Effects

The theory of social embodiment just presented explains and unifies the four social embodiment effects presented earlier. After applying the theory to each effect, we address two further issues that arise in doing so.

A. SOCIAL STIMULI ELICIT EMBODIED RESPONSES IN THE SELF

Earlier we saw that social stimuli produce embodied responses. For example, hearing an examination grade affects posture; thinking about the elderly induces slow movement; being reminded of a liked significant other produces positive facial expressions; thinking about rudeness increases the willingness to interrupt; and thinking about politicians increases long windedness.

All of these effects can be explained as pattern completion across the modality-specific components of a situated conceptualization. In each case, a situated conceptualization that has become entrenched in memory mediates the effect. When part of the situated conceptualization is perceived, the larger pattern becomes active, with its nonperceived components constituting inferences in their respective modality-specific systems. In

all cases for the first embodiment effect, one of these inferences is a bodily state. In many cases, these inferences may arise automatically, as the result of strong links between the conceptualization's modality-specific components.

For example, receiving a low grade activates a situated conceptualization associated with poor school performance. For some people, this situation may have been experienced directly on many occasions. For others, it may have been experienced vicariously when others performed poorly. A variety of modality-specific components may reside in this situated conceptualization, such as feeling ashamed and slumping. In some cases, the links between modality-specific components may be learned, such as coming to believe that a low grade is undesirable. In other cases, the links may have a biological basis, such as performing poorly and feeling ashamed and also feeling ashamed and slumping. Regardless, because all of these modality-specific components are experienced together frequently in this repeated situation, they become increasingly associated through learning, such that an entrenched conceptualization of the situation develops. Later this entrenched pattern produces inferences via pattern completion. Once part of the situation is experienced, such as a low grade, the conceptualization becomes active, which then produces modal inferences, including a slumped posture.

All of the other cases for the first embodied effect can be explained similarly. In each case, a social stimulus triggers an entrenched situated conceptualization, which then produces inferences via pattern completion. What makes this particular set of studies interesting is that some of these inferences are embodied states. Rather than being represented as amodal descriptions, these inferences are represented as states in the motor system.

B. EMBODIMENT IN OTHERS ELICITS EMBODIED MIMICRY IN THE SELF

Earlier we saw that people mimic the embodied states that they perceive in others, including their postures, facial expressions, and communicative manners. One likely mechanism responsible for mimicry is the mirror neuron circuit (e.g., Rizzolatti et al., 2002). Independent of learning, this circuit may induce mimicked actions. We hasten to add, however, that this circuit is likely to operate in the context of situated conceptualizations.

Consider the mimicry of wincing. Narrowly speaking, seeing someone wince may simply reproduce wincing in the self. More broadly, however, wincing belongs to situated conceptualizations that represent larger situations. For example, wincing may belong to situations where an entity or event physically causes pain in an agent, who then attempts to withdraw. On seeing

someone else wince, activation of this situated conceptualization may induce empathy for “feeling the other person’s pain.” It may further induce cooperation in helping remove the source of the pain. For example, seeing a child wince from a splinter might not only induce wincing in a parent, but also induce empathy and the goal of removing the splinter.

In principle, just the perception of wincing may be sufficient to trigger this situated conceptualization. Mimicry of the wincing, however, may provide an even stronger cue for triggering it. Two triggers (perception plus mimicked movement) are better than one (perception alone). Furthermore, embodied cues may be more potent than perceptual ones. Actual wincing may be more likely to activate relevant situated conceptualizations than simply perceiving it.

The point is that mimicry may typically not be an end in itself, at least in complex social situations. Instead mimicry may typically play the role of helping retrieve situated conceptualizations that are useful for processing the current situation effectively.

Another effect of mimicry is to induce social contagion, a point central in many reviews (e.g., Dijksterhuis & Bargh, 2001; Hatfield et al., 1992; Neumann & Strack, 2000; Semin, 2000). If different people learn similar conceptualizations for the same situation, then when two people share an embodied state, they are likely to activate the same conceptualization, thereby achieving synchrony, coordination, and empathy. Imagine that two people have similar situated conceptualizations that include yawning. Further imagine that this conceptualization becomes active in one person and induces yawning in the other via mimicry. Once yawning is induced in both people, it may induce a similar conceptualization, such that they perceive the situation similarly and coordinate their emotions and activities.⁸

C. EMBODIMENT IN THE SELF ELICITS AFFECTIVE PROCESSING

Earlier we saw that embodied states induce affective responses. For example, upright posture induces pride and confidence, whereas slumped posture induces shame and uncertainty. Head nods, arm pulls, and the

⁸ Clearly emotional and behavioral mimicry do not always arise between two individuals, as when one feels angry and the other guilty. In some such cases, biologically based mechanisms may produce complementary states in two individuals, as when a hunter experiences aggressiveness and a prey experiences fear. In other cases, entrenched situated conceptualizations may be responsible, as when a parent models calmness for a child who shows fear at an insignificant threat. An interesting question is whether mimicry mechanisms nevertheless become active automatically in these situations and are then overridden by other more powerful mechanisms that produce complementary states.

smiling musculature induce positive affect, whereas head shakes, arm pushes, and the frown musculature induce negative affect.

Again, all of these effects can be explained as pattern completion across the modality-specific representations of a situated conceptualization. In all of these cases, an embodied state activates a situated conceptualization that includes an affective state. For each effect, the affective state is an inference to an embodied cue. On the one hand, bodily states such as upright posture, arm pulls, head nods, and smiling activate situated conceptualizations associated with positive affect. On the other hand, bodily states such as slumping, arm pushes, head shakes, and frowning activate situated conceptualizations associated with negative affect. Whatever entities and events happen to be present when one of these situated conceptualizations becomes active then acquires the affect associated with it. Again the underlying mechanism is pattern completion via a situated conceptualization.

What makes the third embodiment effect different from the first two is simply the direction of pattern completion. In the first two effects, social stimuli produce embodied states. In the third effect, embodied states produce affective responses.

D. THE COMPATIBILITY OF EMBODIMENT AND COGNITION MODULATES PERFORMANCE EFFECTIVENESS

Earlier we saw that performance is optimal when embodiment and cognition are compatible. Motor movements are faster when they are compatible with affective states. Memory is optimal when movements are compatible with the affective valence of remembered material. Face processing is optimal when the perceiver's expression matches the perceived expression on a face. In general, greater capacity is available for secondary tasks when embodiment and cognition are compatible.

Several factors may underlie these effects. In some cases, redundancy may strengthen a motor response. Consider the task of pulling versus pushing a lever to indicate whether a word is valenced positively or negatively. In this task, perceiving a word triggers a situated conceptualization for its meaning that includes a simulated motor response. On seeing a positive word, for example, a situated conceptualization becomes active for its meaning, which includes bodily motions associated with positive affect. When the response is a similar motion, its redundancy with the simulated action speeds actual movement. Conversely, when the two mismatch, the motor system must simulate one movement while executing a different one, with the resulting movement being less efficient.

Another benefit of compatible embodiment may be redundant cues for retrieval. In face processing, visual cues alone can be used to identify the

emotion expressed. If, however, the visual cues induce the same emotion on the perceiver's face, these embodied cues may help the visual ones activate the correct categorization. Again the embodied cues may be even stronger than the visual ones.

Finally, when embodiment and cognition are redundant, greater processing resources may be available for processing each individually. Consider the encoding of words while performing an action. On seeing a word, a situated conceptualization for its meaning becomes active that includes simulated movements. When these simulated movements are consistent with an action being performed, a common motor process can contribute to both. Conversely, when a situated conceptualization becomes active whose simulated action is incompatible with a current action, the supervisory attentional system must manage two competing actions. As a result, fewer resources are available for performing each individual task. If the cognitive task is learning words for a later memory test, fewer resources are available for encoding the words into memory.

In general, because higher cognition utilizes the motor system for simulating conceptual knowledge, cognition and action function optimally when they perform common motor activities. When they perform different activities, performance suffers, analogous to previous findings that working memory and response mode suffer when their representations compete for common modality-specific resources (e.g., Brooks, 1968; Segal & Fusella, 1970).

E. DIRECT VERSUS INDIRECT EMBODIMENT EFFECTS

In the social literatures, theorists have discussed whether embodiment affects cognition directly or indirectly. For example, unconsciously adopting the facial musculature for a smile could directly produce positive evaluation of an object, such as a pen. Alternatively, adopting this facial musculature could activate an emotional state, such as happiness, which in turn produces positive evaluation. In this latter case, the effect of embodiment on evaluation is indirect, mediated by emotion.

Within the framework presented here, this is not a major issue. Indeed we would predict that both direct and indirect effects of embodiment should occur ubiquitously (which appears consistent with conclusions in the literature; e.g., Wheeler & Petty, 2000). There are at least two reasons why embodiment effects should sometimes be direct. First, automaticity is often defined as the withdrawal of mediating states between a stimulus and a response (e.g., Logan, 1988; Schneider & Shiffrin, 1977). The more a stimulus is consistently mapped to a response, the less necessary mediating states are for making the mapping. Instead the mapping can be made

directly. Second, neuroscientists frequently note that the brain does not consist of a rigid set of linearly organized modules. To the contrary, pathways tend to link brain systems in a nonlinear, nonhierarchical manner. Many long-distance connections exist directly between brain systems that are not adjacent. Such an architecture is consistent with the view that the motor system is linked directly to many other brain systems, without mediating systems residing between them. From an evolutionary perspective, direct links would be advantageous for speeding actions related to survival and reproduction. Not surprisingly, evidence for direct links in social situations exists (e.g., Kawakami, Young, & Dovidio, 2001).

However, mediating structures may often link embodiment and cognition. In particular, pattern completion via situated conceptualizations offers a natural mediating mechanism. For example, bodily movements associated with positive emotion (e.g., upright posture, smiling, arm pulls) may activate situated conceptualizations that include positive affect. In turn, these affective states may become vicariously associated with neutral objects in the environment, such as a pen, thereby making these objects attractive.

Clearly it is important to identify the specific processing sequence that produces a particular embodiment effect. Sometimes these effects may be direct, and sometimes they may be indirect. To our minds, the more important finding is that embodiment plays a ubiquitous role in cognitive processing, both directly and indirectly. Even in indirect cases, embodied representations in situated conceptualizations are central to reasoning and behavior.

F. AMODAL ACCOUNTS OF EMBODIMENT EFFECTS

Some readers have undoubtedly been thinking throughout this chapter that classic amodal theories of representation can explain all of these embodiment effects. Technically they are right. Increasingly, however, their position faces challenges (e.g., Barsalou, 1999b; Glenberg, 1997; Lakoff, 1987; Newton, 1996).

One problem is that amodal theories can explain embodiment results because, in principle, they can explain anything. As theorists have noted, amodal theories have Turing machine power, which means that they can mimic any systematic pattern of results (e.g., Anderson, 1978; Pylyshyn, 1981). This power, however, comes at the cost of unfalsifiability. Because these theories can explain anything, it is impossible for any result to disconfirm them. Put in this light, the ability to explain embodiment effects is not particularly impressive. Amodal theories do not just explain embodiment effects, they explain all sorts of effects that may never occur.

When a theory is unfalsifiable, it can gain credence if it predicts crucial findings *a priori*. Thus we could ask whether amodal theories naturally

predict embodiment effects. To our knowledge, they do not. Researchers did not derive predictions for embodiment effects from amodal theories and then set out to test them. Furthermore, embodiment effects do not follow naturally from amodal theories for two reasons. First, these theories assume that knowledge and modality-specific systems are separate. Second, they tend to view knowledge as abstracting over modality-specific details. For these reasons, embodiment effects strike us, at least, as violating the *a priori* spirit of classic amodal theories.

Another problem for amodal theories is that, so far, little if any direct empirical evidence exists for amodal symbols in the brain. Instead researchers have adopted amodal representation languages for theoretical reasons (Barsalou, 1999b). Clearly, though, one would expect such an important theoretical assumption to have direct empirical support. The gaping lack of direct empirical evidence for amodal symbols suggests that something is amiss.

Perhaps powerful amodal accounts of embodiment effects will develop. Perhaps they will make striking predictions confirmed by the data. Perhaps direct evidence for amodal symbols will be found in the brain. Perhaps both modal and amodal symbols will be part of the theoretical story (Simmons & Barsalou, 2003b).

In the meantime, embodied theories naturally predict and explain these findings. Embodied theories not only anticipate the behavioral findings reported in this chapter *a priori*, they also anticipate large bodies of related neural evidence (e.g., Martin, 2001; Simmons & Barsalou, 2003b). In our opinion, embodied theories constitute a natural and motivated account of these findings. Furthermore, an increasingly strong empirical case can be made for modality-specific symbols in the cognitive system (e.g., Barsalou, 2003). Finally, embodied theories have inspired a considerable amount of research in recent years that probably would not have been conceived within the amodal framework (for reviews, see Barsalou, 2003; Glenberg, 1997; Martin, 2001; Richardson & Spivey, 2002).

V. Conclusion

Now that you have reached this point in the chapter, please relax in your chair, release your palm from pressing up on the table top, and remove the pen from your teeth. Hopefully, the desired effect has been achieved, namely for the first time in your career, you agree with every point stated in an article.

Social embodiment effects can be explained and unified with a few basic assumptions. First, the body is involved extensively in human activity. For

this reason alone, it should not be surprising that bodily states have a central presence in human knowledge.

Second, people develop entrenched knowledge about frequently experienced situations—what we referred to as *situated conceptualizations*. Furthermore, this knowledge is likely to be represented as modality-specific simulations of situational components for the relevant people, objects, actions, introspections, and settings.

Third, when one of these components activates a situated conceptualization, inferences about the situation arise via pattern completion, with unperceived components simulated or executed as inferences. Embodied states can function as cues that trigger situated conceptualizations, or they can be the inferences that result from other components triggering conceptualizations.

Fourth, when current embodied states match those in the current conceptualization, processing is optimal. Embodied states facilitate processing via redundant states, multiple cues, and more available resources for individual tasks. Conversely, when embodied states are inconsistent with the current conceptualization, these benefits do not result.

Rather than being peripheral appendages to social cognition, embodied states appear central. As we have also seen briefly, embodied states are central to nonsocial cognition. We assume that our account of social embodiment provides an analogous account of nonsocial embodiment effects, with pattern completion via situated conceptualizations again providing the basic mechanism. In general, adopting an embodied view changes one's theorizing considerably and inspires empirical studies that would not otherwise be conceived. Given the fundamental importance of action for effective intelligence, it should not be surprising that embodiment is central to cognition in both social and nonsocial domains.

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THE BODY'S CONTRIBUTION TO LANGUAGE

Arthur M. Glenberg and Michael P. Kaschak

I. Introduction

Traditional approaches to understanding language are framed in terms of abstract principles (e.g., rules of syntax), abstract categories (e.g., nouns and verbs), and abstract amodal and arbitrary representational units (e.g., nodes in semantic memory). Emphasizing the abstract facilitates the formalization and simulation of psycholinguistic theories, but leaves little room for biology. This is at odds with the facts that language behaviors depend on a functioning body for the perception of speech and orthographic symbols, the production and comprehension of gestures, and other linguistic activities. Additionally, language often serves to guide real physical action in the world, and the link between amodal and arbitrary symbols and action is problematic at best (Haugeland, 1998). This chapter presents an alternative account of language that is grounded in the functioning of perceptual and action systems as opposed to abstract computational systems.

We begin with a discussion of the symbol grounding problem, which illustrates the need to consider how symbols contact experience. This discussion motivates presentation of the action–sentence compatibility effect (ACE). The ACE demonstrates that the mere understanding of a sentence can interfere with making simple actions. Following presentation of the ACE, we review the indexical hypothesis (IH) as a theoretical account of the relation between language and perception and action systems. The IH makes several strong claims about the nature of memory representations

that contribute to language. First, the representations are modal (i.e., related to the modality through which they were learned) and analogical rather than arbitrarily related to perceptual states. Second, we propose (after recent work in linguistics; Goldberg, 1995) that knowledge of sentence patterns called *constructions* plays an important role in shaping the combination of the perceptual knowledge accessed during language comprehension. In our discussion, we draw on evidence from language acquisition and processing in both children and adults to support our claims. We conclude with a discussion of the role of learning in embodied theories of language comprehension.

II. Symbol Grounding and the Action–Sentence Compatibility Effect

A. SYMBOL GROUNDING AND MEANING

How is it that the words we speak and read can mean anything? At first, this might seem like a bizarre question because if anything has meaning it would seem to be language. However, consider Harnad's version of Searle's (1980) Chinese room argument, which is meant to demonstrate that language by itself cannot generate meaning. Harnad asks us to consider arriving in a country whose language we do not speak (China, perhaps). We have at our disposal a Chinese dictionary (not a Chinese–English dictionary—just the Chinese equivalent of Merriam Webster's). Upon arriving, we see what appears to be a sign written with logograms and attempt to understand the sign. Although we do not know the meaning of any of the logograms, we do have the dictionary, and so we look up the definition of the first logogram. Its meaning is given as a sequence of more logograms. To get to the meaning of the first logogram in the definition, we look it up in the dictionary, but its definition is written in more meaningless (to us) logograms. Obviously, no matter how many logograms we look up, we will never come to know what that sign means. The point of this thought experiment is that conjunctions of symbols cannot by themselves generate meaning. Instead, the symbols must be grounded in something else that can provide meaning. Whereas the need for grounding seems obvious in the context of this thought experiment, grounding is exactly what most standard theories of cognition are missing.

Consider, for example, a semantic network, such as the Collins and Loftus (1975) theory. In this theory, each node is connected to many other nodes, and each node is defined solely in terms of its relations to other nodes. However, just as looking up logograms in the Chinese dictionary cannot result in any meaning, tracing out the connections between

undefined nodes cannot result in any meaning. It is not just semantic networks that suffer from failure to ground its symbols. The same is true for propositional representations of language (each proposition is like a small semantic network; cf. Kintsch, 1988), for connectionist models (each processing unit in a connectionist network is connected to many other ungrounded units; Masson, 1995), and high-dimensional models such as HAL (Burgess & Lund, 1997) and LSA (Landauer & Dumais, 1997) in which words are defined solely by their patterns of co-occurrences with other words. For all of these types of theories, there is little concern for how the symbols might be grounded, and in the rare instances when grounding is considered (e.g., Landauer & Dumais, 1997), the way in which the symbols are grounded plays no functional role in the operation of the theory of meaning.

Note that the problem is not solved by asserting that the symbols in standard theories are somehow connected to perceptual states that ground them. The symbols in these theories are *by intention* amodal (i.e., all perceptual content has been stripped away) and arbitrarily related to the perceptual states generated by their referents (e.g., the semantic memory node for “bird” no more resembles a bird than it does anything else). These two properties are essential in standard theories for two related reasons. The first reason is a central claim of cognitivism: All thinking is the rule-like manipulation of symbols, and thus thinking is the same process in biological systems and artificial systems (Newell, 1980). The second reason is to ensure that simulations on computers capture all important features of the theory. That is, if an important property of representations were perceptual states, then thinking could not be simulated on computers because computers cannot have perceptual states, only descriptions of those states using arbitrary symbols. Because standard cognitive theories use amodal and arbitrary symbols, an important fact follows: New thoughts generated by manipulating the symbols (e.g., being told that a zebra looks like a horse with stripes) cannot be matched to perceptual states produced by the referent, exactly because the symbols are arbitrarily related to the perceptual states of the referents. More generally, Putnam [(1981) and as reviewed in Lakoff (1987)] has proven that there is no way to guarantee that sets of amodal and arbitrary symbols can be mapped onto the correct referent. Consequently, if people thought in terms of amodal and arbitrary symbols, there would be no guarantee that those thoughts could ever correspond to reality. The problem is analogous to solving sets of equations in mathematics. The equations consist of amodal and abstract symbols that are manipulated by rules (e.g., the rules of algebra). However, the same set of equations can equally well describe amazingly diverse phenomena (e.g., a tractor plowing a field, blood flowing through veins, a satellite traveling in

space), and there is no way to guarantee that the equations are about one of those phenomena and not another.

Instead of using amodal and arbitrary symbols that are inherently impossible to ground, another approach to cognition is to use symbols grounded in experience, that is, grounded in the way that the body perceives and acts in the world (Lakoff, 1987; Newton, 1996). On this view, a word or phrase means something because it corresponds analogically to some component of experience. As one example, Lakoff (1987) discusses an experience-based view of the concept of "container." He proposed that a consistent structured experience, such as the experiences of manipulating various containers, gives rise to a structured image schema. That schema incorporates aspects of experience such as that a container has an inside, a boundary, and an outside. Furthermore, the schema incorporates constraints on the container and how it interacts with other objects. For example, an object can be inside the container or outside, but not both. According to Lakoff, image schemas provide the grounding for the notions of container and containment, as well as for linguistic terms such as "in" and "out." Furthermore, image schemas are used to ground abstract concepts through metaphorical extension. Thus, "p or not-p, but not both" is grounded by extension of "inside the container or outside, but not both."

Another example of grounding conceptual knowledge in experience is the perceptual symbol (which will be incorporated into the indexical hypothesis as described later). According to Barsalou (1999), perceptual symbols are based on the brain states that result from perceiving objects. They are not complete images because only those parts of the objects to which attention has been devoted contribute to the perceptual symbol. Although perceptual symbols are abstract in the sense that many specific objects may correspond to a particular perceptual symbol, these symbols are modal and analogical, not arbitrary. Finally, perceptual symbols can enter into simulations (e.g., of a horse with stripes), and knowledge, or expertise, corresponds to skill in forming these simulations. Because perceptual symbols are analogically (not arbitrarily) related to what they represent, the symbols can be compared to perceptual states. Thus, thoughts about what a horse with stripes might look like can be compared to the perceptual states arising from seeing a zebra, and one can say, "Yes, that is what I was thinking about," or "No, I had the stripes going horizontally."

Glenberg (1997, Glenberg & Kaschak, 2002; see also Newton, 1996) offered a third, albeit related, way to ground language. He suggested that language is grounded in human action. That is, the meaning of an utterance corresponds to the actions being described or, more generally, how the utterance changes the possibility for action. Thus, a description of an object

(“it has a handle on the top”) changes how we are prepared to interact with that object. Likewise, the description of a situation (“that is the chair that Joe is sitting in”) changes how we act within that situation (by sitting elsewhere). Uttering various speech acts, such as promises (“I will send the check tomorrow”), changes the way we will act in the future.

The major purpose of this chapter is to demonstrate that embodied accounts of meaning (i.e., accounts that ground meaning and language in bodily experience) have wide applicability, empirical support, and provide a more compelling account of language and meaning than standard amodal, arbitrary symbol accounts. However, before developing any of these claims in detail, we present evidence that the meaning of sentences is closely connected to action.

B. THE ACTION–SENTENCE COMPATIBILITY EFFECT

At first blush, it would seem that language has little to do with action: I speak; you listen and understand. However, it is also the case that an important (if not primary) function of language is to modify overt behavior. For example, we use language both to coordinate activity (e.g., “lift on the count of three...”) and to guide individual action (e.g., when following written instructions). There are two hypotheses as to how language might guide action.

Hypothesis A: Language is understood using a system of amodal symbols, but then is translated into a response code for guiding action. Hypothesis B: Language is understood directly in terms of action.

If hypothesis B is correct, we might suppose that the same neural systems used to plan and guide action are also used to comprehend language. In this case, hypothesis B predicts that the mere understanding of a sentence should facilitate (or interfere with) congruent (or incongruent) action, and similarly, physical action could facilitate or interfere with understanding. This is the action–sentence compatibility effect.

Glenberg and Kaschak (2002) produced evidence for the ACE in a sentence comprehension experiment. Participants in the experiment judged if written sentences were sensible (e.g., “Open the drawer”) or nonsense (e.g., “Open the plate”). The sensible sentences varied on two dimensions (although this was not revealed explicitly to the participants). First, half of the sensible sentences, the toward sentences, implied action toward the reader (e.g., “Open the drawer”); the other half, the away sentences, implied action away from the reader (e.g., “Close the drawer”). Second, sentences were of three types: imperatives (as with the previous examples), concrete

transfer sentences that described a concrete object being transferred between people (e.g., “Andy handed you the pizza / You handed Andy the pizza”), and abstract transfer sentences that described the transfer of information or ownership (e.g., “Liz told you the story / You told Liz the story”).

There was one additional independent variable that allowed us to demonstrate the ACE: the manner in which participants indicated that a sentence was sensible or not. To view the sentence on the computer screen, the participant pushed the middle button on a three-button box held in the lap. The box was positioned so that the buttons were oriented along the midline of the body extending away from the participant. The sentence stayed visible only while the middle button was depressed. In the yes-is-near condition, the participant indicated that the sentence was sensible by moving her hand from the middle button to the near button (i.e., by moving toward her body). The participant indicated that the sentence was nonsense by moving her hand from the middle button to the far button. In the yes-is-far condition, the response assignments were reversed. That is, the participant indicated that a sentence was sensible by moving to a response button away from her body.

Consider the predictions if sentence understanding and action require the same neural systems (hypothesis B). Understanding an away sentence requires consideration of the actions, and those actions consist of moving away from the body. However, in the yes-is-near condition, taking the action of indicating that the sentence is sensible requires moving toward the body. Consequently, the action system is engaged in consideration of incompatible actions, which should slow processing. Similarly, the mere understanding of a toward sentence should interfere with making the response in the yes-is-far condition. In fact, the data (Fig. 1) show just this interaction.

The interactions seen in Fig. 1 are very close to what is predicted if sentence understanding makes use of an action system. In addition, evidence from the abstract transfer sentences speaks against hypothesis A that action plays a role only after the sentences are comprehended. Consider what this hypothesis predicts for a sentence such as “You told Liz the story.” After understanding the sentence, the experimental participant prepares to execute action, which in this case is moving her mouth and articulators. There is nothing in hypothesis A that suggests that moving articulators should interfere with the yes-is-near response, as seen in Fig. 1. Instead, understanding of abstract transfer, much like the understanding of concrete transfer, is based on conceptualizing transfer as movement from one individual to another. Details of how this happens are presented in the next section. [See Haugeland (1998) for a logical argument against hypothesis A based on the difficulty of creating an interface between an arbitrary symbol and real action.]

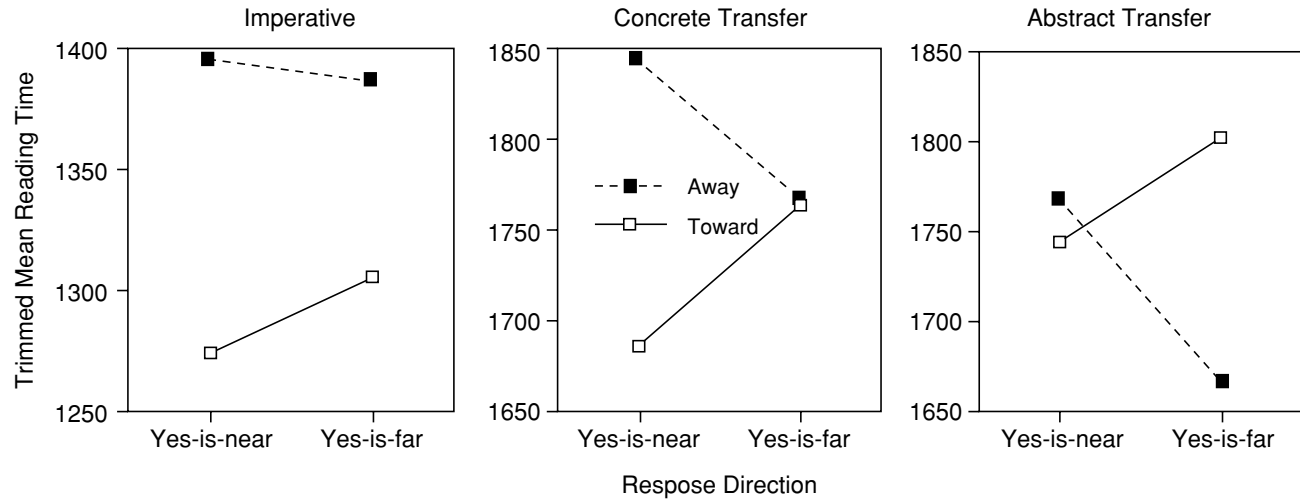


Fig. 1. The ACE. For each type of sentence, imperative, concrete transfer, and abstract transfer, participants indicated if the sentence was sensible. Reaction time was affected by the implied direction of the actions in the sentence (away and toward) and the actual direction needed to make a response (yes-is-near or yes-is far).

III. How Language Becomes Embodied Meaning

A. THE INDEXICAL HYPOTHESIS

The indexical hypothesis (Glenberg & Robertson, 1999, 2000; Kaschak & Glenberg, 2000) describes how the symbols of language become grounded in a perception- and action-based code. The IH stems from an account of meaning developed by Glenberg (1997). Consider the following claim about what it means for a situation to be meaningful.

The meaning of a situation to an individual consists of a set of potential actions available to that individual in that situation. The set of actions is determined by the goal-directed mesh of affordances.

Note that the definition regards meaning as what matters to an individual. This individual construal of meaning is in contrast to objectivist accounts (for a discussion of objectivist accounts, see Lakoff 1987; Lakoff & Johnson, 1980), which assert that situations and sentences have objectively correct meanings independent of individuals.

The claim specifies that meaning arises from affordances, a term borrowed from Gibson (1979). This term refers to an interactive quality, namely how an individual with a particular sort of body can interact with an object that has particular physical characteristics. For example, a chair affords sitting for an adult human, but not for a newborn, a fish, or an elephant. In fact, it is because an object affords sitting that makes it a chair, not that its representation has some listing of features. Consequently, kitchen chairs, balans chairs, beanbag chairs, bar stools, and so on can all be considered chairs when they have nothing in common except for the fact that they support the human body in a sitting position. However, chairs also afford many other actions for adults: standing on, lifting to ward off an attacking dog, and so on. Thus, for an adult, a chair can be a means of defense, but it cannot serve this function for an infant. In contrast, for a small child (or a mouse), a chair can afford hiding, but it cannot do so for an adult. Hence the meaning of chair to an individual—what that person can do with the chair—is a function of how the individual's body can interact with the chair (i.e., the chair's affordances).

The definition of meaning further specifies that the set of actions that determine meaning requires the goal-directed mesh of affordances. Mesh is a combinatorial process meant to be distinctly different from association formation. In standard cognitive theories, an association is a relation between two concepts (or nodes). Associations build up on the basis of frequency and recency, but otherwise, there are few constraints on what can be associated. Thus, for unrelated concepts, one could associate two arbitrarily selected

concepts just as easily as any other arbitrarily selected concepts. In contrast, affordances mesh when actions can be combined smoothly to accomplish a goal. For example, an affordance of a chair, that one can stand on it, can be combined smoothly with an affordance of a light bulb, that it can be grasped, to accomplish the goal of changing the bulb in a ceiling fixture.

In summary, according to the action-based definition, the meaning of a situation to an individual arises from that individual's consideration of what goals can be accomplished in that situation, and what can be accomplished depends intimately on the individual's body.

As noted in the discussion of symbol grounding, words and sentences are arbitrary symbols that need to be grounded to be meaningful. The indexical hypothesis describes three processes that are used to ground words and sentences in affordance-based meanings: (1) words are *indexed* to analogical perceptual symbols, (2) *affordances* are derived from these representations, and (3) the affordances are combined into patterns of action as directed by the syntax of the sentence. We illustrate these processes with an analysis of the sentence, "Andy handed you the pizza." The first process is to index words and phrases to objects in the environment or to perceptual symbols (Barsalou, 1999). In many situations, the relevant objects and perceptual symbols are already specified by prior utterances and interactions (for a discussion of common ground, see Clark, 1996) and so indexing can proceed smoothly. Research by Tanenhaus and colleagues (e.g., Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995; Chambers, Tanenhaus, Eberhard, Filip, & Carlson 2002) demonstrates that indexing words to common ground objects is extremely quick and can be accomplished even before the name of the object is completely uttered.

When the objects are not perceptually available, listeners and readers will use the linguistic information to retrieve perceptual symbols corresponding to phrases such as "Andy" and "the pizza." Clearly, an individual's experience with the relevant entities will play an important role. Thus, many people will index "Andy" to a male human, but some will index "Andy" to a female, and one can imagine that if someone has a pet fish named "Andy," then the perceptual symbol of the fish will be retrieved when "Andy" is read. Similarly, the verb "handed" is indexed to experiences of handing.

The second process described by the IH is the derivation of affordances from the perceptual symbols, not the words. Derivation of affordances is not algorithmic, instead it is guided by several types of information: previous experience with objects (i.e., simulation competence), the other perceptual symbols already indexed (e.g., the actions underlying "handing"), the syntax of the sentence (as described shortly), and the particulars of the situation. Consider two important findings of Chambers et al. (2002). Participants followed oral instructions such as "Put the book inside the box." On hearing

the word “inside,” participants restricted their eye movements to objects in the array that were container-like. That is, “inside” quickly specifies the sort of affordances the locative term must have. In addition, eye movements were further restricted by affordances of the objects in the particular situation. That is, if the array of objects included several containers, but only one of them was large enough to hold the book, then the eyes were restricted to that object early in processing.

The third process described by the IH is to mesh the affordances as guided by syntax. Given the tremendous variety of affordances that can be derived from perceptual symbols such as those for “Andy” and “pizza,” how does a comprehender know what to do with them? One solution is provided by an approach to grammar called construction grammar [e.g., Goldberg (1995) and described more fully later]. One type of construction, so-called verb–argument construction, is the pairing of a sentence form with a particular meaning (see Table I). For example, the transitive form, noun–verb–object, as in “Andy hit/threw/ate the pizza,” is paired with the meaning “subject noun acts on the object.” That is, it is a claim of construction grammarians that part of the meaning of a sentence arises from knowing the meaning of the construction, not just from knowing the meanings of the words.

As another example, consider the caused motion construction, “noun–verb–object–oblique,” as in “Pat sneezed the foam off the cappuccino” (example from Goldberg). Here the form is paired with the meaning “subject noun causes object to move to oblique.” What is amazing about the cappuccino example is that everyone understands the sentence easily even though (a) “to sneeze” is an intransitive verb that, according to most grammars, cannot take an object, such as “foam” (note the difficulty with “Pat sneezed the foam”), and (b) certainly no dictionary would give as a definition of “to sneeze” that it is a means to move something. Given (a) and (b), how do we understand the sentence? Goldberg argues (and we review data later supporting that argument) that the “move to oblique” meaning comes from the construction, not the words.

A third verb–argument construction is the double-object construction, noun–verb–object1–object2 (e.g., “Andy handed you the pizza”). This form is paired with the meaning, “subject noun transfers object2 to object1,” as in “Andy gave/handed/threw/tossed you the pizza.”

How might constructional knowledge guide the mesh of affordances? There are at least two answers to this question. First, constructional knowledge can help determine which affordances are derived. Kaschak and Glenberg (2000) demonstrated that people derive different affordances in order to understand different types of transfer even with the same objects. Second, constructional knowledge provides the goal that determines which affordances mesh and how they mesh. Thus, to accomplish transfer (the goal

specified by a double-object construction), Andy must have hands in order to “hand the pizza” and those hands must be large enough, strong enough, and flexible enough to grip a pizza without affecting it adversely. Similarly, the pizza must have the right properties to be handed (i.e., it cannot be too large or too hot). Finally, Andy must take appropriate action so that the pizza is transferred to the recipient. If a comprehender is unable to derive affordances that can be combined to simulate that transfer, then that comprehender will judge the sentence as nonsensical, as would happen if a comprehender indexed “Andy” to a pet fish (cf. Glenberg & Robertson, 2000).

B. THE INDEXICAL HYPOTHESIS: SIX MISCONCEPTIONS

This section discusses six misconceptions about the indexical hypothesis. First, although we have described three steps in language comprehension, we do not mean to imply that the steps are completely dissociable or strictly ordered. For example, constructional knowledge (step 3) is used to guide the derivation of affordances (step 2). Similarly, as Chambers et al. (2002) demonstrated, indexing of noun phrases (e.g., “the box”) can be guided by the previous interpretation of prepositions such as “inside.”

Second, whereas many of our examples are easily imageable, we do not mean to imply that perceptual symbols are equivalent to visual images. As Barsalou (1999) noted, perceptual symbols are traces of neural activity and are multimodal. Gibbs and Colston (1995) discussed how perceptual representations such as Lakoff’s image schemas need not correspond to our intuitions of what an “image” is like.

Third, and related, we are not asserting that simulation of the actions corresponding to sentences must be consciously available. In fact, it is likely that experienced comprehenders are so skilled at deriving common affordances that they experience little or no conscious imagery while using language. Nonetheless, when dealing with language about an unfamiliar domain, processing may be slowed so that even skilled comprehenders experience imagery. We do not propose any functional significance for this experience, however.

Fourth, we do not mean to imply that comprehenders must simulate all aspects of a situation. As Graesser (1997) noted, it is unlikely that in comprehending a sentence such as “Andy handed you the pizza” that all aspects of the event are simulated. The simulation is unlikely to include details such as the toppings on the pizza, whether it was steaming, Andy’s clothes, and so forth. The constructional account provides a specification of the minimum that needs to be accomplished by the comprehender, namely a check that the various actors and objects can interact in such a manner as to accomplish the specified goals.

The fifth misconception is that people with atypical development or atypical perceptual systems must necessarily understand language and the world very differently from others. For example, how could a child born without hands understand a sentence such as “You handed Andy the pizza?” In fact, it may well be that such a child would understand such a sentence differently, for example, by creating a simulation that meshes affordances of a pizza (perhaps in a box) with his ability to move objects (perhaps using an elbow). However, it is likely that the child would have little difficulty in understanding “Andy handed you the pizza” as a literal handing event. There are several ways in which this can arise. First, given the coevolution of perception and action systems, it is likely that perceptual systems allow people to derive affordances for situations in which they cannot literally act. Thus, the child without hands can still perceive how human hands can afford various actions. In fact, such a “body schema” may be necessary to explain an infant’s impressive ability to imitate others (Meltzoff & Moore, 1997; Rizzolatti & Arbib, 1998). Second, several theorists (e.g., Newton, 1996; Tomasello, 1999) have noted that language requires an ability to understand others as ourselves or, to say it differently, to project our own abilities and desires onto others and vice versa. If this type of projection is intact in the atypically developing child, it will allow him to see the world as others do and hence to understand language about the world as others do.

The sixth misconception is that the IH applies only to comprehension of concrete events. Data from the abstract transfer sentences illustrated in Fig. 1 speak against this misconception. However, why should understanding a sentence such as “Liz told you a story” be affected by the direction of the “yes” response? Our answer invokes a developmental/learning account, similar to that offered by Tomasello (2000a). We suppose that young children learn about transfer of objects (e.g., rolling balls, grabbing bottles) long before they are verbal. Through repeated pairing, these transfer events become associated with particular words such as “give,” and a proto-construction (e.g., a verb island construction as described later) focused on a small set of high-frequency verbs is learned. Note that this learning is in the context of action: When a parent tells a toddler to “Give me the spoon,” it is not an amodal and arbitrary representation of the event that is associated with “give.” Instead, the proto-construction incorporates the action of reaching out. It is these actions that ground and give meaning to the associated words. With additional experience, the invocation of a subject, a verb, and two objects in a particular order (a double-object construction) leads to the interpretation of transfer, i.e., a reaching out and giving or receiving set of actions. At this point the meaning of the construction is set: transfer by taking action.

The child's linguistic experience will come to include double-object descriptions of transfer events using a wide variety of verbs, such as "to hand," "to throw," "to roll," and so on. Comprehension of these sorts of sentences requires the child to coerce (as with the cappuccino example) the typical actions associated with the verbs into those that will accomplish transfer. In fact, Gentner and France (1988) have demonstrated that verb coercion of this sort is commonplace and much easier than changing the meaning of nouns [see also in Kaschak and Glenberg (2000), reviewed later]. Thus, the child learns a skill of figuring out how typical actions associated with a verb need to be reconstrued when the verb appears in the double object construction, namely the actions must conform to some movement of the second object away from the subject and toward the first object. Of course, the child is also experiencing abstract transfer events and their descriptions such as "Liz told you a story." Here the double object construction coerces the meaning of "to tell" as a means of transferring an object (e.g., "a story") from the subject (e.g., "Liz") to the first object (e.g., "you"). This coercion is detected as an ACE for the abstract transfer sentences illustrated in Fig. 1. This sort of learning may underlie the conduit metaphor for communication (Lakoff & Johnson, 1980). That is, Lakoff and Johnson (1980) noted that people describe communication events as if communication channels were physical conduits and words were containers of information. Hence people will say, "I gave you that idea," "It is difficult to put my thoughts into words," "The meaning is in the words," and so on (examples from Lakoff & Johnson, 1980). In all of these instances, the transfer of information is talked about as if it were the transfer of an object.

The next two sections review in more detail data consistent with several claims of the IH. The first of these examines data demonstrating the use of perceptual symbols in language comprehension. The second does the same for constructions. The final section of the chapter deals with the role of learning in the IH and presents preliminary data suggesting that the learning of new constructions relies on the same general mechanisms as the experiential learning that we propose as necessary to produce the ACE.

IV. Perceptual Symbols in Language Comprehension

When words and phrases are indexed, they are mapped to either objects in the environment or to perceptual symbols underlying conceptual knowledge. Because perceptual symbols are based on traces of brain activity that preserve modal information, they are not related arbitrarily to the objects they represent. This review is structured around four types of research. The first examines evidence that perceptual symbols are used in conceptual tasks.

The second type of research demonstrates the use of perceptual symbols in tasks involving simple sentences and, importantly, sentences describing novel situations. The third research area is at the intersection of basic and applied research and demonstrates how interventions inspired by embodied accounts of language can enhance memory and comprehension.

A. PERCEPTUAL SYMBOLS IN CONCEPTUAL TASKS

Barsalou, Soloman, and Wu (1999) reviewed some of the most convincing evidence that conceptual representations are modal and analogical in contrast to the assumption in standard cognitive models that representations are amodal and arbitrary. For example, they used a feature listing procedure to examine the effects of a “revealing” modifier (i.e., a modifier that potentially reveals internal features). Suppose that one is asked to list the features of a watermelon or, in the revealing condition, a half watermelon. On standard models, such a revealing modifier should have little effect on the listing of features. That is, a half watermelon is smaller than a whole watermelon, but otherwise it has the same features to the same extent and frequency as a whole watermelon. In contrast, if conceptual representations are based on perceptual symbols that can be used to create simulations, then the simulation in the revealing condition should reveal features that are not normally easily accessible. Thus, whereas a whole watermelon is predominately green, a half watermelon is predominately red with black seeds; a whole watermelon is hard and smooth, whereas a half watermelon is soft and irregular. As predicted by the perceptual symbol account, the features listed, and their order of production, were changed remarkably when revealing modifiers were used.

As another example, Pecher, Zeelenberg, and Barsalou (2003) investigated the modal nature of perceptual symbols. They noted that in perceptual tasks, participants are slower to respond to successive signals in different modalities than when the signals are in the same modality. According to Barsalou (1999), simulation using perceptual symbols makes use of the same brain regions as perception of the corresponding objects. Thus, Pecher et al. (2003) reasoned that switching modalities in a conceptual task might also slow responding compared to maintaining modalities. In their experiments, participants were presented object–property pairs (e.g., BLENDER–loud) to verify that the property corresponded to the object. Preceding critical pairs were object–property pairs probing the same modality (LEAVES–rustling) or a different modality (CRANBERRIES–tart). As predicted by the perceptual symbol account, there was a significant cost (in reaction time) when the modalities switched.

B. PERCEPTUAL SYMBOLS IN SENTENCE UNDERSTANDING

Among the most convincing evidence that adult readers contact and use perceptual symbols while reading comes from a series of experiments conducted by Zwaan and associates (Stanfield & Zwaan, 2001; Zwaan, Stanfield, & Yaxley, 2002). Participants read a sentence such as “The pencil is in the cup.” Shortly after the sentence was read, a picture was presented, and the participant responded “yes” if the picture represented a concept referred to in the sentence (e.g., a pencil), and they responded “no” otherwise. In the match condition, the pictures were presented in an orientation consistent with that implied by the sentence (e.g., a pencil pictured with its long axis vertical, as it would rest in a cup). In the mismatch condition, the picture was presented in a different orientation (e.g., a pencil pictured with its long axis horizontal). Stanfield and Zwaan (2001) reported a match effect: Responding “yes” in the match condition was faster than responding “yes” in the mismatch condition. The strong implication is that reading and understanding the sentences generated a modal representation in which the pencil (in this case) was oriented vertically and that the modal representation helped identify the matching picture. Zwaan et al. (2002) reported similar matching effects (a) using a different probe procedure and (b) when match is defined by object shape rather than orientation. Fincher-Kiefer (2001) used yet another methodology to converge on the same conclusion: When understanding sentences, people instantiate models with perceptual content.

Glenberg and Robertson (2000) asked participants to judge the sensibility of sentences describing novel situations. As in the following example, each sentence was preceded by a context, and there were three forms of the to-be-judged sentence.

Context: Mike was freezing while walking up State Street into a brisk wind. He knew that he had to get his face covered pretty soon or he would get frostbite. Unfortunately, he did not have enough money to buy a scarf.

Afforded and related: Being clever, he walked into a store and bought a skimask to cover his face.

Afforded: Being clever, he walked into a store and bought a newspaper to cover his face.

Nonafforded: Being clever, he walked into a store and bought a matchbook to cover his face.

The sentence in the afforded and related condition included a word that was highly associated with other important concepts (e.g., “skimask” is associated with “scarf” and “face”). The sentence in the afforded condition included a word that was relatively unassociated with other important

concepts (e.g., “newspaper” is not strongly associated with “scarf” or “face”), but which names an object with the right affordances to achieve the goals of the situation. Finally, the sentence in the nonafforded condition included a word that was unassociated with the other important concepts and did not have the right affordances to achieve the goals (e.g., “matchbook”). As might be expected from this example, participants quickly and easily judged the afforded sentence as just about as sensible as the afforded and related sentence, but they judged the nonafforded sentence as nonsensical.

What makes this simple demonstration important is that the results are completely uninterpretable from the point of view of standard cognitive theories. That is, the afforded and nonafforded conditions were equated in the ways typically coded in arbitrary symbols: The final words were equated for grammatical class, “semantic” features such as animacy, frequency, associations to context, and propositional information. Furthermore, it is unlikely that participants engaged in logical reasoning to derive a conclusion that the afforded object could suffice. That is, it took no longer to read the afforded sentences than the afforded and related sentences that presumably did not require this sort of reasoning.

Apparently, participants simulate the actions underlying sentences to determine if those actions are coherent (i.e., if the actions mesh). It is just this process that is unavailable to standard theories. Those theories use representations that are related arbitrarily to referents. Consequently, manipulation of those symbols cannot make use of perceptual/action states, only syntactic rules. As an example, consider how a computer presented with an Arabic numeral such as “3” might represent the information. After some processing to recognize the numeral, it would be encoded as a quantity using a binary representation, such as “0000011” that strips away modal information. That sort of representation is sufficient to answer questions about quantity, such as “Is 3 a greater quantity than 4?” However, the binary representation is useless in answering a question such as “Is the Arabic numeral ‘3’ more rounded than the numeral ‘4’?” The point is that highly coded representations are often exceptionally efficient and effective in dealing with expected operations, but they can be useless in dealing with novel situations. Because language is so effective in communicating about novel situations, one suspects that language understanding cannot depend exclusively on amodal and arbitrary representations.

C. PERCEPTUAL SYMBOLS IN CONNECTED DISCOURSE AND APPLIED SETTINGS

We have been arguing that meaning is action based and that those actions are derived from perceptual symbols. Consequently, one would suspect that incorporating action into learning tasks would facilitate that learning.

Consider, for example, the effectiveness of subject-performed tasks in memory experiments. When presented with a list of activities to memorize tasks (e.g., “break the toothpick,” “snap your fingers”), memory is improved remarkably when the tasks are actually performed by the participants (e.g., Zimmer, Helstrup, & Engelkamp, 2000). Consistent with an account based on perceptual symbols and action, Nilsson, Nyberg, Klingberg, Aberg, Persson, and Roland (2000) used positron emission tomography to demonstrate that on recalling subject-performed tasks, those areas of the brain associated with manipulation are more active than when recalling after memorizing the phrases without overt action.

A related finding was reported by Noice and Noice (2001), who demonstrated the efficacy of movement associated with connected discourse. Noice and Noice (2001) required pairs of students to study a dialogue by having the pairs (a) act out the dialogue with scripted movements that had been practiced before the dialogue was introduced, (b) read the dialogue aloud to each other without movement, or (c) memorize the dialogue. Proportions of verbatim recalled in the three conditions were .38 (movement), .21 (reading), and .14 (memorization). Thus, the movements improved recall by over 100% compared to the memorization condition and by over 50% compared to the reading-aloud condition (for a similar demonstration, see Scott, Harris, and Rothe, 2001).

Glenberg and Robertson (1999) used a transfer design to demonstrate how indexing to perceptual symbols facilitates the interpretation of written instructions. In the first phase of the experiment, participants learned the names for the parts of a compass and the parts of a topological map. One group learned the parts by reading and rereading a script. A second group heard the script (once) as the audio track of a videotape that showed an image of the compass along with a hand pointing to each part as it was named. That is, the hand facilitated indexing the name to the part. In the next phase of the experiment, these two groups demonstrated virtually identical scores on a verbal multiple choice test. In the final phase of the experiment, the participants were asked to use the compass and map to find the name of a landmark. Explicit instructions were given for how to do this task and, importantly, the only technical terms used in the instructions were those introduced and tested earlier. In this third phase, the group that had previously indexed the part names were faster and more accurate in following the explicit instructions. The conclusion is that using language to guide action requires more than familiarity with the words. Instead, those words must be grounded in the right experiences so that appropriate affordances can be derived.

Finally, if meaning is action based, then one would suspect that some form of action could be used as an intervention to assist reading

comprehension. Suppose that children learn to index spoken words as a matter of course because so much talk to infants and toddlers is indexical. That is, parents may talk about the bottle or the ball with which the child is currently interacting or words describing actions may be indexed by demonstration, such as waving goodbye while saying to the toddler, "wave bye-bye." The situation is not as transparent when learning to read, however. For example, most children in a phonics program will have to concentrate on learning the shapes of letters, associating letters with sounds, learning how groups of letters correspond to particular sounds, and blending the sounds. Other children in whole word programs will face the daunting task of learning the association between complex shapes (written words) and pronunciations. Whereas this learning is necessary for skilled reading, it takes the focus off the point: The meaning of the text. In addition, written texts lack the prosody, repetition, gesture, and feedback of oral language. Consequently, many of the cues that children might use to help index oral words are missing for the written words.

These considerations argue that some children may be adept at oral language comprehension, and yet because of failure to index written words to perceptual symbols, these children may have a difficult time comprehending written text. On this account, a successful intervention would be to facilitate indexing during reading by asking the child to either act out the text (reminiscent of Noice & Noice, 2001) or to manipulate objects referred to in the text. For example, Rubman and Waters (2000) asked third- and sixth-grade children to either read a text twice or read the text once and then to use a storyboard to depict the story. Dependent measures were recall of the text and the ability to detect inconsistencies. For both dependent variables, both age groups benefited from storyboard construction.

Glenberg, Gutierrez, Japuntich, and Kaschak (2002) worked with younger children to determine possible benefits of action on reading comprehension. In their experiments, first- and second-grade readers were assigned to one of three groups: a classroom control, a nonmanipulate group, and a manipulate group. Children in the latter two groups read short narratives referring to toy scenes that were displayed in front of them. For example, while reading a story about "breakfast on the farm," a toy farm scene, including a barn, a corral, a tractor and cart, and a variety of animals and other props, was on the table in front of the child. Five sentences in each story were highlighted. Children in the nonmanipulate group were instructed to read and then reread these highlighted sentences. Children in the manipulate group were instructed to read the highlighted sentence and then to manipulate the toy scene to correspond to the sentence. The benefits of manipulation were quite apparent. Children in the manipulation

condition outperformed children in the nonmanipulation condition by 50% on both free recall and comprehension tests.

D. PERCEPTUAL SYMBOLS, ACTION, AND GESTURE

We have developed the argument that meaning involves a consideration of the actions available in a situation and that understanding language requires creating a simulation using brain areas also used in planning and guiding action. In this case, when thinking or when dealing with language, there may be some “leakage” (e.g., Rizzolatti & Arbib, 1998) in which the actions are partially expressed. Because the motor system is already engaged in language production, that leakage would be especially likely during production. We believe that this reasoning helps explain that prevalence of gesture in communicative situations (McNeill, 1992).

One question of interest in regard to gesture is its function. That is, does gesture help the speaker by, for example, facilitating lexical retrieval (Alibali, Kita, & Young, 2000; Iverson & Goldin-Meadow, 1997; Krauss, 1998) or is gesture designed to help the comprehender understand the message (Clark, 1996; Kelly, Barr, Church, & Lynch, 1999; Ozyurek, 2002)? Our view suggests that both questions can be answered in the affirmative. We suppose that speakers note the cooccurrence of words and gesture in their own production (because of leakage) as well as the facilitating effects of their gestures on their own production (e.g., Krauss, 1998). Furthermore, speakers note how gestures of others help them to comprehend and how their own gestures help others to comprehend. Clark (1996), for example, discussed how gestures function as demonstrations within the context of a discourse and that these gestures convey information that is difficult or impossible to capture in language. Kelly et al. (1999) demonstrated that gestures can facilitate the interpretation of indirect requests. Thus, gesturing toward a window while saying “It is hot in here” helps the comprehender understand the utterance as a request to open the window. Given the facilitating effects of gesture for both speaker and comprehender, it is no surprise that with social support the gestures become closely linked to linguistic production. In this way, what started out as leakage becomes an automatic response.

How is it that gestures can be integrated seamlessly with language during comprehension? The indexical hypothesis suggests that language is understood by performing simulations using the same neural systems that plan and execute actions. Similarly, we understand the gestures of others in terms of our own actions (Newton, 1996, Wilson, 2001). Thus, gesture and language are processed by the same systems, allowing gesture to augment the simulation generated from language. This answer also explains why

gestures that mismatch the content of the linguistic message are difficult to understand (e.g., McNeil, Alibali, & Evans, 2000; Kelly & Church, 1998). As in the ACE, conflicting simultaneous uses of the motor system lead to processing difficulty.

V. Grammatical Constructions in Language Comprehension

Earlier, we argued that an important process in comprehending language is the meshing of affordances under the guidance provided by the construction of the sentence. This proposal borrows from construction grammarians (Kay & Fillmore, 1999; Fillmore, Kay, & O'Connor, 1988; Lambrecht, 1994) the notion that abstract sentence patterns, such as the double object, transitive, and caused motion constructions (see Table I for examples), carry meaning above and beyond that contributed by the lexical items in the sentence. This section reviews evidence that supports the claim that construction-based information is used in comprehending sentences and that linguistic knowledge is best seen as being organized into sets of constructions. We begin with a discussion of verb-argument constructions and move on to present evidence regarding other kinds of sentence patterns, which, through learning, have come to have interesting semantic and pragmatic properties.

Constructions of the sort discussed by Goldberg (1995) have a long history in linguistic theory [e.g., the work of Bloomfield (1933) and the

TABLE I
SYNTACTIC FORM-MEANING PAIRS^a

Form	Example	Hypothesized meaning of form
Transitive N – V – OBJ	“Mike kicked the toy”	“X acts on Y”
Double object N – V – OBJ1 – OBJ2	“Mike gave David a toy”	“X transfers Y to Z”
Caused motion N – V – OBJ – OBL	“Mike pushed the top off the table”	“X causes Y to go to Z”
Way construction N – V – [poss-way] – OBL ^b	“Joe made his way to the sink”	“X creates and follows a path to OBL”

^aAdapted from Goldberg (1995).

^bA prepositional phrase specifying the direction and goal of the path.

American Structuralists; Mathesius (1961) and other work from the Prague School], although these ideas have largely been ignored by Chomskyan linguistics and psycholinguistics. The past 5 years have seen a change in this pattern, and a growing body of evidence now suggests that linguistic knowledge consists, in part, of knowledge about constructions and that this knowledge is brought to bear when individuals are comprehending sentences. Several experiments from our laboratory support this claim.

Kaschak and Glenberg (2000) provided evidence for the role of constructions in sentence comprehension by exploring how readers come to understand sentences containing innovative denominal verbs (see Clark & Clark, 1979). An innovative denominal verb is a verb that has been created anew from a noun and that has no standardized “verb” meaning. The following sentences present examples of such verbs:

- (1) Lyn *crutched* Tom her apple.
- (2) Mary *spatulae’d* June the cookie dough.
- (3) Peter *ice axed* his way across the steep traverse.

Innovative denominal verbs present an interesting challenge to theories of language comprehension based on the claim that the event structure of the sentence is derived solely from the semantics of the verb (see Pinker, 1989). Innovative denominal verbs lack both the necessary semantic structure to project the event structure of a sentence and present the interesting problem that no simple problem-solving heuristic will suffice to ascertain the meaning or event structure implied by such verbs (for a discussion of the difficulties of interpreting such verbs, (see Clark & Clark, 1979). Kaschak and Glenberg (2000) argued that a straightforward account of the comprehension of these verbs could be had if one assumed that language comprehenders have knowledge of constructions and the affordances of the objects named by the denominal verb.

This account was supported by a series of experiments showing that the interpretation of innovative denominal verbs is strongly influenced by the construction in which they appear (i.e., the construction coerces a meaning from the innovative verb). We presented participants with innovative denominal verbs in the double object construction (Lyn crutched Tom her apple to help him out) and the transitive construction (Lyn crutched her apple to help Tom out). In both choice tasks and paraphrase tasks, participants indicated that their interpretations of these sentences were shaped by the construction of the sentence. That is, they indicated that double object sentences implied transfer and transitive sentences implied “acting on.” Their interpretation of the innovative verb itself depended highly on the construction in which the verb appeared—again, verbs

presented in the double object construction were thought to have a transfer component to their meanings, whereas those presented in the transitive construction had a more general “acting on” meaning.

In the same set of experiments, we showed that construction-based knowledge was not sufficient to explain the comprehension of these verbs. By manipulating the available affordances of the object being named by the innovative denominal verb, we demonstrated that comprehension of innovative denominals depends on having the right affordances to satisfy the event constraints established by the construction. Thus, “Lyn crutched Tom her apple” will be understood easily if the crutch has the affordances to support a transfer action (e.g., it is sturdy enough to smack the apple from Lyn to Tom), but will not be understood if it does not have the needed affordances (e.g., the crutch has been weakened by termites).

The claim that constructions of this sort play an important role in language comprehension has been supported by evidence from a variety of sources. Kako (1999) explored the factors that govern the comprehension of nonsense verbs and found that the construction in which the form appeared strongly determined its interpretation. Fisher (1994), Bencini and Goldberg (2000), and Naigles and Terrazas (1998) have performed similar experiments with adult participants and standard verbs and have reported similar effects of construction form on sentence interpretation. Townsend and Bever (2001) presented evidence for the role of sentence templates (similar to Goldberg’s constructions) in language comprehension. Work in language development supports these claims as well. Gleitman and colleagues (Landau & Gleitman, 1985; Gleitman & Gillette, 1995) have argued that knowledge of constructions is an important means through which children acquire the meanings of novel verbs. The influence of constructions on a child’s verb acquisition has been observed in many experiments (see Gleitman & Gillette, 1995).

Tomasello (2000a,b; Tomasello & Brooks, 1999) argued that all of language acquisition (not just verb acquisition) can be seen as the acquisition of constructions (in the broad sense of “form-meaning pairings” rather than in the more specific sense being discussed here). He suggested that children acquire individual form-meaning pairings (such as “doggie” or an abstract “give X” template) and slowly learn to generalize across these pairings. For example, the child may initially use a verb island construction such as “give X” exclusively with the verb *give* and a limited set of X predicates, but will learn to insert new verbs and predicates into the structure over time. Tomasello (2000a) used this pattern of development to propose that children do not show evidence of acquiring abstract grammatical rules; instead, they show evidence of acquiring a repertoire of constructions.

The strength of the constructionist approach becomes apparent when it is contrasted with the alternative hypothesis presented earlier: sentence meaning is projected from verb meaning. The problem of understanding novel verbs (or verbs used in novel contexts) is quite daunting for such an approach. Upon encountering the new usage, the child or adult must find some means of ascertaining the meaning of the word. Typically, verb-based approaches rely on a set of rules to give the verb the appropriate semantics. How the comprehender would choose the correct rule without making recourse to the construction (i.e., the pattern of words around the verb) is not clear. Indeed, the logic underlying the existence of such semantic transformation rules is circular. The only way one knows about the existence of a rule is to observe a verb of a particular meaning occurring in a particular sentence frame. Given the flexibility with which verbs can be used in different constructions (witness the *cappuccino* example), it appears that we can only posit the existence of a given rule after the fact.

Whereas most of the research on constructionist accounts has examined what might be termed verb argument structure constructions, there is also evidence for the existence of form-meaning pairings associated with other types of abstract sentence frames. Consider the incredulous response construction (IRC), typified by the following sentences:

- (4) Him be a doctor?
- (5) The IRS give me a refund?

The IRC is an abstract sentence pattern (accusative subject + tenseless verb + predicate) that has a very limited range of pragmatic uses. Specifically, IRCs are used to ridicule a previously uttered proposition, as in the following exchange:

- (6) A: I hear that Sam is going to be a doctor one of these days.
B: Him be a doctor? That's crazy!

In keeping with this limited range of uses, the IRC can only be used acceptably with a limited set of prosodic structures. These structures are typically used to indicate ridicule or derision (Lambrecht, 1990; Akmajian, 1984). We have collected data suggesting that adult language users are keenly aware of these properties of IRCs. If IRCs are presented with a flat, monotonic prosody, participants indicate that the sentences are unacceptable in English. The acceptability of IRCs increases somewhat when they are presented with an appropriate prosodic structure, but increases greatly when the sentences are presented with an appropriate prosodic structure and in an appropriate context.

In a further experiment, we explored the reading of IRCs and similarly structured control sentences (e.g., "He is a doctor"). They presented

TABLE II
EXAMPLE PASSAGE FROM IRC EXPERIMENT

Introduction

Robert called his mom from his dorm room one evening.
The topic of conversation turned to his old girlfriend, Hannah.

Context manipulation

Robert heard that she had gone to the police academy last year. (QUESTION Context)
Robert remembered that she was afraid of taking risks. (INCREDULITY Context)

Filler sentence

When his mom told him that she heard Hannah had become a firefighter, he replied,

Critical sentences

“Hannah be a firefighter?” (IRC)
“Hannah is a firefighter?” (CONTROL)

Question

Does Robert think Hannah should be a firefighter?

participants with passages of the sort shown in Table II. In some cases, the passage presented a situation where the critical sentence (the IRC or the control sentence) should be interpreted as a question; in other cases, the passage presented a situation where the critical sentence should be interpreted as a ridiculing comment on a previously uttered proposition. If IRCs are limited in their acceptable range of uses, we should find that time to read these sentences is approximately equal to that of the control sentences in the “incredulity” context (since IRCs are used for this purpose), but that IRCs create processing difficulty in the “question” context (because the IRC pattern cannot be used to ask a question). Additionally, the control sentence should not be particularly difficult to understand in either context because that sentence pattern can be used for a range of pragmatic purposes. This is the pattern of reading times we observed (see Table III; the means reported in Table III and Table V and Table VI are the mean residual reading time in each condition once length was regressed on the raw reading times).

At this point, two misconceptions regarding the role of constructions in language comprehension deserve mention. First, it is a misconception to construe an adoption of a constructionist approach as the adoption of the view that comprehenders must wait until the end of the sentence to ascertain its meaning. Clearly, there is a correlation between particular constructions and particular verbs, just as there are cues (such as prosody) to the presence of constructions like the IRC. Given the detection of cues such as prosody or a particular verb, the comprehender may guess as to what the construction is. In many cases (such as when the verb *give* is used in the double object

TABLE III
RESIDUAL READING TIME FOR IRC AND CONTROL
SENTENCES (STANDARD DEVIATIONS IN PARENTHESES)

Sentence	Context	
	Question	Incredulity
IRC	231 (304)	-43 (318)
Control	-39 (287)	-109 (308)

construction), this guess will be correct. If it is not, the comprehender will revise their interpretation of the sentence based on the construction.

Second, and relatedly, positing constructional knowledge does not obviate the role of verbs in determining sentence meaning. Rather, the meaning of the verb combines with the meaning of the construction in interpreting the sentence. In this combination, however, construction meanings always dominate verb meanings. That is, the meaning of a verb can be altered to fit with the meaning of the construction in which it is found, but the meaning of constructions are not altered by the semantics of the verb that appears in the sentence.

Together with the other evidence cited in this section (and with analyses from linguistics), our IRC data support the view of language promoted by Kay, Fillmore, and colleagues (Kay & Fillmore, 1999; Fillmore, Kay, & O'Connor, 1988; Goldberg, 1995; Tomasello, 2000a), namely the view that knowledge of language is knowledge of constructions. Whereas this view is at odds with the linguistic theory assumed by most psycholinguistic accounts, we find it noteworthy that we can find general support for this approach in both adult and child language users. There are two important implications of this support. First, the fact that all levels of language development can be characterized using a constructional approach suggests that this approach can be used to build a general psycholinguistic account of language use and development.

The second implication of our claims is drawn from the work of Culicover (1999). Culicover (1999) presented several case studies of what he calls *syntactic nuts*: words, phrasal patterns, and sentence patterns that contain syntactic irregularities that do not mesh with the syntax of the rest of English. He suggests that such patterns (constructions) would need to be learned individually rather than being derived from general syntactic rules. This learning would ostensibly rely on the same general purpose, nonlinguistic learning mechanisms that are required to learn words. If all of language is seen as a set of constructions, it follows that language is

learned via general human learning capacities rather than via language-specific learning mechanisms (for similar arguments, see Seidenberg & MacDonald, 1999). We see the adoption of a construction-based account of language as a first step toward developing a theory of language acquisition and processing that eschews the positing of language-specific mechanisms in favor of the general learning and memory retrieval mechanisms that have been shown to underlie skill acquisition and performance in a variety of other domains (e.g., Logan, 1988, 2002).

VI. Learning and the Indexical Hypothesis

To this point, we have reviewed a variety of evidence in support of the indexical hypothesis. This evidence has pointed to the role of perceptual and motoric representations, as well as grammatical information, in shaping the comprehension of language. An important component of this approach that has been left largely implicit in the previous sections is that the indexical hypothesis is an inherently developmental theory. That is, the outcome of the indexing, derivation of affordances, and meshing of those affordances is largely determined by the history of the individual. This section brings this notion to the foreground and discusses the role of learning and memory in the indexical hypothesis.

We have proposed that a child's early exposure to language is largely indexical. The topics used in conversation with infants, the words chosen, and the interaction between the caregiver and the infant mostly center around the people, objects, and actions in the present environment (e.g., Masur, 1997). If, as we have proposed, language is acquired through the same general learning mechanisms that govern other kinds of skill and knowledge acquisition, then it is not surprising that the indexing that occurs between words, objects in the surrounding environment, and (eventually) internal representations would be shaped by factors such as attention and frequency. Tomasello (1999) argued that joint attention between an infant and a caregiver is an essential component of language acquisition. The ability of the infant and caregiver to jointly attend to objects and events aids the child in connecting linguistic stimuli such as words to the appropriate objects and actions in the environment. Through repeated pairings of word forms with objects and events in the environment, the appropriate indexing develops. As the internal representation of the word form and of the object solidifies, the presentation of the word will facilitate retrieval of information about the object, and vice versa.

Data presented by Glenberg and Robertson (1999) provide further evidence for the role of learning in the indexing process. This study showed

that understanding language in technical domains, such as using a compass, requires having the proper experiences with language. Consider, for example, the phrase “point the direction of travel arrow” used in the transfer phase of the experiment. Without appropriate technical experience, participants will index a word such as “point” to frequent experiences, such as pointing a finger, pointing a car, or pointing a rifle. None of these actions, however, are appropriate for pointing the direction of travel arrows that are on the base of a compass. Instead, the compass must be held flat in the palm of the hand and the whole hand pointed at the relevant location. Those participants who had previously indexed the phrase “direction of travel arrows” to the base of the compass were able to coerce the meaning of the verb “to point” to fit the affordances of the compass.

At the end of the previous section, we discussed the role of learning in building a repertoire of constructions to use in communication. We and others (e.g., Kay, 1997) have argued that constructions of all sorts, even constructions that are abstract syntactic patterns, can be acquired through a general learning mechanism. Our laboratory has conducted a series of experiments demonstrating this point (Kaschak, 2003). The first of these experiments involved the incredulous response construction discussed earlier. In the first experiment, we gave participants a grammaticality test involving a range of sentence types and a range of syntactic errors (the test was modeled on that used by Allen & Seidenberg, 1999). The test included several IRCs. We knew from previous experiments that IRCs, when presented out of context, would be judged as unacceptable most of the time by a high percentage of participants. We followed the grammaticality test with a second task in which the participants were to make some judgments about a series of recorded conversations. The judgments were to be made on general factors such as how friendly the conversation sounded, how well the conversants knew each other, and so on. Unbeknownst to the participants, these conversations were intended as training on the IRC. Half of the participants (control group) heard conversations that contained no IRCs, whereas the other half of the participants (IRC training group) heard 5 conversations in which an IRC was used (there were 10 total conversations to be rated).

The conversation rating task was followed by a grammaticality test similar to the first. Table IV presents data from this experiment. As is evident from the acceptability rates of the IRC, mere exposure to this constructional pattern was enough to greatly alter the degree to which the participants in the training group deemed IRCs to be acceptable English sentences.

Further evidence for the learning of constructions was garnered by reanalyzing the reading time experiment conducted on IRCs and reported

TABLE IV
PROPORTION OF “ACCEPTABLE” RESPONSES FOR IRC
(STANDARD DEVIATIONS IN PARENTHESES)

Training	Time	
	Pretraining	Posttraining
IRC training	.22 (.23)	.50 (.35)
Control training	.24 (.22)	.34 (.34)

TABLE V
RESIDUAL READING TIME OF IRC AND
CONTROL SENTENCES ACROSS TIME
(STANDARD DEVIATIONS IN PARENTHESES)

Construction	Time		
	First third	Second third	Final third
IRC	587 (560)	−64 (369)	−241 (308)
Control	208 (357)	−154 (281)	−276 (256)

earlier (original data in Table III). In this experiment, participants read both IRCs and similar control sentences (IRC: “Him be a doctor?”; control: “He is a doctor?”). Because IRCs are syntactically odd (the accusative subject paired with a tenseless verb is a pattern not seen in other English sentences) and occur relatively infrequently compared to other constructions in the language, we expected that IRCs would be more difficult to process than the control sentences at the outset of the experiment. The question of interest is the degree to which exposures to the IRC will ameliorate the processing difficulties posed by this construction. Table V presents the reading times for IRCs and control sentences for the first, second, and final third of the experiment (data are collapsed across contexts). Early in the experiment, IRCs were read much slower than the control sentences. However, by the final third of the experiment, IRCs come to be processed as quickly as the control sentences. These data suggest that participants can quickly learn to process syntactically odd, low-frequency structures as readily as they process higher frequency structures such as those of the control sentences.

A third experiment was conducted using a construction that is common in some regions of the United States, but was unfamiliar to the upper

TABLE VI
RESIDUAL READING TIMES FOR NEEDS CONSTRUCTION AND
CONTROL SENTENCE (STANDARD DEVIATIONS IN PARENTHESES)

Construction	Time		
	First third	Second third	Final third
Needs	346 (438)	-51 (261)	-184 (160)
Control	37 (216)	-63 (197)	-131 (200)

Midwestern participants in our experiments (for details, see Murray, Frazier, & Simon, 1996). This construction (which we call the needs construction) is typified by the following sentences:

- (7) The floor needs cleaned.
- (8) The walls need painted.

We presented participants with a series of passages containing examples of the needs construction and similar control sentences (e.g., "The floor needs to be cleaned."). As before, our interest is in the processing of the construction itself. Initially, we expected that the needs construction would cause processing difficulty (due to its unfamiliarity to the participants). Our concern was whether the participants would learn to process this pattern as quickly as the more standard English pattern represented by the control sentences. Data from this experiment, presented in Table VI, suggest that our participants were indeed capable of learning to process the needs construction.

Results of these three experiments suggest that adults are capable of learning about low-frequency syntactic patterns, as well as learning about novel syntactic patterns, under more or less incidental learning conditions. That is, at no time were the participants directed to learn about the IRC or needs construction. The learning occurred indirectly, through the processing of the constructions themselves. We find these data compelling for a couple of reasons. First, they contradict the common belief that whereas adults are good at acquiring linguistic components such as words and idioms, they are poor at learning syntactic patterns (Johnson & Newport, 1989). Our data show that adults well past any putative "critical period" for language learning are capable of learning new syntactic patterns in their native language and that they are capable of doing so quite rapidly. Second, given that any putative language acquisition device should be inoperable with regard to learning about one's native language in our college-age

participants, it seems that any learning that occurred must have done so via nonlinguistic learning mechanisms. This lends further support to our contention that language is acquired and processed entirely through domain general mechanisms.

VII. Conclusion

We have argued for an embodied approach to language comprehension. This approach is motivated by four considerations. The first is the symbol grounding problem: Amodal and arbitrary symbols by themselves cannot be used to generate meaning. Instead, symbols need to be grounded, and Putnam's argument demonstrates the impossibility of getting the right grounding when starting with arbitrary symbols. The second motivation is the success of grounded symbol systems in accounting for capabilities of human conceptualization (Barsalou, 1999; Lakoff, 1987), including the ability to engage in reasoning about the abstract. The third motivation consists of data demonstrating that grounded symbols are not just a theoretical or philosophical nicety. Instead, the work of Zwaan and colleagues, as well as the ACE (Glenberg & Kaschak, 2002), demonstrates that the mode of grounding plays an integral role in language comprehension. In fact, it is hard to imagine how language about novel situations could possibly be understood without recourse to symbols grounded in perception and action (Glenberg & Robertson, 2000).

The final consideration is learning. The chapter began by noting that traditional approaches to understanding language require abstract principles (e.g., rules of syntax), abstract categories (e.g., nouns and verbs), and abstract, amodal, and arbitrary symbols. Explanations of how these structures could be learned require the postulation of special mechanisms such as a language acquisition device. In contrast, the learning of several of the components required by the indexical hypothesis, namely perceptual symbols and constructions, can be accomplished by general learning mechanisms, and we have demonstrated how those mechanisms are operative in both children and adults.

In his famous critique of Tolman, Guthrie (1935) complained that "Signs, in Tolman's theory, occasion in the rat *realization*, or *cognition*, or *judgment*, or *hypotheses*, or *abstraction*, but *they do not occasion action*. In his concern with what goes on in the mind of the rat, Tolman neglected to predict what the rat will do. So far as the theory is concerned the rat is left buried in thought; if he gets to the food box at the end that is his concern, not the concern of the theory" (p. 172, emphasis in the original). Contemporary psychology of language has adopted Tolman's concerns for the mind, but it

has inappropriately dismissed Guthrie's concern for action. The indexical hypothesis and embodied theories of cognition are part of a corrective swing of the pendulum from rampant cognitivism toward a consideration of how the body contributes to language and how language contributes to action.

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USING SPATIAL LANGUAGE

Laura A. Carlson

I. Introduction

The title of this chapter is an adaptation of the title of Clark's (1996) important volume entitled "Using Language." This is appropriate in that the guiding principles, processes, and constraints identified by Clark as underlying language use undoubtedly govern the comprehension and production of spatial descriptions. The particular focus on this particular domain of language (spatial) emerges out of a long history of examining the manner in which language is mapped onto perception (e.g., Bloom, Peterson, Nadel, & Garrett, 1996; Clark & Chase, 1972; Miller & Johnson-Laird, 1976; Jackendoff, 1983; Levelt, 1984; Talmy, 1983). There are several reasons for all of this interest. First, spatial terms are potentially ambiguous (e.g., think of the typical confusion associated with understanding the terms "left" and "right" that are based on an ambiguity associated with defining these terms relative to the speaker, the listener, or some other source). Researchers in language have long been interested in examining ambiguity resolution as a means of understanding both processing and representation of lexical items. Second, within a modular view of the cognitive architecture (e.g., Jackendoff, 1987, 1992, 1996), linguistic information is represented separately from spatial information, raising several important questions about how information is translated from one to the other, allowing us to speak about what we see. Third, spatial language offers an important means for investigating the extent to which language

influences other nonlinguistic cognitive processes (e.g., Bowerman, 1996; Levinson, 1996). For example, while the spatial component may be held constant across languages (e.g., showing all speakers the same spatial arrangement of objects), the manner in which these arrangements are represented may be dictated by the manner in which the arrangements are described (Levinson, 1996).

The goal of this chapter is to summarize a body of research that has focused on understanding the processes and representations involved in the apprehension of particular type of spatial language: a simple spatial description. An example is provided in (1), uttered by a speaker to a listener who is holding the coffee pot.

(1) “The coffee mug is below the coffee pot.”

The apparent simplicity of the utterance belies the complex set of processes and representations that are needed for mapping the linguistic elements onto an arrangement of objects. Examining this process is a necessary first step in tackling each of the important issues outlined earlier. First, understanding the processes and representations involved in apprehension enables an assessment of the conditions under which ambiguity arises and how it is overcome. Second, identifying the representations necessary for mapping between language and space helps elucidate the nature of the information operating at the language/space interface. Third, identifying how this process unfolds within one particular language sets up a future test of its applicability cross-linguistically, especially with respect to languages with different manners of speaking about space, thereby addressing whether such processes and representations are language specific or language general.

The structure of the chapter is as follows. First, it provides an overview of the constituent processes involved in apprehending a spatial term and presents some evidence supporting this framework. Next, it focuses more narrowly on one particular constituent process, that of mapping the spatial term onto a direction in space. This is accomplished by setting a number of parameters that define the space referred to by the spatial term. Each of these parameters is discussed in turn, and factors influencing their settings are identified. These first two sections focus on the interpretation of a simple spatial description [as in (1)] in which the spatial term and the objects being spatially related have already been selected by a speaker and are being comprehended by a listener. The final section evaluates the applicability of this framework to the speaker’s selection of the relevant objects and spatial term and offers some conclusions and implications.

II. Constituent Processes during Apprehension

A. COMPONENTS OF A SPATIAL DESCRIPTION

A considerable amount of research has focused on the processes and representations employed in the apprehension of simple spatial descriptions (e.g., Bloom et al., 1996; Carlson-Radvansky & Irwin, 1993, 1994; Carlson-Radvansky & Logan, 1997; Clark & Chase, 1972; Garnham, 1989; Glushko & Cooper, 1978; Greenspan & Segal, 1984; Herskovits, 1986; Jackendoff, 1983; Levelt, 1984, 1996; Logan, 1995; Logan & Sadler, 1996; Miller & Johnson-Laird, 1976; Talmy, 1983; Tversky, 1991). Across this body of work, there is general agreement about several components that together govern the interpretation of a simple spatial description. These components are described using (1) as a sample utterance.

1. *Goal of the Utterance*

Clark (1996) argued that language is a joint activity engaged in by both speaker and listener; as such, there is an inherent goal in any linguistic utterance. For example, assume the speaker of (1) is at the office coffee machine, and a colleague is standing nearby holding the coffee pot while reading his mail. By telling the colleague that the mug is below the pot, the speaker may intend to accomplish one of several goals. If the colleague knew that the speaker had brought back the coffee mug as a souvenir from a trip, the goal of the utterance might be to specify the location of the mug so that the colleague could inspect it. To accomplish this goal, the speaker defines the location of the coffee mug (more generally, the located object) by indicating its spatial relationship to an object whose location is presumed known by the listener—the coffee pot (more generally, the reference object). The utterance is facilitative because it narrows the search domain for the located object from an undefined area to the space immediately surrounding a salient object.

However, this utterance could also be intended to fulfill a completely different goal, that of asking the colleague to pour coffee into the mug. That is, because the mug and the coffee pot are arranged spatially in a typical interactive fashion, the speaker's utterance could be interpreted as drawing attention to the interaction, thereby serving as an implicit and somewhat sarcastic request for the colleague to fill the mug with coffee.

This example illustrates two important constraints on the apprehension of a spatial term. First, the goal of the utterance must be identified correctly by the speaker and the listener (Clark, 1996; Sperber & Wilson, 1995). Thus, it will be important in any discussion of research on apprehension to specify the particular goals of the speaker and listener, and the underlying structure

of the task that is being studied. Second, there is a significant influence of the particular objects being related spatially and the nature of their interaction, both on the interpretation of the utterance as a whole and on the manner in which the spatial term is assigned to space (Carlson-Radvansky, Covey, & Lattanzi, 1999; Carlson-Radvansky & Tang, 2000; Carlson-Radvansky & Radvansky, 1996; for an overview, see Carlson, 2000). Thus, it will be important in any discussion of apprehension to examine the contribution of not only the spatial term, but also the objects being related.

2. *Role of Located and Reference Objects*

A second common characteristic to theories of apprehension is that the two objects being related spatially have particular roles, with the reference object serving as a landmark from which to describe the located object. As such, the reference object is presumed to be found easily and is generally considered to be larger and more permanently located than the located object (Landau & Jackendoff, 1993; Talmy, 1983; Taylor, Gagné, & Eagleson, 2000; Tversky, Lee & Mainwaring, 1999; but see DeVega, Rodrigo, Ato, Dehn, & Barquero, 2003). This idea is illustrated nicely by contrasting sentences (2) and (3) that convey the same spatial relation between the same objects, yet (3) sounds odd (from Talmy, 1983).

(2) The bicycle is near the house.

(3) The house is near the bicycle.

It has also been suggested that the located object is more salient, has been introduced more recently in the scene or into awareness, and is conceived as geometrically simpler (Talmy, 1983; see also Landau & Jackendoff, 1993).

3. *Use of a Reference System*

A third characteristic shared by theories of apprehension is the use of a reference system that maps the linguistic spatial term onto the spatial relation between the reference object and the located object. At its most general level, a reference system can be thought of as a family of representations (Shelton and McNamara, 2001), with each specific representation defined by the particular objects and the particular spatial relation being described. Logan and Sadler (1996) formalized this idea by associating a set of parameters with the reference system; the set of values assigned to the parameters defines a specific representation, referred to as a reference frame. The *orientation* parameter refers to the association of coordinate orthogonal axes with the vertical (above/below) and horizontal (front/back and left/right) dimensions. The *direction* parameter specifies the

relevant end point of a given axis (i.e., the above end point of the vertical axis). The *origin* indicates where the reference frame is imposed on the reference object. The *scale* parameter indicates the units of distance to be applied to space. The *spatial template* parses the space around the reference object into regions for which the spatial term offers a good, acceptable, or unacceptable characterization of the located object's placement (Carlson, Regier, & Covey, 2003; Carlson-Radvansky & Logan, 1997; Logan & Sadler, 1996). Section III examines the setting of each of these parameters more closely.

Not all spatial terms require all parameters of a reference system. For example, "near" requires scale, origin, and a spatial template, but not orientation or direction, whereas "front" requires scale, orientation, direction, origin, and spatial template. Moreover, for parameters necessary for a given spatial term, different sources of information (the viewer, the environment, or the reference object) can be used as the basis for setting these parameters, resulting in different types of reference frame [relative, absolute, and intrinsic, respectively (Levinson, 1996)]. Accordingly, establishing a reference frame involves both determining which parameters will be set (dependent on the spatial term) and selecting an appropriate source of information to define the range of values for each parameter.

Whether a given source of information is used as the basis for setting all of the necessary parameters for a given term or whether particular parameters may be set on the basis of different sources of information is an open and interesting question. For example, setting the origin of the reference system for the spatial term "above" is influenced by functional characteristics of the objects (Carlson-Radvansky et al., 1999), implicating an object-based or intrinsic system; however, the orientation and direction parameters for "above" are associated much more strongly with environmental information (Carlson-Radvansky & Irwin, 1993, 1994), implicating an absolute system.

B. A COMPUTATIONAL FRAMEWORK

One of the more articulated theories of apprehension that specifies particular processes and representations is Logan and Sadler's (1996) computational framework. According to this framework, apprehending spatial terms involves the following processes: (a) identifying and spatially indexing the reference and located objects (finding the relevant objects); (b) imposing a reference frame with appropriate settings on the reference object (assigning directions to space); and (c) evaluating the goodness of fit of the spatial term with respect to the placement of the located object within various regions on the spatial template (computing and comparing the spatial relation).

One important feature of this framework is that these constituent processes apply to a wide range of tasks within both production and comprehension, thereby accommodating various goals of the speaker and addressee. For example, in a relation judgment task, the speaker either informs the addressee of the whereabouts of a given object or seeks such information, as in 4a and 4b. In a cueing task, the emphasis is on the identity of one of the objects, and spatial relation is provided as a means of picking out the relevant object, as in 5a and 5b. Finally, in a verification task, the goal is to determine whether the spatial description is true of a given situation (6a), with an emphasis either on the relation (6b) or on the objects (6c).

- (4a) The mug is **BELOW** the coffee pot.
- (4b) Where is the mug?
- (5a) The **MUG** is below the coffee pot.
- (5b) What is below the coffee pot?
- (6a) The mug is below the coffee pot.
- (6b) Is the mug **BELOW** the coffee pot?
- (6c) Is the **MUG** below the coffee pot?

Particular words are capitalized in 4–6 to indicate the emphasis that a speaker may place in the service of communicating a particular goal. This raises an important methodological point. Many previous studies examining the processes and representations involved in apprehension have relied on written comprehension in which participants read spatial descriptions (Carlson & Logan, 2001; Carlson-Radvansky & Irwin, 1993, 1994; Carlson-Radvansky & Logan, 1997; Carlson-Radvansky & Tang, 2000; Clark & Chase, 1972; Logan & Sadler, 1996) rather than oral comprehension in which they hear spoken utterances. Participants in these studies are serving as addressees, much like readers serve as addressees for authors. However, the written version does not have a traditional means for conveying emphasis, as is the case for speech in which one can emphasize a word by pronouncing it more carefully, louder, or with a longer duration. As such, the particular goal is not overtly conveyed by the spatial description, as reflected by the fact that the descriptions corresponding to the various goals in 4a, 5a, and 6a are identical. Thus, in interpreting the results from these types of studies it is particularly important that the goal for the addressee is identified.

C. EVIDENCE SUPPORTING THE COMPUTATIONAL FRAMEWORK

Some evidence supports Logan and Sadler's (1996) decomposition of apprehension into the constituent steps (e.g., Carlson & Logan,

2001; Carlson-Radvansky & Logan, 1997; Carlson-Radvansky & Irwin, 1993, 1994; Logan & Compton, 1996; Logan, 1995). However, the evidence comes from separate experiments with different methodologies that target each step in isolation. In order to generalize across these differences, one must rely on the untested assumptions that the steps are independent and operate similarly across tasks. In addition, these tasks use measures that are tied to the final response of the subject, making it difficult to locate the influence of a given factor at a particular step.

To overcome these potential difficulties, Carlson, West, Taylor, and Herndon (2002) examined the constituent processes in apprehension (finding the relevant objects, assigning directions to space, and computing and comparing the spatial relation) using event-related potentials (ERPs). ERPs provide a continuous online measure of cognitive processing with real-time temporal resolution that enables one to obtain independent evidence for each step within the same task (e.g., Coles & Gratton, 1986; Donchin & Coles, 1988; Meyer, Osman, Irwin, & Yantis, 1988). In this study, participants performed a speeded sentence/picture verification task in which they were shown a sentence such as “The ball is above the watering can” followed by a picture containing two objects (e.g., a ball and a watering can) in some spatial relation. The task was to determine whether the sentence was an acceptable description of the picture as quickly and accurately as possible. Particular manipulations that targeted the constituent processes were employed, and distinct modulations of the ERPs were observed that were associated with these manipulations.

1. Finding the Relevant Objects

Processes involved in finding the relevant objects in the display were expected to be influenced by manipulating the orientation of the reference object, given evidence that rotation of the reference object increases the difficulty of the identification process (e.g., McMullen & Jolicoeur, 1990; Maki, 1986). This manipulation resulted in an amplitude modulation of P3, the third positive deflection in the ERP waveform following the onset of the picture stimulus. The time course and topography of this effect are presented in Fig. 1. In the data one can clearly see that the amplitude of the P3 was greater when the reference object was in an upright canonical orientation (solid line) than when it was rotated 90° into a noncanonical orientation (dot and dashed lines). This effect is consistent with other data indicating that the amplitude of the P3 component is sensitive to the ease with which a task relevant stimulus can be identified (Bajrić, Rösler, Heil, & Hennighausen, 1999; Donchin & Coles, 1988; Kok, 1997, 2001). Within the sentence/picture verification paradigm, the sentence picks out particular

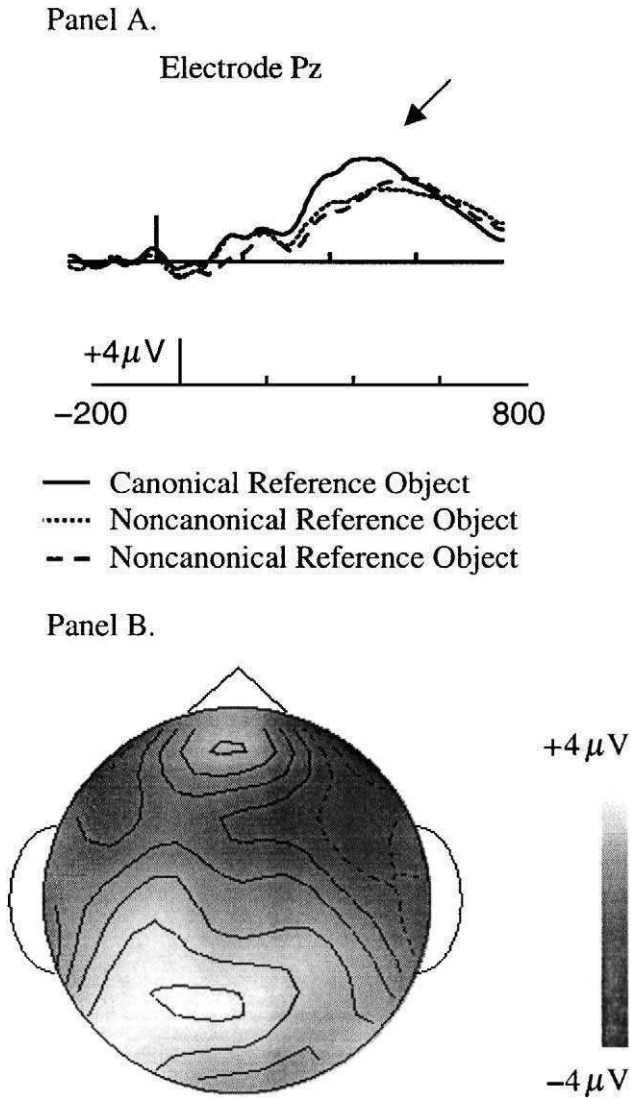


Fig. 1. Event-related potentials (A; electrode Pz) and topographic map (B) showing an influence of the orientation of the reference object on the P3 effect.

objects that must be identified. This process is more difficult when the objects are harder to identify, thereby reducing the amplitude in the noncanonical conditions relative to the canonical conditions.

2. *Assigning Directions to Space*

Processes involved in assigning directions to space were expected to be influenced by manipulation of the different sources of information used to define the parameters of the reference frame. When multiple sources of information are available and assign competing directions to a given spatial term, there is significant competition (Carlson-Radvansky & Irwin, 1994). For example, consider the three pictures depicting a ball (the located object) around a watering can (reference object) at the bottom of Fig. 2. In the canonical absolute/intrinsic picture, the ball can be considered above the watering can both with respect to the picture environment (absolute frame) and with respect to the top side of the watering can (intrinsic frame). However, in the noncanonical absolute picture, the ball is above the watering can with respect to the absolute frame but not with respect to the intrinsic frame. This is because rotation of the reference object results in a dissociation of intrinsic above from absolute above. Similarly, in the noncanonical intrinsic picture, the ball is above the watering can with respect to the intrinsic frame but not with respect to the absolute frame. In previous work, significant competition was observed for mapping the spatial term “above” onto placements of the located object in the noncanonical absolute and noncanonical intrinsic conditions relative to the canonical absolute/intrinsic conditions (Carlson-Radvansky & Irwin, 1994). Moreover, the degree of competition depended upon one’s preference for using the different reference frames, with a stronger preference observed for the absolute frame than the intrinsic frame for defining “above” (Carlson-Radvansky & Logan, 1997).

Carlson et al. (2002) used this competition as a means of targeting the processes involved in assigning directions to space. Specifically, an instructional manipulation was used that defined which reference frame to use across different blocks of trials. In one block of trials, participants were told to define above with respect to the absolute frame, in another block with respect to the intrinsic frame, and in another block with respect to either the absolute or intrinsic frame, with the order of blocks counterbalanced across subjects. Competition was expected in the intrinsic and either blocks of trials, because in these blocks, the less-preferred intrinsic reference frame served as the basis for responding on all trials in the intrinsic block and on some trials in the either block. However, competition was not expected in the absolute block of trials in which participants were instructed to base their responses solely on the more-preferred absolute reference frame.

ERPs at electrode FPl are shown in Fig. 3 as a function of instruction condition, along with a topographical map illustrating the distribution of

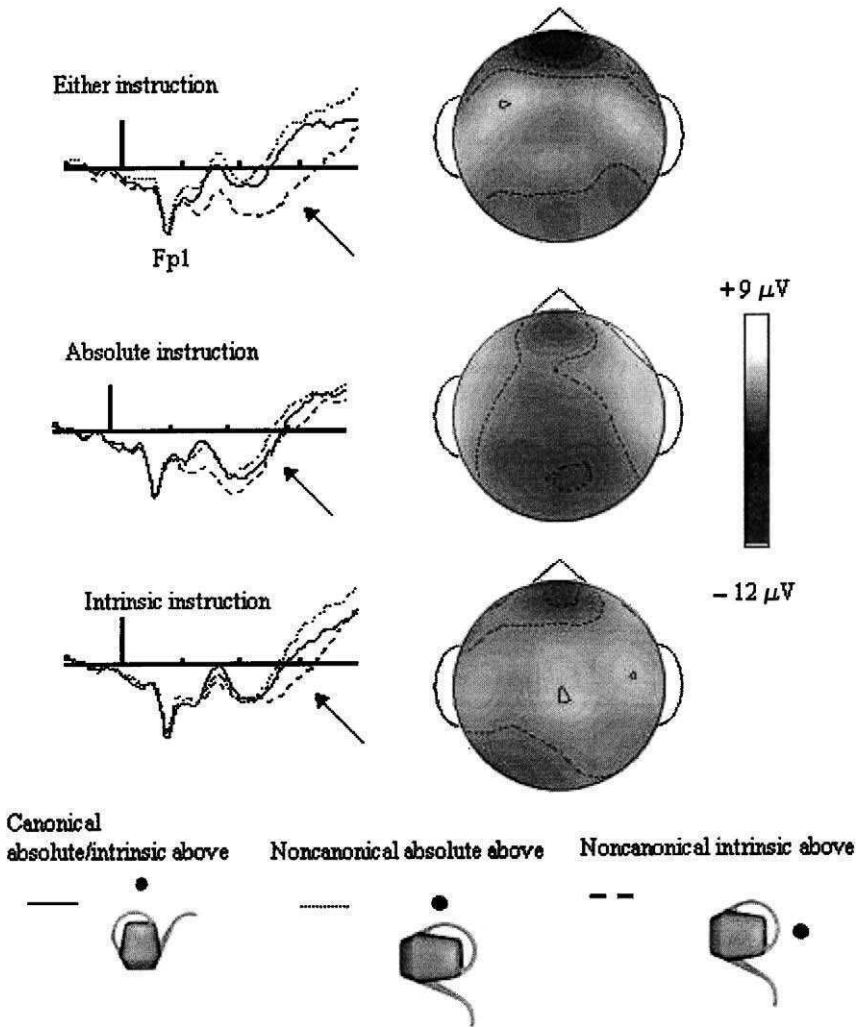
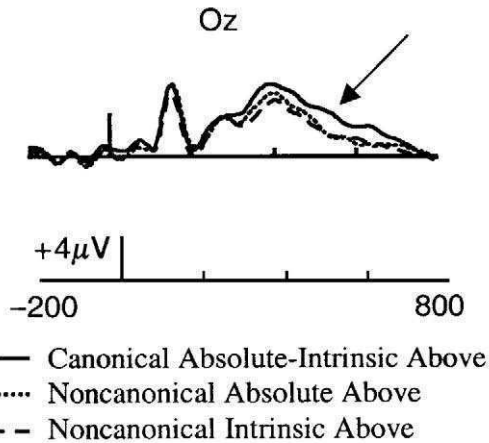


Fig. 2. Event-related potentials and topographic maps showing competition between reference frames as a function of instruction condition on a frontal slow wave. (A) The either instruction condition, (B) the absolute instruction condition, and (C) the intrinsic instruction condition.

the effect over the scalp. The magnitude of competition was reflected in the amplitude of a frontal slow wave that began around 450 ms after stimulus onset and persisted over the remainder of the trial, with the less-preferred intrinsic frame (dashed line) separating from the more-preferred absolute

Panel A.



Panel B.

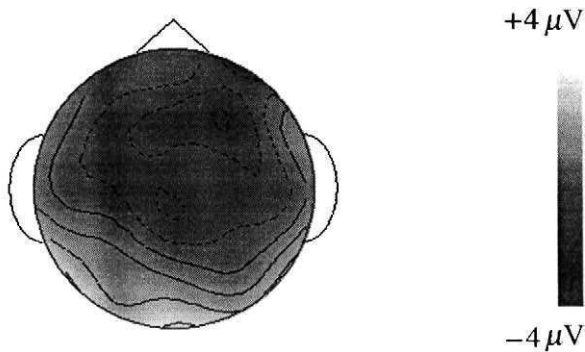


Fig. 3. Event-related potentials (A; electrode Oz) and topographic map (B) showing an influence of the orientation of the reference object and the resulting change in accessing the underlying spatial templates on a parietal slow wave effect.

frame (dotted line) and the canonical absolute/intrinsic frame (solid line) in the either and intrinsic blocks but not in the absolute block of trials. The frontal distribution of this slow wave is consistent with the modulations of the ERPs observed in other studies examining the neural correlates of conflict processing (West & Alain, 1999; Liotti, Woldorff, Perez, & Mayberg, 2000) and with evidence from functional neuroimaging studies indicating that the frontal cortex is consistently activated when stimulus or

response competition exists within a task (Banich, Milham, Atchley, Cohen, Webb, Wszalek, Kramer, Liang, Wright, Shenker, & Magin, 2000; Taylor, Kornblum, Minoshima, Oliver, & Koeppe, 1994).

3. Computing and Comparing the Spatial Relation

Processes involved in computing and comparing the spatial relation were expected to be influenced by manipulation of the orientation of the reference object. This constituent step involves evaluating whether the placement of the located object falls within a good, acceptable, or bad region of a spatial template associated with a particular term (e.g., the one provided in the sentence). Assuming that a spatial template is constructed for each active reference system (Carlson-Radvansky & Logan, 1997) on noncanonical trials in which the reference object is rotated and the absolute and intrinsic reference frames assign different directions to the same relation, multiple templates associated with “above” would be constructed and evaluated (i.e., a template for absolute above and a template for intrinsic above). In contrast, on canonical trials, these multiple templates would be aligned, thus rendering the same response. As such, it is possible that only one template may need to be evaluated or, if many are evaluated, it is likely that there would be some facilitation due to the generation of the same response (e.g., redundancy gain; Miller, 1982; Mordkoff & Yantis, 1991; Raab, 1962). Either way, processing on noncanonical trials would be expected to be different from processing on canonical trials.

As shown in Fig. 3, the effect of the orientation manipulation was observed as a modulation of a parietal slow wave that began around 450 ms postpicture onset, with noncanonical trials (dashed and dotted lines) separating from canonical trials (solid line). A topographic map illustrates the distribution of this effect over the scalp. Importantly, this modulation was distinct both spatially and temporally from the effect of rotation on the P3 component, indicating that different neural generators contribute to the identification of relevant objects and computing the spatial relation. It is possible that this modulation reflects slow wave activity associated with working memory processes such as updating and search (Kok, 2001) that would occur during the evaluation of multiple spatial templates.

III. Assigning Directions to Space: Setting the Parameters

As reviewed in Section II, evidence supports the breakdown of apprehension into constituent steps of finding the relevant object, assigning directions to space, and computing and comparing the spatial term. Most previous

research has focused on the assignment of directions to space, a process that is accomplished through the setting of the relevant parameters of the reference system. This section discusses ongoing research on the setting of each of these parameters, with a particular focus on the influence of the particular objects and their interaction on these settings.

A. THE ORIGIN PARAMETER

1. Defining the Origin Relative to a Functional Part

Origin has been defined as the intersection point of the axes of a reference frame (Miller & Johnson-Laird, 1976) and is taken to indicate where the reference frame is imposed on the reference object. Given theoretical suggestions that the reference object is represented in a relatively abstract, axial-based form (Landau & Jackendoff, 1993; Regier, 1996; Talmy, 1983), it has typically been assumed that the origin is imposed on the basis of the geometric properties of the reference object, most usually at its center of mass (Gapp, 1995; Regier, 1996; Schirra, 1993). However, Carlson-Radvansky et al. (1999) demonstrated that the identity of the reference and located objects and their functional interaction play a significant role in defining the origin. Specifically, they presented participants with pairs of pictures of real-world objects and asked participants to place one object above or below the other object. Placements of the located object were assumed to reflect the best use of these spatial terms. Given that other paradigms have shown that the best use falls on the axis of the reference frame (Carlson-Radvansky & Logan, 1997; Hayward & Tarr, 1995; Logan & Sadler, 1996), these placements are taken to indicate the origin of the reference frame (for discussion, see Carlson, 2000). The pairs of objects were created with the constraint that the located object would typically be placed above or below a given part of the reference object in order to fulfill a particular function. This part is referred to as the functional part. For example, a tube of toothpaste (located object) is typically placed above the bristles (functional part) of a toothbrush (reference object) in order to fulfill the function of putting toothpaste on the toothbrush. A coin (located object) is typically placed above the slot (functional part) in a piggy bank (reference object) in order to insert the coin in the bank. The reference objects were photographed from a sideways perspective that offset the functional part from the center of mass of the object. This enabled an examination of whether participants would define the best placement of “above” relative to the center of mass of the object, indicating reliance on geometric factors for defining the spatial term or relative to its functional part, indicating a sensitivity to the identity of the reference object and its functional relationship with the located object.

Placements were measured relative to a line running through the center of mass of the objects, with deviations from this line toward the functional part coded as a functional bias. The critical result was that all objects showed a functional bias. Given that the objects varied in how far apart the functional part was from the center of mass of the object, the best way to characterize the functional bias was to express it in terms of the percentage of this distance, with 100% indicating a placement directly over the functional part and 0% indicating a placement directly over the center of mass. On average, located objects were placed at positions that corresponded to 72% of the distance between the center of mass and the functional part. This deviation was significantly smaller, although still positive (45%), when a functionally unrelated object matched in size and shape was used instead of the functionally related object (e.g., ring versus coin for the piggy bank; tube of oil paint versus tube of toothpaste for the toothbrush). The fact that there was a functional bias for these unrelated objects indicates an influence of the functional parts of the reference object on defining where the reference frame would be imposed. The fact that the functional bias was stronger for functionally related located objects indicates an influence of the functional interaction between the objects on setting the origin.

2. The Role of Context in Defining the Functional Part

One potential limitation to the Carlson-Radvansky et al. (1999) work is that the functional bias was defined with respect to a functional part that was predetermined by the experimenters as functionally important, particularly in the context of a given located object (e.g., the tube of toothpaste interacts with the bristles, rendering the bristles the functional part). It is likely that these parts are not always considered the most functional parts of the objects. Indeed, although all reference objects showed a positive functional bias, the degree of bias varied widely across pairs of objects and across different types of functional interactions (see Carlson and Covell, in press). Moreover, many objects have many functional parts, and these parts may become differentially important depending upon the goal for which one is using the object.

Kenny and Carlson (2003) began an investigation into the role that context plays in defining the functional importance of the parts of an object. At the beginning of the experiment, participants watched a video that depicted objects involved in one of three types of interactions; this constituted the critical context manipulation. Two of the interactions emphasized different functional parts of the reference object. For example, in a scene with a toaster serving as a reference object, one interaction

involved putting a piece of bread into the slots of toaster. The bread was the located object, and the functional part was the slots. In contrast, a different interaction involved pressing down the lever activating the toaster. The hand was the located object, and the functional part was the lever. In the third interaction, the toaster was simply picked up and then put back down. There was no located object, and no functional part was emphasized. This was the neutral context condition and served as a baseline from which to assess the relative importance of the functional parts in the absence of context.

A given participant saw only one type of interaction for a given object, but across participants, each type of interaction was viewed by at least seven participants for each of 18 reference objects. Following the video, all participants performed an identical placement task in which they were asked to place pictures of a beanbag (a functionally unrelated object) *near* pictures of the objects that they viewed in the video; these objects thus served as reference objects. A functionally unrelated located object (beanbag) was used so that placements would not be biased by virtue of the identity of the object and its possible interaction with the reference object. This is important because we were interested in assessing whether a previous interaction with a reference object would bias one's later interpretation of space surrounding that object in a seemingly unrelated task. The prediction was that if the context provided by the video served to highlight one functional part of the object over another, and if this functional salience played a role in defining space around the reference object, then one should see a bias in participant's placement of the located object toward that functional part. This would contrast with Logan and Sadler's (1996) findings from a placement task in which participants were instructed to draw a dot "near" a square; placements were distributed around all sides of the reference object.

Data for two reference objects (bottle opener and toaster) are shown in Fig. 4. The symbols correspond to the placements of the beanbags by different participants and are coded as a function of the type of interaction that participants viewed prior to the placement task. Four features in the data can be noted. First, for participants who saw the neutral context, placements were at both functional parts and in other locations around the reference object. Second, for participants who viewed a functional context, there was a systematic bias to place the beanbag near the functional part that was emphasized by the context. For example, participants viewing the bread context for the toaster were more likely to put the beanbag near the slots than near the lever or anywhere else, whereas participants viewing the lever context for the toaster were more likely to put the beanbag near the lever than the slots or anywhere else. To quantify this effect, for each object, we defined a midpoint between the two functional parts and measured

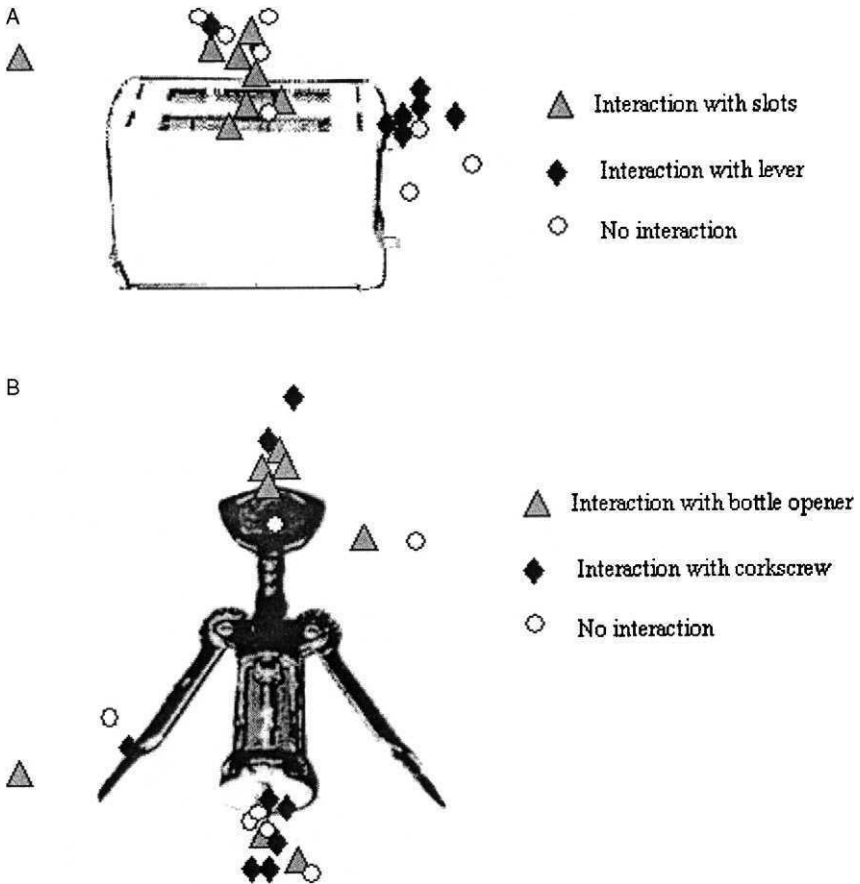


Fig. 4. Placements of the beanbag around a toaster (A) and bottle opener (B) coded as a function of the observed interaction with the object.

placements in the two context conditions relative to this midpoint, coding them as positive if they were biased toward a contextually emphasized part and negative if they were biased away from the contextually emphasized part. Given that the distances between the parts varied across objects, the deviations were converted into proportions of the distance between the midpoint and the center of the functional part, with 0% indicating placements over the midpoint and 100% indicating placements over the center of the emphasized functional part. On average, there was a positive bias ($M = .31$, $SEM = .11$) that differed significantly from 0 [$t(17) = 2.74$, $p < .014$], indicating a preference for placing the located object with respect to the emphasized functional part. Third, this bias was not complete; not all

participants within a given context placed the beanbag with respect to the emphasized functional part. This is similar to the incomplete bias (mean deviation <100%) obtained by Carlson-Radvansky et al. (1999) for placements of a functionally related object relative to a preselected functional part. Presumably the center of mass of the object also played a role in biasing the placements; this is currently being investigated. Finally, the functional parts seem to have differential salience, as reflected in different degrees of bias. To demonstrate this, for each object, placements were recoded as deviations from the midpoint of the distance between the centers of the two functional parts, with negative values associated with placements biased to the leftmost functional part (arbitrarily defined as part 1) and positive values associated with placements biased to the rightmost functional part (defined arbitrarily as part 2). Mean deviations and statistical comparisons are shown in Table I. The fact that the functional bias toward part 2 was significantly different from the neutral context indicates an influence of the video context on performance in the spatial language task. The fact that the neutral context had a negative value indicates a preexisting bias to place the object toward functional part 1. Moreover, emphasizing part 1 did not enhance this bias. Current work is examining more precisely how the type of functional part impacts its salience. Table I also shows the mean number of placements that were biased positively toward part 2. These were computed by calculating the number of positive placements (out of eight possible) for each object and then averaging across objects. The relatively large number of objects that were biased positively for the context emphasizing part 2 indicates that the deviation percentages were not due to large deviations associated with one or two particular objects.

TABLE I

MEAN DEVIATIONS AND NUMBER OF OBJECTS EXHIBITING A POSITIVE DEVIATION AS A FUNCTION OF CONTEXT CONDITION^a

Context	Mean deviation	Mean No. biased toward part 2
Emphasize part 1	-.109 (.138)*	3.6 (.422)*
Emphasize part 2	.505 (.148) [†]	5.7 (.341) [†]
Neutral	-.106 (.158)*	3.9 (.491)*

^aMean deviations are expressed as the proportion of distance between midpoint and the functional part, with negative deviations reflecting a bias toward part 1 and positive deviations reflecting a bias toward part 2. The maximum number of placements per object was 8. Conditions with different superscripts are significantly different ($p < .01$). Standard errors are in parentheses.

In summary, there was a contextual influence on performance in the placement task, with prior experience with the reference object in a particular interaction biasing the salience of the functional parts (see also Lin and Murphy, 1997) and in turn altering the parsing of space around the object within a spatial language task. However, this bias was not complete and varied in strength across parts within an object and across objects. Thus, functional information about the reference object seems to work in concert with other information, most likely geometric, in setting the origin. Moreover, it is likely that the relative influence of these two sources of information depends on the particular spatial relation (Carlson, 2000; Coventry, Prat-Sala, & Richards, 2001). For example, Coventry and colleagues (2001) showed a stronger functional bias for the spatial terms over/under than for above/below. We are currently pursuing the influence of these types of contexts on setting the origin with respect to particular functional parts for other spatial terms, including “above” and “below.”

B. ORIENTATION AND DIRECTION PARAMETERS

1. *Distinct Representations for Axes and End Points*

The two parameters “orientation” and “direction” are hierarchical in nature in that orientation corresponds to the assignment of an axis of a reference frame to a particular spatial dimension (horizontal or vertical), whereas direction corresponds to the particular end points of a given axis. Nevertheless, these are distinct parameters that seem to be represented separately. For example, Logan (1995, 1996) used a spatial cuing task in which participants had to report the color of a located object that was indicated by its spatial location with respect to a central reference object. In some conditions, a distractor object appeared at the opposite end point from the located object (e.g., a located object placed above a reference object and a distractor placed below it), and the two objects could be the same color or different colors. This is an interesting comparison because when the objects were the same color, participants only need to compute the orientation of the relevant axis in order to make their judgment. That is, because the end points were the same, they could pick either object and respond correctly, with no need to assign the spatial term to a particular endpoint. However, when the target and distractor differed in color, participants need to compute both the orientation and the direction in order to access the correct end point and report the correct color. Logan found that response times were significantly faster when the target and distractors were the same color than different colors, indicating that the orientation and direction parameters can be set separately.

Converging evidence for separate representations for direction and orientation comes from research on patients with spatial deficits (McCloskey & Rapp, 2000; Hoffman, Landau, & Pagani, 2003). For example, Hoffman et al. (2003) observed that patients with Williams syndrome have impaired representation of direction but not axial structure in a block construction task, more often placing blocks at the opposite end point within the correct axis (e.g., below rather than above) than on a different axis (e.g., left rather than above).

2. *Selecting a Reference Frame: Evidence for Inhibition*

a. An Initial Demonstration Given that these parameters operate at different levels of representation, it is important to specify the locus at which a given process operates. Carlson-Radvansky and Jiang (1998) examined this question in the context of selecting a reference frame when different sources of information do not agree on the orientation to assign a given axis (for an overview, see Carlson, 1999); an example would be rotating the reference object into a noncanonical orientation, thereby dissociating the absolute and intrinsic reference frames (see Section IIC2 and Fig. 2, bottom). Competition is assumed to result due to the simultaneous activation of these reference frames (Carlson-Radvansky & Irwin, 1994), and resolving this competition requires the selection of one frame over another.

Carlson-Radvansky and Jiang (1998) demonstrated that the selection of a reference frame involved inhibiting the nonselected frame actively, such that use of that frame on subsequent trials was difficult. This is consistent with the manner in which selection operates within other domains, such as visual attention, in which selection is more efficient when the nonintended items are made less accessible (for reviews, see Fox, 1995; May, Kane, & Hasher, 1995). With respect to spatial language, Carlson (1999) speculated that such inhibition could serve as a useful mechanism that would bias speakers to consistently use the same reference frame across utterances within a conversation, thereby enabling coordination between speaker and listener (Garrod & Anderson, 1987; Schober, 1993).

The general paradigm is illustrated in Fig. 5 using stimuli from Klatt and Carlson (2003). Trials were grouped in pairs, with each pair consisting of a prime trial followed by a probe trial. There were different types of trial pairs, defined by the prime display. For all types, the probe trials were identical, using the same objects and the same spatial term; in the case of the probe trial in Fig. 5, the reference object was a sport utility vehicle, the located object was a ball, and the spatial term was “above.” The critical dependent variable was the response time on these probe trials for verifying that the spatial term corresponded to the spatial relation between the objects in


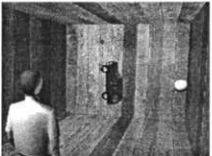

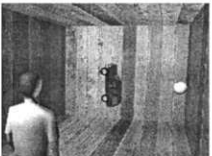




TRIAL TYPE	PRIME DISPLAY AND TERM	PROBE DISPLAY AND TERM
CONTROL	 ABOVE	 ABOVE
END POINT	 ABOVE	 ABOVE
SAME AXIS	 BELOW	 ABOVE
ACROSS AXES	 RIGHT	 ABOVE

Fig. 5. Prime and probe displays illustrating the negative priming paradigm used to assess the level at which inhibition was applied within the reference frame.

the display. Participants were instructed to define “above” both with respect to the absolute reference frame and with respect to the intrinsic reference frame, such that they should make a “yes” response if the located object was placed with respect to either frame.

Of interest was how the probe response times varied as a function of the different types of prime trials. In the *control* prime trial, participants would respond “yes” on the basis of defining above with respect to the absolute reference frame. Because the reference object (soccer ball) does not have predefined intrinsic sides, the intrinsic reference frame is not active. Consequently, there is no competition, and hence no need for inhibition. In contrast, in the *end point* prime trial (referred to as the matched relation condition by Carlson-Radvansky & Jiang, 1998), the reference object (shoes) has predefined sides, thereby supporting the use of an intrinsic reference frame. The reference object has been rotated, dissociating the intrinsic frame from the absolute frame. This results in competition among the frames and a consequent need for selection. Note that the placement of the located object is above with respect to the absolute reference frame. Accordingly, participants would select absolute above, as on the control prime trial. The difference is that the intrinsic frame is available and presumably active on the experimental prime trial, but not on the control prime trial. On all probe trials, the located object is placed above with respect to the intrinsic reference frame; accordingly, participants need to use intrinsic above. If selection involves inhibition of active competing frames, then intrinsic above would have been inhibited on the end point prime trial but not the control prime trial. As a consequence, use of intrinsic above on the end point probe trial should be more difficult than on the control probe trial, as reflected in longer response times. This difference between experimental and control probe trials is referred to as negative priming.

Carlson-Radvansky and Jiang (1998) found significant negative priming on the end point trials, suggesting that inhibition was applied to intrinsic above on the prime trial. Importantly, they also found significant negative priming on same axis trials (mismatched relations, Carlson-Radvansky & Jiang, 1998), illustrated in Fig. 5. On these trials, the spatial term on the prime trial (i.e., below) is at the opposite end point as the spatial term (i.e., above) on the probe trial. Because an equal amount of negative priming was observed for these trials as for end point trials, this suggests that inhibition was applied to the intrinsic vertical axis, encompassing both end points. This could suggest that selection of the absolute frame over the intrinsic frame on the prime trial occurred prior to the assignment of particular end points, consistent with the idea that orientation can be assigned separately from direction (Logan, 1995, 1996).

b. How and Why Is Inhibition Applied? Central to understanding how and why inhibition is applied during reference frame selection is determining why a given frame is activated on the prime trial. Klatt and Carlson (2003) set about to address this question. One obvious possibility is that it is

activated because it corresponds to the spatial term that is being verified. For example, assignment of the spatial term “above” on the prime trial would involve picking out the vertical axis on the absolute frame, picking out the vertical axis on the intrinsic frame, determining whether the placement of the located object fell along the vertical axis of either frame, and if so, choosing the appropriate frame and inhibiting the other. Klatt and Carlson (2003) reasoned that if this were the case, then negative priming should only be observed when spatial terms referring to the same axis are used on prime and probe trials (as in end point and same axis trials), but *not* when spatial terms corresponding to different axes are used on prime and probe trials, referred to as *across axes* trials, illustrated in Fig. 5. For example, use of the term “right” on the prime trial should active the left/right axis on both absolute and intrinsic frames, with a corresponding inhibition of the intrinsic left/right axis. As such, negative priming should only be observed when left/right are probe terms and not when above/below are probe terms.

To assess this issue, in separate experiments, negative priming was assessed using above/below or left/right as probe terms and above/below, front/back, and left/right as prime terms. The resulting negative priming effects and standard errors of the mean are presented in Table II as a function of prime and probe term. Counter to the hypothesis that the spatial term on the prime picks out the appropriate intrinsic axis that is subsequently inhibited, the pattern of negative priming effects indicates that the intrinsic above/below axis is always inhibited, regardless of the prime, and that the intrinsic left/right axis is never inhibited. This interesting result suggests a primacy associated with the intrinsic above/below axis,

TABLE II

MEAN NEGATIVE PRIMING EFFECT (IN MS) AND STANDARD ERROR OF THE MEAN (IN PARENTHESES) AS A FUNCTION OF PRIME TRIAL TYPE^a

Prime term	Probe term	Level	Negative priming
Above/below	Above/below	End point	-48 (13.6)*
Below/above	Above/below	Within axis	-32 (18.1) [†]
Left/right	Above/below	Across axes	-38 (9.6)*
Front/back	Above/below	Across axes	-29 (5.9)*
Left/right	Left/right	End point	3 (20.9)
Right/left	Left/right	Within axis	-14.3 (19.5)
Above/below	Left/right	Across axes	-15.9 (14.2)
Front/back	Left/right	Across axes	-3 (14.2)

^aSymbols after negative priming effect indicate outcome of tests of significance against 0 ms, with * $p < .001$; [†] $p = .08$.

perhaps due to its involvement in object recognition (i.e., in assigning the top and bottom sides to the reference object). This would be consistent with the idea that intrinsic axes underlying object recognition are recruited for spatial language use within the intrinsic reference frame (Logan & Sadler, 1996). Moreover, these data indicate that inhibition of a nonselected frame occurs prior to assigning the spatial term to a specific axis or end point and is applied to axes that are active as a consequence of earlier processes, such as identifying the objects during the constituent step of finding the relevant objects.

C. THE SCALE PARAMETER

1. Conveying Distance

Logan and Sadler (1996) postulated the existence of a scale parameter for reference frames that is typically assumed to refer to the distance between located and reference objects. However, no precise definition of this parameter has been offered, and it is not clear whether Logan and Sadler's use of "scale" as opposed to "distance" was intended to presuppose in addition that this distance was divided into fixed intervals. Moreover, very little empirical work has been done to test which spatial terms convey a distance (much less a scaled distance), thereby requiring this parameter. For example, Logan and Sadler (1996) asserted that projective spatial terms such as "above" or "right" do not require the scale parameter, suggesting that a distance may not be conveyed when these terms are used.

Carlson and colleagues (2003) tested whether spatial terms such as "above," "below," "left," and "right" convey a distance during use by having participants perform a speeded sentence/picture verification task with sentences containing these spatial terms and displays containing letters. Pairs of trials (primes and probes) were constructed, and the critical manipulation was whether the distance between the letters was held constant or changed across the prime and probe trials of a given pair. All other relevant features were manipulated across prime and probe trials within a pair, including the identity of the letters, their placement in the display, and the spatial term being verified. The logic was that if use of a spatial term on a given trial involved setting the distance parameter of the reference frame, then there should be facilitation on a subsequent trial when the same distance setting could be used, relative to when the parameter had to be set to a different distance. Carlson et al. (2002) showed considerable savings on probe trials when the preceding prime trials had the same distance as opposed to a different distance, and this effect did not depend on maintaining the identity of the letters, the placement of the letters, or the spatial term across the prime and probe trials.

This is strong evidence that the use of projective spatial terms such as “above” involves computing a distance between the relevant objects, counter to the claim by Logan and Sadler (1996). Three additional points must be made with respect to this finding. First, the distance corresponded to the physical distance between the two objects in the display rather than a distance that had to be inferred or computed. As such, one could think about the facilitation in terms of movements of attention from the reference object to the located object. Across consecutive trials, when attention had to move the same distance, there was a benefit, relative to when attention had to move a different distance. This interpretation still supports the setting of a distance parameter within a reference frame, based on Logan’s (1995) suggestion that reference frames are the mechanism by which attention moves through space.

Second, given that the distance corresponded to physical space, it is not clear whether it would have been scaled. The displays were constructed by placing the letters within cells of an invisible grid, and it is possible that across trials, participants may have been able to reconstruct the underlying grid, mapping the distance between the letters onto units corresponding to the rows and columns of the grid. However, until there is direct evidence in support of a scaled distance, Carlson et al. (2002) proposed that this parameter should be referred to as “distance” rather than “scale.”

Third, the letters in the display were functionally unrelated objects, a necessary feature of the design to ensure that any distance effects that were observed could be attributed to the spatial term. However, spatial terms are used more typically in the context of describing locations of real objects, some of which may be functionally related. It is likely, therefore, that the distance conveyed by a spatial term is dependent on the particular objects being spatially related, an issue addressed next.

2. Influences of Object Characteristics on the Conveyed Distance

The following thought experiment illustrates nicely the potential impact of the particular objects on the distance implied by the spatial description. Recall the scene surrounding utterance 1, in which the colleague placed his mug below the coffee pot. When imagining this scene, a certain distance is assumed, a distance at which the presumed interaction between the two objects (pouring coffee into the mug) will be successful. Now imagine changing the mug into an espresso cup. It is likely that the distance that is inferred between the two objects is now necessarily smaller. Carlson et al. (2002) examined the potential influence of the size of the located and reference objects on the distance inferred between them using a paradigm developed by Morrow and Clark (1988) for examining the verb “approach.”

Specifically, participants were provided with a setting sentence that described a perspective onto a scene, as in sentence 7.

(7) I am standing in my living room looking across the snow-covered lawn at my neighbor's house.

This was followed by one of the following sentences (8–11) that related two objects spatially.

(8) The neighbor has parked a snowblower in front of his mailbox.

(9) The neighbor has parked a snowblower in front of his house.

(10) The neighbor has parked a snowplow in front of his mailbox.

(11) The neighbor has parked a snowplow in front of his house.

The task was to estimate the distance between the two objects. Critical manipulations included the size of the located object (small, i.e., snowblower, and large, i.e., snowplow) and the size of the reference object (small i.e., mailbox and large i.e., house). A given participant saw a given sentence only once, but across the set of materials, provided estimates in all conditions. In addition, some participants provided ratings for the spatial terms front/back, others for near/far, and others for left/right.

The critical finding was that distance estimates varied as a function of the size of the objects, with estimates associated with smaller objects significantly smaller than estimates associated with larger objects. One possible reason for this finding is that smaller objects need to be closer together to enable a successful interaction (Morrow & Clark, 1988). This is a clear demonstration of an influence of the objects and their interaction on the setting of the distance parameter.

In addition, there was a distinct contribution of the particular spatial term on the distance that was conveyed. That is, for a given spatial description, holding the identity and size of the reference and located objects constant, the distance inferred for “near” was significantly smaller than the distance conveyed for “far.” This is an obvious finding, given that distance is an explicit component to the definition of these terms. More interestingly, the distance estimated for “front” was significantly smaller than the distance estimated for “back.” Note that these estimates were provided by the same participants so the effect cannot be explained by differences across subjects in the estimation process. Rather, it may be related to the idea that “front” is privileged relative to “back,” given that it corresponds to our typical direction of locomotion, the direction in which our perceptual apparatus point (Clark, 1973), and the region in which we are most likely to interact with other objects. Moreover, this observed difference between front and back is consistent with the idea that they are asymmetric terms, with “front” mapped onto a disproportionately wider space that extends into the left and

right regions relative to a narrower “back” region (Franklin, Henkel, & Zengas, 1995); memory for objects placed in front of oneself is also more accurate than memory for objects placed behind oneself. How such differences in front and back are converted into smaller front estimates is an interesting question. In contrast, there was no difference in the magnitude of the distance estimates between “left” and “right,” terms that are considered symmetric (and hence easily confusable).

These results provide evidence for a distance parameter of a reference frame that is set in accordance with either a physical distance or an inferred distance. Two sources of influence on the manner in which the distance is set are the characteristics of the objects being related, such as their size, and the particular spatial term being used.

D. SPATIAL TEMPLATES

Spatial templates parse space around the reference objects into regions. There is a spatial template for each spatial term, and during apprehension, they are imposed in sequence on the reference object and aligned with the reference frame on the basis of its parameter settings (Logan & Sadler, 1996; for a detailed discussion relating spatial templates and reference frames, see Carlson et al., 2003). For example, the orientation parameter is used to align the good region of the “above” template with the above end point of the vertical axis. Placement of the located object is then evaluated with respect to the regions demarcated within the spatial template. Logan and Sadler (1996) initially identified three regions within a spatial template (good, acceptable, and bad) on the basis of a rating task in which participants were shown displays containing a central reference object and a located object placed in various locations around it. For each placement, participants provided an acceptability rating of a spatial term as a description of the spatial relation between the objects. Logan and Sadler (1996) plotted the acceptability ratings as a function of the placement of the located object, referring to the resulting plot as a spatial template (see also Hayward & Tarr, 1995). The “good” region corresponds to best placements of the located object; this region is associated with placements that fall on the relevant axis of the reference frame. The acceptable region corresponds to placements with intermediate acceptability surrounding the relevant axis. The bad region corresponds to unacceptable placements in regions at the opposite end point of the relevant axis or along different axes.

1. Mechanisms Underlying the Spatial Template: The AVS Model

The shape of a spatial template and its regions is generally preserved across the different types of reference frames, across different reference and located

objects, and across different spatial terms. This suggests a common set of mechanisms involved in spatial template construction that operate across the diverse contexts. Regier and Carlson (2001) presented a computational model that defines spatial term use with respect to two general mechanisms: attention and vector sum (AVS) coding of direction. According to the AVS model, an attentional beam is centered at a point on the reference object and radiates out to encompass the located object. Attentional strength is maximal at the focus of the beam and drops off with distance (Downing & Pinker, 1985; LaBerge & Brown, 1989). As a result, some parts of the reference object receive more attention than others. The attentional beam is illustrated in Figure 6a, with the rectangle as the reference object and the filled circle as the located object.

In addition to the attentional beam, the direction of the located object with respect to the reference object is represented as a population of vectors that project from each point along the reference object to the located object, as illustrated in Fig. 6b. The representation of direction as a sum over a population of vectors has been observed in diverse neural subsystems (e.g., Georgopoulos, Schwartz, & Kettner, 1986; Wilson & Kim, 1994), suggesting that it may be a widely used means of encoding direction.

The attentional beam and the vector sum are combined by weighting each vector as a function of the amount of attention being allocated to its point on the reference object, shown in Fig. 6c. The resulting weighted vectors are then summed to create an overall direction (shown in Fig. 6d), and its alignment with respect to a reference direction (such as upright vertical for “above”) is measured (Fig. 6e). In general, perfect alignment with the reference direction corresponds to the best use of a spatial term, corresponding to Logan and Sadler’s (1996) good region. Acceptability drops off in a linear fashion with increasing deviations from the reference axis, corresponding to Logan and Sadler’s acceptable regions. Finally, there is a cut-off below which the term is not considered acceptable, regardless of the vector sum, corresponding to Logan and Sadler’s bad region. Regier and Carlson (2001) provided a formal presentation of the model and demonstrated that it outperforms various competing models both quantitatively in terms of the fit to empirical data and qualitatively in terms of its output illustrating the effects of interest.

2. Function and the AVS Model

The AVS model was developed and tested using several different types of reference objects, including rectangles (as in Fig. 6), triangles, and L-shaped figures. However, these are all strictly geometric shapes, and as such, one limitation of AVS is that it ignores the role of the function of the objects

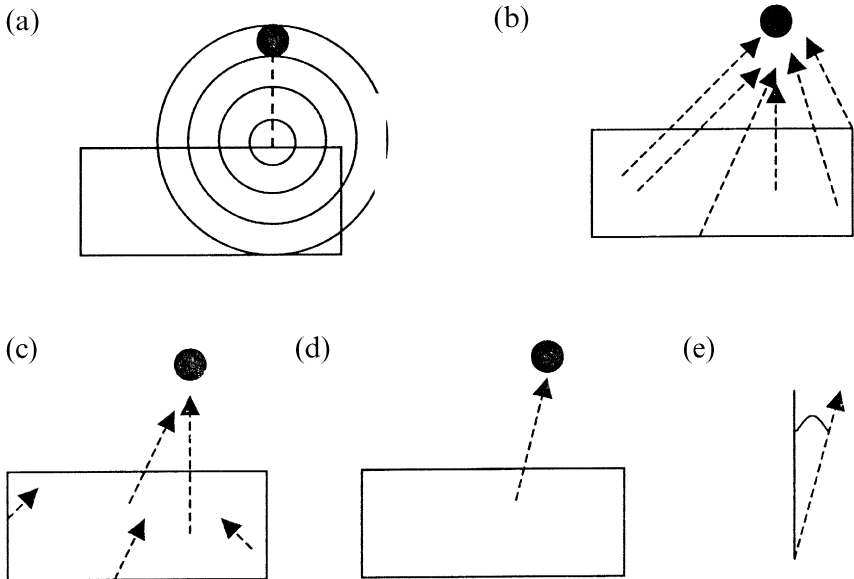


Fig. 6. Illustration of the attention-vector sum model applied to “above.” (a) An allocation of the attentional beam to the reference object (rectangle). (b) Vectors rooted at points across the reference object, pointing toward the located object. (c) The vectors are weighted by the amount of attention being paid to their roots. (d) The direction associated with the resulting vector sum. (e) The computed direction compared to a reference orientation (in this case, vertical upright). Copyright © 2001 by the American Psychological Association. Reprinted with permission from Regier and Carlson (2001).

and their interaction on spatial language use. Carlson and Corrigan (2003; see also Regier, Carlson, & Corrigan [2003]) extended the AVS model (AVS_{FUNC}) to include a functional parameter that corresponded to the functional importance of a given point on the reference object. In AVS_{FUNC} , the total amount of attention that is paid to a particular point on the reference object depends on both a distance parameter (as in the original AVS) and a functional component. This implementation is based on the suggestion that functionally important parts of objects receive greater attentional allocation (Lin & Murphy, 1997).

The functional parameter could be set to zero, indicating that the corresponding point on the reference object was not functionally important. In this case, attentional allocation to the point would depend solely on distance. For objects with functional parts, the functional parameter would be set to a positive value between 0 and 1, selectively biasing the allocation of attention to points within the functional part. Recall the toothbrush/toothpaste study by Carlson-Radvansky et al. (1999) discussed in Section

IIA1. In that study, participants were asked to place functionally related (e.g., toothpaste tube) and unrelated (e.g., tube of oil paint) objects above reference objects (e.g., toothbrush), and the critical finding was that placements were biased in the direction of an important functional part, with this bias being stronger for functionally related located objects than for functionally unrelated objects.

Simulations run with the AVS_{FUNC} model replicated these data successfully. When the located object was the tube of toothpaste (the functionally related object), attentional allocation to the bristles (functional part) was assumed to be the greatest and the functional parameter was set to a high value (.8). When the located object was the tube of oil paint (unrelated object), attentional allocation to the bristles was assumed to be moderately biased and the parameter was set to an intermediate value (.3). A third simulation was conducted assuming no functional bias, with the parameter set to a value of 0.

Simulation data for these three parameter settings are shown in Fig. 7 using the toothbrush as the reference object. The model outputs a value between 0 and 1 that corresponds to an acceptability rating, with 1 indicating the best use of above. Note that when attentional allocation to the bristles

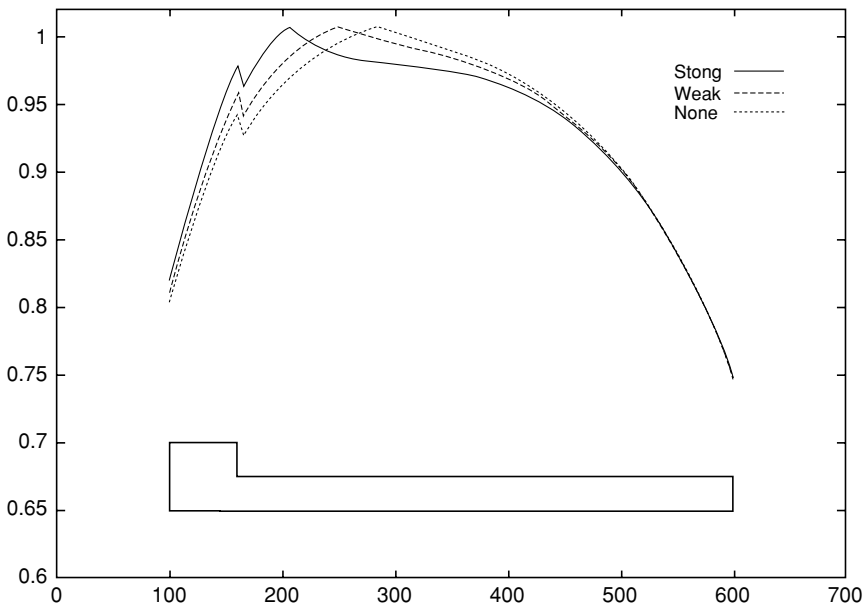


Fig. 7. Simulation data for three values of the function parameter for AVS_{FUNC} (strong, $F = .8$; weak, $F = .3$; none, $F = 0$). From Regier, Carlson, and Corrigan (2002).

was strong (solid line; $F = .8$), the peak is about 73% of the distance toward the functional part. When the attentional allocation was weak (dashed line; $F = .3$), the peak was at 46% of the distance. These correspond very closely to empirical data obtained by Carlson-Radvansky et al. (1999), where the bias was 72 and 45% toward the functional part, respectively. These simulations demonstrate that the construction of a spatial template around the object depends critically on the functional importance of the parts of the object. More generally, the AVS_{FUNC} model offers a means of combining the geometric and functional influences on the parsing of space around the reference object.

IV. Generalizations and Conclusions

As reviewed in Section II and III, the Logan and Sadler (1996) computation model offers a compelling framework for examining the use of spatial language. Section II presented support for the constituent steps of apprehension (finding the relevant objects, assigning directions to space, and computing and comparing the spatial relation), and Section III examined more closely how directions were assigned to space by discussing research pertaining to setting the various parameters of a reference frame. Further work is needed to examine the other constituent processes in more detail.

The majority of this work has focused on an addressee's interpretation of a simple spatial description in which the spatial term and the objects being related spatially have already been selected by a speaker and are being comprehended by a listener. In contrast, very little work has been done examining the speaker's selection of the relevant objects and spatial term. It is likely that this same computational framework can apply within this context.

For example, assume that the speaker has the goal of conveying the location of a sought-for object to an addressee. The speaker must find the located object and select an appropriate reference object. Factors that may impact the selection of an appropriate reference object are its size, salience in the discourse or within the environment, and the permanence of its location (Talmy, 1983). These processes could operate within Logan's constituent step of finding the relevant objects. In addition, directions must be mapped onto space around the reference object. This would fall within Logan's constituent step of assigning directions to space and would presumably operate through the setting of parameters of a reference frame in much the same manner as presented in Section III. Finally, the spatial relation between the objects must be computed and a spatial term selected. This would correspond to Logan's constituent step of computing and comparing the spatial relation.

Moreover, it is possible that there could be interactions between these constituent steps, indicating that the constituent steps are not necessarily serial and independent, a point emphasized by Carlson et al. (2003). One possible interaction among the steps may be observed in the speaker's selection of a reference object and the selection of a spatial term. For example, based on an analysis of corpora of written texts from Spanish and German, DeVega and colleagues (2002) suggested that the features that characterize the located and reference objects may vary depending on the spatial terms being used. Specifically, spatial terms referring to the vertical dimension (i.e., above or below) seem to use located objects that are partitive and smaller than the reference objects, whereas spatial terms referring to the horizontal dimension (i.e., front, back) seem to be associated with animate located and reference objects that are more similar in size. With respect to apprehension, DeVega et al. (2003) suggested that such regularities may bias the speaker's formulation and an addressee's interpretation of a spatial description. Relatedly, in comprehension, Chambers, Tanenhaus, Eberhard, Filip, and Carlson (2002) have shown that constraints provided by a spatial preposition limit the evaluation of objects in the scene as possible reference objects. For example, participants were shown a display of multiple objects and were asked to put one object *inside* another object. The critical result was that upon hearing "inside" participants restricted their attention to the objects that could serve as containers, indicating that information associated with the meaning of "inside" directly influenced which objects were considered as potential reference objects.

In conclusion, the production and comprehension of simple spatial descriptions are complicated endeavors, involving the integration of information pertaining to the objects being spatially related and their potential interaction, constraints imposed by the spatial term and its required parameters, and the goals of the speaker and the listener. A full understanding of apprehension will require examining each of these factors in isolation and also in combination. As such, the contributions of this chapter are offering an illustration of the diverse set of methodologies that may need to be employed, outlining a rich framework that can be used to organize such an examination, and describing what is currently known about using spatial language. This work also serves as a foundation for addressing issues surrounding the language/space interface and its applicability across languages.

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IN OPPOSITION TO INHIBITION

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Daryl E. Wilson, and Uri Bibi

I. Introduction

What does inhibition in psychology mean? Most psychologists have presupposed that its meaning in psychology is practically the same as in physiology. They begin with illustrations of neural inhibition and end with illustrations of inhibition among ideas. (Breese, 1899, p. 6)

The concept of inhibition is firmly entrenched in our language and in our thinking, both in our everyday lives and in our scientific theorizing. We are used to the idea that an impulse, a thought, or an action can be expressed or it can be withheld. To see that this is so, we need only turn to the source of (almost) all quotes for matters psychological, William James. In his chapter on functions of the brain, James (1890, Vol. I, p. 67) said: “Inhibition is a *vera causa*, of that there can be no doubt.” He as readily acknowledged its role in behavior (James, 1904, p. 178): “Voluntary action, then, is at all times a resultant of the compounding of our impulsions with our inhibitions.” Lest there be any remaining uncertainty about his position, he concluded in his chapter on will (James, 1890, Vol. II, p. 583, his italics) that “*Inhibition is therefore not an occasional accident; it is an essential and unremitting element of our cerebral life.*”

According to the *Oxford English Dictionary* (OED), the derivation of the word *inhibition* lies in the Latin verb *inhibere* (cf. *in* + *habere*, literally, to

“hold in” or to restrain); hence the basic idea has a long history. By the 14th century, the Latin word gave rise to the Old French *inibicion* (used initially in the legal sense of prohibition). The OED lists four very related senses of the word: (1) “the action of inhibiting or forbidding;” (2) in law, the act of prohibition; (3) “the action of preventing, hindering, or checking;” and (4) “a voluntary or involuntary restraint or check.” These four senses demonstrate the breadth in use of the term. It is also in widespread use: Its mean familiarity rating in the MRC database (Wilson, 1988) is almost precisely at the 50th percentile.

In their psychological dictionary, English and English (1958, p. 262) discriminated three senses of the concept inhibition. We refer to these senses as suppression, restraint, and blocking. *Suppression* pertains to the prevention of a process from beginning or from continuing once begun, encompassing both psychological and physiological processes. *Restraint* refers to a mental state in which behavior is difficult to initiate or is curtailed. *Blocking* represents the classic psychoanalytic sense wherein a process, seen as instinctual, is kept from coming into consciousness (in psychoanalytic theory, by the activity of the superego).

To a psychologist, there are two principal applications of the concept of inhibition. The first applies to the nervous system: Neurons can serve either excitatory or inhibitory functions. The second applies to thought and behavior: Cognitive processes—thoughts—can be activated or inhibited. The purpose of this chapter is to hold the *cognitive* concept of inhibition under the light. We wish, therefore, to make clear from the outset that this chapter is *not* about the neural concept of inhibition, with which we have no quarrel. Nevertheless, despite the emphasis in neuroscience, especially in cognitive neuroscience, on relating mind mechanisms to brain mechanisms, we *do* wish to question the cognitive concept of inhibition, suggesting that the evidence for such a mechanism is disputable and that there are problems with the concept itself.¹

The core of the problem is that the concept of inhibition at the cognitive level cannot derive directly from the concept of inhibition at the neural level. We believe that such reification creates a false sense of comfort in theorizing. Put starkly, an electrochemical impulse in a neuron cannot possibly explain

¹ The concept of inhibition has also been applied in another domain of behavior: making a physical response. The question here is whether, and if so how, we can restrain an otherwise prepared response. The most concerted attack on this question has used the stop signal paradigm of Logan and colleagues (De Jong, Coles, & Logan, 1995; Logan & Cowan, 1984; Logan & Irwin, 2000; Logan, Schachar, & Tannock, 1997). On some proportion of trials, the participant is signaled not to make an otherwise appropriate physical response. The evidence is clear that people can cancel a planned movement successfully, given sufficient notice. We also do not wish to contest this motor sense of inhibition. It is interesting that writers at the turn of

a thought, despite being involved intimately in providing the means for that thought to occur. Of course, the cognitive software runs on the neural hardware; we are not neuro-Luddites. Yet, we would no more expect to find cognitive inhibition because there is neural inhibition than we would expect to find cognitive glia or cognitive ion channels because their neural counterparts demonstrably exist. To stress this point, we also do not see a necessary connection between cognitive activation and neural excitation. The level of analysis is entirely different.

As researchers, it is certainly a laudable and appropriate goal to link brain to mind—this is unquestionably one of the most important and exciting frontiers of science today—but we must not expect the mechanisms that brain and mind use to be the same. Marr (1982) distinguished three levels of analysis at which we must understand a machine that is processing information: computational theory, representation and algorithm, and hardware implementation. [To understand their application to cognition, a good place to begin is with the exchange between Broadbent (1985) and Rumelhart and McClelland (1985) concerning the McClelland and Rumelhart (1985) distributed memory model.] Our view is that inhibition at the level of hardware implementation in the nervous system may inform, but should not be confused with, psychological theory, which is usually at the level of representation and algorithm. Nor should it be confused with the more formal computational analysis of the problem.

This chapter sets the stage with a thumbnail sketch of the history of inhibition and then narrows in on the cognitive concept. From there, we present several “case studies” of cognitive phenomena in the domains of attention and memory, phenomena that have been widely seen as indicative of the operation of inhibition. We argue that the inhibition accounts offered for these phenomena are far from unassailable and that inhibition as a cognitive concept is home to several different ideas, not a single coherent idea. Along the way, we develop an alternative noninhibition account that appears to provide a reasonable explanation and to have some generality as a cognitive mechanism. We conclude with a reconsideration of the meaning and place of inhibition in cognition, posing a challenge to theories of cognition.

the century also often saw motor inhibition as qualitatively different from cognitive inhibition. Thus, in listing five potential varieties of inhibition, Breese (1899, pp. 12 and 13) saw only the last one, which he called “inhibition as a psychophysical phenomenon,” as plausible. The first four were all concerned with inhibition of ideas and associations; the final one related to motor inhibition. We would argue that this motor sense of inhibition is different from the sense applied to attention, memory, and other cognitive activities. We accept that physical responses can be planned and then canceled.

II. A “Reader’s Digest” History of Inhibition

Like the word itself, the origin of the concept of inhibition lies not in the nervous system, but in the realm of mind and behavior. Diamond, Balvin, and Diamond (1963) and Smith (1992) both provided thorough and engaging accounts of this history, accounts to which we cannot do justice here, but upon which we will rely heavily for our sketch. The story begins with the mind–body problem, with emphasis on how the mind’s control of the body is a continual struggle. In *Phaedrus*, Plato saw the will as a charioteer attempting to control two horses, one of desire and one of reason. Both Hippocrates and Aristotle wrote of how two simultaneous stimuli were not independent, with each influencing the other. Buddhism (see Warren, 1896) emphasized reaching a level of “cessation” where all bodily functions are arrested. Over a millennium and a half later, Descartes and Locke saw will as controlling action and emotion. This most fundamental duality has indeed probably always been with us. Control is essential, but does control require the counterforce of inhibition? For many, the answer is necessarily “yes”; our aim here is to question this response as it applies to cognition, not as it applies to the nervous system. First, however, we briefly outline the history of the concept in both domains, beginning with the nervous system.

A. NEURAL INHIBITION

Discussions of opposing forces in the nervous system can be dated back to Descartes (1650).² Yet, in early neuroscientific research on the transmission of signals within the nervous system, neurons were thought to carry activation flowing in one direction in a single form: excitation (see, e.g., Müller, 1834). This framework appeared to be adequate for quite some time until evidence began to accrue that the nervous system had to be more complex than such a conceptualization could reasonably capture. Bell (1823) was the first to clearly propose opposing forces, based on his experiments on the muscles of the eye. Bell unquestionably had the idea of inhibition, although without using the term (see also Bell & Bell, 1826). He even recognized the controversial nature of his idea, adding a footnote saying “The nerves have been considered so generally as instruments for stimulating the muscles, without thought of their activity in the opposite capacity” (Bell, 1823, p. 295).

² Intriguingly, Sherrington (1951), who is often cited as the “father” of neural inhibition, credits Descartes with introducing the idea of inhibition to physiology, although Descartes’ view was of two opposing excitations, not an excitation and an inhibition.

³ Our citation of these articles is based on the discussions by Diamond et al. (1963) and by Smith (1992). The original sources are, respectively, in German and Latin.

Bell's work did not have much impact. Nor did Volkmann's (1838) research demonstrating vagal inhibition of the heart in frogs, although when Weber and Weber (1845) tackled the same problem, their work received more attention.³ According to Smith (1992), the word "inhibition" was first used in physiology in 1858, in an address given by Lister (1858) to the Royal Society of London, and then quickly came into common usage. Those looking for the point of origin of the concept of inhibition in physiology, however, often identify Sechenov's (1863) discovery of central inhibition as the real breakthrough. Sechenov showed that brain structures in the frog could inhibit a spinal reflex, clearly much less of a "reciprocal" idea than its predecessors, which always proposed opposing forces at the same level. The fundamental opposition between excitation and inhibition was becoming a basic principle of the nervous system. In 1883, Brunton (p. 419) offered the classic definition of inhibition: "By inhibition we mean the arrest of the functions of a structure or organ, by the action upon it of another, while its power to execute those functions is still retained, and can be manifested as soon as the restraining power is removed." Still, however, Meltzer (1899, p. 661) was able to say at the turn of the century that "the phenomenon of inhibition is distrusted in physiology." That attitude changed with the century.

By the beginning of the 20th century, inhibition in the nervous system was rapidly becoming more widely accepted. The name most often associated with the concept of neural inhibition is Sherrington (1906). He argued for the concept of neural inhibition not just at the neuronal level, but also at the level of the organization of the nervous system. He was ultimately awarded the 1932 Nobel Prize for Physiology or Medicine for his research and writings that solidified the place of inhibition in neurophysiology. The nervous system now had inhibition: What about behavior and the mind? Two of Sherrington's contemporaries carried these banners: Pavlov and Freud. Their goal remained, though, to link behavior and mind to the brain and nervous system as directly as possible.

After his early work on the basic physiology of digestion and his discovery of conditioning, which won him the Nobel Prize in Physiology or Medicine in 1904, Pavlov devoted his later career to developing his laws of conditioning. For him, inhibition played the role of reducing a conditioned response in frequency or likelihood, and he distinguished two kinds of inhibition (Pavlov, 1928). The first was external inhibition, in which a new stimulus interferes with an existing response. The second was internal inhibition, in which a new conditioned response interferes with an existing unconditioned response. These ideas were absolutely central to his theory of learning and to his overarching goal of relating learning to processes in the nervous system.

Writing at the same time as Sherrington (1906) and Pavlov, Freud (1928) took as a fundamental premise of the mind the idea that impulses were sometimes suppressed or repressed. Inhibition was what made repression or suppression possible, and hence what permitted a civilized existence. For Freud, inhibition restrained the ego in two ways: (1) It minimized conflict with the id and the superego and (2) it permitted a dampening of “psychic energy.” Smith (1992) suggested that Freud even recognized the duality of inhibition as both the process and the product of that process. More often, he focused on inhibition as product, and his sense of the word—stopping the expression but not the existence of an impulse—has come to be the most common sense of the word in everyday speech. As Pavlov brought inhibition to behavior, so Freud brought inhibition to the mind, both driven by the strong motive for a fundamental, physiologically based explanation.

B. COGNITIVE INHIBITION

Inhibition has long been seen as a crucial element in a complete explanation of cognition. Early on, inhibition in thought was seen as suppression of movement (Ferrier, 1876; Ribot, 1889), a view that persisted into the early part of the 20th century (Breese, 1899; Münsterberg, 1900). But then, with very occasional exceptions (e.g., Guthrie, 1930), inhibition disappeared as a cognitive concept and did not really reemerge until the work of Postman and Bruner midway through the century (Postman, Bruner, & McGinnies, 1948; Bruner, 1957) as the influence of behaviorism began to decline.

The inclusion of inhibition in cognitive theorizing has, therefore, followed a quite slow time course. With the cognitive revolution of the 1950s, the concept reappeared, but gradually at first. In the “serial days” of the 1960s and early 1970s, when cognitive processes were seen as running off sequentially, activation was seen as the result of facilitation. Indeed, the terms “activation” and “facilitation” were often used interchangeably. Thus, semantic priming could produce a speeded response to decide whether *doctor* was a word in a lexical decision task when the preceding word was *nurse* rather than *bread* because *nurse* facilitated *doctor* by activating some of the relevant representational information in memory (Meyer & Schvaneveldt, 1976). Unlike in the domain of neuroscience, there was no need for a counteracting force in these early accounts, so inhibition had no place in cognition. Even the relatively few interference phenomena that existed, such as the Stroop effect (Stroop, 1935), were seen as the result of a kind of “tug of war” between competing tendencies: Activation of two representations, particularly because they were so related, made choosing the correct one difficult. Despite occasional references to the effect as

“Stroop inhibition,” it was generally called “Stroop interference.” In this context at least, “interference” was seen as describing a behavioral situation whereas “inhibition” suggested an explanation of that situation.

Gradually, though, the concept of a force opposing facilitation and causing interference gained favor in cognition, as described in the “case studies” that follow. Many labels have been used, with repression, suppression, and inhibition being the most frequent among them, but inhibition has become by far the usual term, evidently because of the analogy to the operation of neurons. As Dagenbach and Carr (1994, p. xiii) put it, “we might speculate that the desire to have what is known about the way the nervous system works reflected in our cognitive models may be a relevant factor in renewed interest in inhibitory processes.” As a result, the concept of inhibition has come to be widely used and widely accepted in cognition [see, e.g., the two edited collections by Dagenbach and Carr (1994) and by Dempster and Brainerd (1995)].

C. PREFACE TO THE CASE STUDIES

Whenever some experimental manipulation results in a decrease in performance relative to a specific baseline control condition, it has become the norm to refer to this as inhibition, in essence using the same word for both the mechanism and the phenomenon. Thus, in the case of response time, for example, any manipulation that speeds a response beyond its normal resting state, or baseline, is called facilitation; any manipulation that slows a response relative to baseline is frequently dubbed inhibition, not interference. A principal purpose of this chapter is to argue against this trend to routinely explain interference effects as due to inhibition, and instead to present an alternative account in terms of memory retrieval and the resolution of conflict between multiple response candidates. To build this case, we will rely on two sets of case studies, which form the empirical heart of this chapter.

We cannot survey and criticize all of the cognitive situations in which some form of the concept inhibition is used to explain behavior (for other, more favorable, overviews of inhibitory situations, see Arbuthnott, 1995; Dempster & Corkill, 1999). Indeed, the very fact that there are so many different situations where inhibition is invoked demonstrates the “flexibility” of the concept, with its numerous nuances of meaning relating back to the three senses identified by English and English (1958). Instead, we have chosen to single out four well-known cognitive paradigms to illustrate our argument: two from the realm of attention and two from the realm of memory. Within each realm, we present one example that we have explored in our laboratory and one studied in other laboratories. It has not escaped our attention that almost all of our illustrations have connections to

cognitive research at the University of Toronto. The opportunity to relate our ideas to the work of our colleagues is a welcome one.

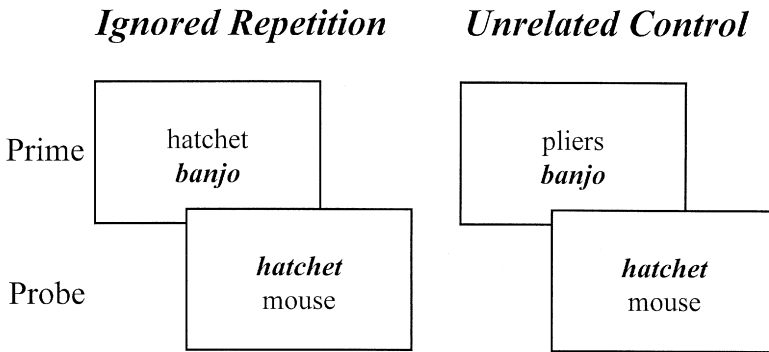
Our aim is to select cognitive paradigms and situations that are familiar in the field, ones with which inhibition accounts have been firmly linked and which have therefore served to move forward the “inhibition agenda.” Under attention, therefore, we will illustrate with negative priming and inhibition of return. Under memory, we will use as examples directed forgetting and retrieval-induced forgetting. We will begin each subsection with the inhibition account and then move to the noninhibition account. The end of each section briefly alludes to selected other phenomena where noninhibitory accounts have been put forth as alternatives to existing inhibitory accounts, simply to show the diversity of the situations involved.

III. The Attention Case Studies

A. NEGATIVE PRIMING

The phenomenon that is probably most responsible for the rise in popularity of inhibition as an explanatory mechanism in cognition is *negative priming*. This was first observed by Dalrymple-Alford and Budayr (1966) in the context of the Stroop (1935) effect. That there is Stroop interference on incongruent color-naming trials (i.e., we are slow to say “yellow” to the word BLUE printed in yellow) indicates that we do not—and perhaps ordinarily cannot—ignore the word, at least not completely (for a review see MacLeod, 1991). Now consider two consecutive Stroop trials, the first being the word RED printed in blue and the second the word GREEN printed in red. Responding “blue” to the color on the first trial necessarily means not responding “red” to the word. The problem is that “red” is the appropriate response on the second trial, after having just been ignored. Dalrymple-Alford and Budayr reported that interference was enhanced when the ignored word on the first trial became the attended color on the second trial, relative to sequences where successive words and colors were unrelated.

Negative priming lay dormant for a decade until it was revived by Neill (1977), Lowe (1979), and Tipper (1985), and has since become one of the most familiar cognitive tasks (for reviews, see Fox, 1995; May, Kane, & Hasher, 1995; Tipper, 2001). Most of the recent work has moved to the version of the task shown in Fig. 1 that permits more items/responses to be used. Two words appear on each trial. A cue (e.g., a particular item color; illustrated by bold italics in Fig. 1) indicates which is to be attended (the target in red) and which is to be ignored (the distractor in white). If the ignored word on the first (prime) trial becomes the attended word on



Probe Naming RT = 630 ms (Ignored Repetition)
 610 ms (Unrelated Control)

Negative Priming = 20 ms (Ignored – Unrelated)

Fig. 1. The negative priming paradigm (for reviews, see Fox, 1995, May et al., 1995). Example prime and probe trials and illustrative response times from the critical probe trial are shown. Note that participants would be naming the bold italicized target word on each trial (which would actually be presented in red, with the ignored distractor word presented in white).

the second (probe) trial, processing of that word as the probe target is slower than is the case for completely unrelated successive trials.

The very use of the word “negative” coupled with the familiar idea of priming suggests that activation of the ignored word is pushed below baseline. This “suppression” is not problematic if the target on the subsequent probe trial is unrelated to the suppressed prime word, but it causes slowed responding when the probe target is the distractor from the preceding prime trial. Thus, Tipper (1985, 2001; see also Houghton & Tipper, 1994) has championed an account of negative priming as arising due to inhibition of the ignored word on the prime trial that results in it taking longer to reach the activation necessary to permit response production on the probe trial. This explanation fits nicely with the name of the task. Quickly, negative priming became the hallmark measure of inhibition and the task was pressed into service to explore suspected deficits in inhibitory processing in such diverse groups as schizophrenic patients (Beech, Powell, McWilliam, & Claridge, 1989; but see MacDonald, Antony, MacLeod, & Swinson, 1999) and elderly people (Hasher, Stoltzfus, Zacks, & Rypma, 1991).

Tipper (2001, p. 322) claimed that “Negative priming is therefore a means of observing an inhibitory process that is assumed to be a normal component of selective attention.” The representation of the distractor on

the prime trial becomes, as Tipper put it, “associated with inhibition.” This, in turn, impairs processing of that same item when it becomes the target in the probe display. Under this view, attention selects an item both by accentuating the target and by deaccentuating the distractor(s), an idea that goes back at least to Pillsbury (1908). Houghton and Tipper (1994) presented a model in which a template is created for the key feature that indicates the object that requires a response (action). Inputs that match the template are excited; those that mismatch are inhibited. Template matching is the core of the model, although the model also emphasizes suppression of distractors, with greater inhibition placed on distractors that are more likely to interfere (“reactive inhibition,” an idea that goes back at least as far as Wundt, 1902). Tipper (2001, p. 336) summarized a considerable body of research that he saw as consistent with such an inhibitory explanation of negative priming, concluding that “Thus far, there is little clear evidence to unequivocally discount the notion that negative priming reflects an inhibitory selection mechanism.”

Although the inhibition account of negative priming has dominated, plausible noninhibitory explanations of the phenomenon do exist. We consider two (for more discussion, see MacDonald & Joordens, 2000; Tipper, 2001). First, Neill and Valdes (1992) and Neill and Mathis (1998) proposed, on the basis of Logan’s (1988) instance theory of automaticity, that we routinely retrieve information from memory to assist with current processing. This retrieval may well be done automatically and unintentionally. Neill’s episodic retrieval account holds that the most likely information to be retrieved is the most recent: that from the preceding trial. On ignored repetition trials, the memory check will thus retrieve a “do not respond” status for the distractor from the prime trial, which conflicts with the “respond” status of the attended word on the probe trial. The resulting delay on the probe trial—negative priming—is a consequence of time spent resolving this conflict, despite the fact that the item is actually repeated.

A second alternative to inhibition as an explanation of negative priming is the feature mismatch account (Lowe, 1979; Park & Kanwisher, 1994). Like the episodic retrieval account, this is a retrieval-based explanation, the difference being that the focus of the mismatch shifts from response conflict to stimulus feature conflict. In the typical negative priming experiment, each trial has one word in one color (red) and one in another color (white), and the participant must consistently respond to one of the colors on each trial. Referring to the ignored repetition trial on the left side of Fig. 1, the word “hatchet” appears in white (do not respond) and the word “banjo” appears in red (respond) on the prime trial. On the probe trial, however, the participant must respond to the word “hatchet,” which now appears in red. Thus there is a disagreement in color because the red target on the probe

trial will have switched from white on the preceding prime trial. Resolving this stimulus conflict produces a slowing—negative priming.

Increasingly, these retrieval-based accounts have been gaining support, as indeed have episodic retrieval theories of priming more generally (e.g., Ratcliff & McKoon, 1988; Whittlesea & Jacoby, 1990). But is it the retrieval of stimuli, responses, or both that is crucial in eliciting negative priming? Malley and Strayer (1995) showed that negative priming occurred only for small sets of stimuli and their responses (a dozen or fewer). The effect vanished and even turned to positive priming for larger sets. Malley and Strayer did not, however, manipulate the numbers of stimuli and responses independently.

In our laboratory, Chiappe and MacLeod (1995) used a set of 10 items consisting of two instances from each of five categories. Negative priming was unaffected by a switch in task—from naming to categorization or vice versa—between prime and probe trials. The differing numbers of responses—5 in categorization versus 10 in naming—did not matter. This suggests that the number of stimuli, not the number of responses, is important.

We are testing this conclusion further. Using four instances from each of five categories, MacLeod, Bibi, and Stamenova (ongoing) had participants name items in one block of trials (i.e., 20 item names) but categorize them in the other block (i.e., 5 category names). If the limitation on negative priming stems from the number of responses, then there should be negative priming when categorizing (5 responses) but not when naming (20 responses). If the limitation is on stimuli, then the 20 stimuli should be a sufficiently large set to eliminate negative priming regardless of the nature of the response. There was, in fact, no negative priming in this study, consistent with the set size limitation being on the stimuli, not on the responses.

Convergence on the importance of the stimuli themselves comes from two other studies conducted at the University of Toronto at Scarborough. MacLeod, Chiappe, and Fox (2002) directly tested the feature mismatch account of negative priming. Recall that, in the standard procedure, a color signal indicates which is the target word on each trial, with red always meaning respond and white always meaning ignore. Thus, the ignored item in white becomes the response-relevant item in red on critical ignored repetition trials. Could this color mismatch underlie negative priming, consistent with the feature mismatch account? MacLeod et al. (2002) replicated the standard procedure in one block (the “constant red-red” block) and observed standard negative priming for two independent sets of materials (categorically related and associatively related words). These results are shown in the left-hand side of Fig. 2.

In another block (the “switch red-white” block), MacLeod et al. (2002) made a seemingly small change in procedure: Participants were told to

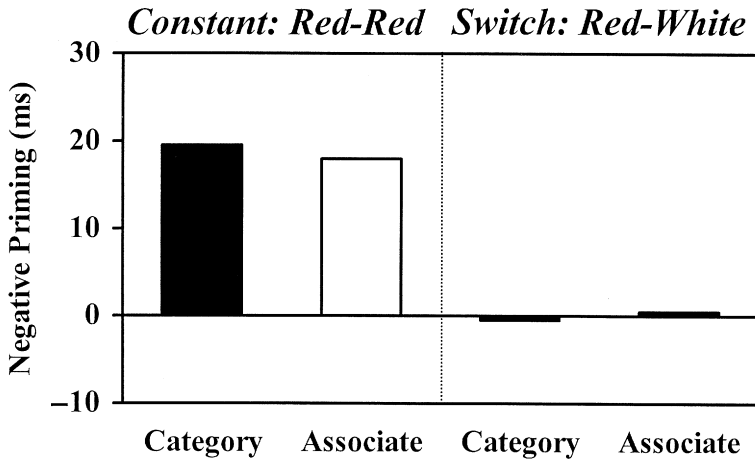


Fig. 2. Negative priming appears when there is a stimulus mismatch between prime and probe trials, in the “constant red–red” condition, but disappears when this mismatch is removed, in the “switch red–white” condition. Data are from MacLeod et al. (2002), collapsed over the identity conditions in the main and replication experiments.

alternate between responding to the red item on one trial and the white item on the next. In this way, the ignored (white) item on the prime trial became the target (also white) on the probe trial, with no change in the stimulus. As the data in the right-hand side of Fig. 2 show, negative priming vanished for both sets of materials. When the ignored stimulus kept its color upon becoming the target, there was no feature mismatch and hence no basis for negative priming under the feature mismatch account. Both the episodic retrieval and the distractor inhibition accounts would predict negative priming in this situation. We note in passing that it would be interesting to extend this approach to the location version of negative priming as well.

MacDonald and Joordens (2000, experiment 1) used a procedure that they had introduced earlier (MacDonald, Joordens, & Seergobin, 1999) in which participants have to say which of two words on each trial has the larger referent (e.g., MOUSE, DONKEY). Interestingly, this task, which necessitates that both words be attended on each trial, produces extremely large negative priming—on the order of 100 ms instead of the usual 20 ms. MacDonald and Joordens had two types of blocks. In one, the rule was to always respond with the larger item such that, in the ignored repetition condition, ignored items moved from being smaller on the prime trial to being larger on the probe trial, causing a selection feature mismatch. In the other block, participants were to alternate between responding to the larger

item and responding to the smaller item. In this case, the ignored repetition item was the smaller one on both the prime and the probe trials, constituting a selection feature match. Just as MacLeod et al. (2002) found, there was negative priming in the mismatch condition but it disappeared in the match condition. Impressively, this meant that a 100-ms effect was eliminated by removing the selection feature mismatch.

MacDonald and Joordens (2000, experiments 2 and 3) replicated this finding using number words (e.g., which is larger: THREE or SIX?). In experiment 3, their *pièce de résistance*, they obtained negative priming only when there was a selection feature mismatch between the trials (i.e., when the number word changed from being the smaller to the larger or when the number word changed color). Negative priming disappeared when the repeated item was congruent on the selection feature across the prime and probe trials. Indeed, mismatch even slowed responding on attended repetition trials. In their laboratories, Park and Kanwisher (1994) and Milliken, Tipper, and Weaver (1994) have also reported negative priming only with a mismatch on the selection feature of a repeated item between prime and probe trials.

It is our contention that negative priming results from the resolution of a conflict between the selection feature of the current stimulus and that of the previous stimulus. This conflict arises because we routinely run a memory check to find information relevant to the current situation. The most likely information to turn up in that memory check is the recent information from the latest trial; it is in fact quite likely to still be in working memory, and thus readily accessible. When that information is relevant (i.e., concerns the same item) but there is disagreement on the selection dimension, this disagreement must be resolved, a process that adds to the normal processing time. Automatic memory retrieval provides the stimulus feature conflict; resolving that conflict produces interference. Under this account, there is no inhibition at all. Indeed, automatic memory retrieval is ordinarily beneficial so we would not want to suppress our (immediate) past, whether in terms of the stimulus, as we have emphasized here, or the response, as Neill and Mathis (1998) emphasized. It is only in somewhat contrived situations, such as the negative priming task, that this normal episodic retrieval works against us.

In his recent defense of the inhibition account of negative priming, Tipper (2001, p. 321) maintained that “there is *no* firm evidence to discount inhibition models.” He argues that episodic retrieval is fundamental to an inhibition account, indeed claiming that “there is no necessary conflict between inhibition and episodic accounts of negative priming” (p. 329). We see this as substantially blurring the distinction and would argue that it is just as reasonable to conclude—in line with parsimony—that there is no

firm evidence to *require* an inhibition explanation of negative priming. Memory retrieval is a systemic element of cognition; if it alone can explain negative priming, there is no need to overlay a highly flexible set of inhibitory processes of the sort advocated by Tipper (2001, p. 335).

In fact, explaining negative priming would appear to require the retrieval of recent relevant information from memory, coupled with resolution of the conflict created by the current information and the retrieved information. We contend that memory is always in use, in conjunction with processing of the present, to assist with the determination of our responses and actions. So often in the world we can simply do what we just did again to perform successfully, using memory to avoid any need for problem solving (see Jacoby, 1978). We therefore rely heavily on memory. It is only when that reliance leads to conflict that we must slow down to make a decision, and this relatively infrequent cost is worth the much more frequent benefit of relying on memory. Negative priming creates a situation that emphasizes that cost. We now consider another attentional paradigm where there is a cost to looking back and where inhibition has also been posited as the cause.

B. INHIBITION OF RETURN

To perform tasks in a visually complex environment successfully and efficiently, task-relevant objects must be located and identified quickly. Although visual search often involves eye, head, and body orientation movements, a covert attentional search can increase the efficiency of the search process. To minimize repeated searching of the same location, it would be useful if a mechanism existed that biased covert attention toward novel, previously unsearched locations. To realize this bias, Posner and Cohen (1984) proposed an inhibitory attentional mechanism, stating that "...the inhibition effect evolved to maximize sampling of the visual environment" (p. 550). They suggested that a peripheral visual stimulus initially attracts attention to its location, but that an inhibitory mechanism then decreases processing of further information at that location. Shortly thereafter, Posner, Rafal, Choate, and Vaughan (1985) called this mechanism *inhibition of return*. No doubt because of the extensive literature that has developed regarding this phenomenon over the past two decades—but perhaps in part because the word "inhibition" is included in its name—inhibition of return has been very widely cited as evidence of a pivotal role for inhibition in attention.

Posner and Cohen (1984) derived the idea that previously attended locations are inhibited from examining the time course of the effects of uninformative spatial cues on target processing. Fig. 3 illustrates their method, which is quite typical of "standard" inhibition of return experiments.

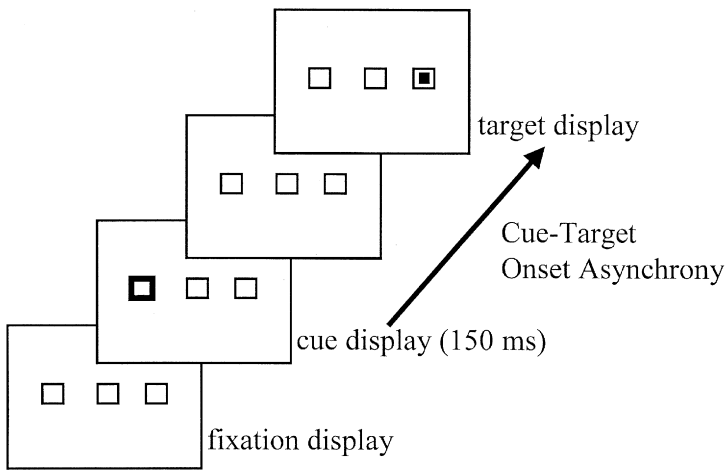


Fig. 3. The standard inhibition of return procedure, after Posner and Cohen (1984). The cue location is independent, and therefore nonpredictive, of the target location. The variable time between the cue and the target is referred to as cue-target onset asynchrony.

First, three outline boxes are presented in a horizontal row, with participants instructed to fixate on the center box and to move only their attention, not their eyes, during the trial. Second, one of the peripheral boxes is brightened, which is assumed to reflexively draw attention to that cued location (cf. Yantis & Jonides, 1984). Third, a filled square target is presented in the center box (60% of trials), in the cued box (10% of trials), or in the uncued box (10% of trials). Because the task is simply to detect as quickly as possible that the target has been presented, the remaining 20% of trials are catch trials without a target. Across trials, the cue and target locations are independent.

Posner and Cohen (1984) found that for brief (0, 50, and 100 ms) cue-target onset asynchronies, detection of the target was faster at the cued than at the uncued location, the intuitive pattern. Generally, the cause of this facilitation at the cued location has been attributed to an automatic capturing, or reflexive orienting, of attention by the peripheral cuing event. It might be expected that the brief facilitation would simply dissipate with time as attention moved back to the central fixation point. However, Posner and Cohen (1984) found that for cue-target onset asynchronies of 300 and 500 ms, detection was now slower at the cued location than at the uncued location. This slowing is the empirical manifestation of inhibition of return (IOR). The entire data pattern is shown in Fig. 4.

To account for IOR, competing theories have proposed inhibitory effects that function at the perceptual, attentional, and response levels of

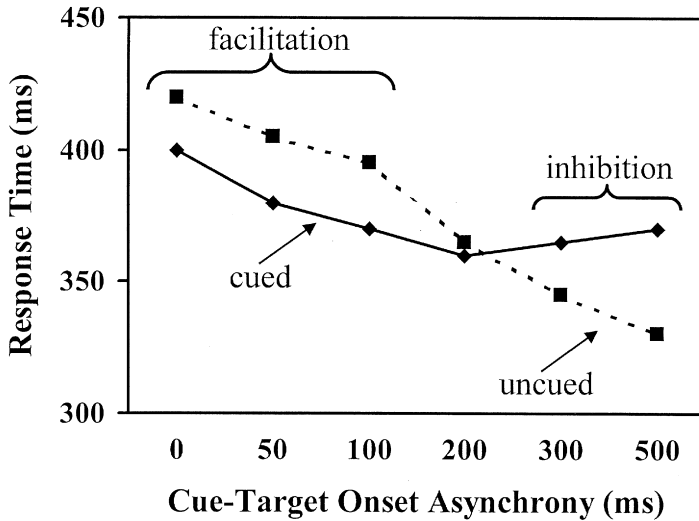


Fig. 4. Typical findings in the inhibition of return procedure (Posner and Cohen, 1984). At short cue-target onset asynchronies (0, 50, or 100 ms), the cue facilitates detection of the target; at longer cue-target onset asynchronies (300 or 500 ms), the cue inhibits detection of the target.

processing. At the perceptual level, it has been suggested that IOR may slow the rate at which perceptual information accumulates at the cued location (e.g., Abrams & Dobkin, 1994; Gibson & Egeth, 1994; Handy, Jha, & Mangun, 1999). Others have suggested that the effect of IOR on perceptual processing is not direct, but mediated by its influence on the attentional system. As the name of the phenomenon was intended to suggest, IOR may inhibit the attentional system from reorienting back to the cued location, resulting in either delayed or slower perceptual processing at the cued location (e.g., Rafal, Egly, & Rhodes, 1994; Reuter-Lorenz, Jha, & Rosenquist, 1996). For example, Rafal et al. (p. 295) stated that IOR "...does not directly inhibit perceptual processing (at the cued location); rather it slows the reorienting of attention and this slowing compromises...detection of subsequent targets there." Reuter-Lorenz et al. (1996) found that the same variables (e.g., target modality, target intensity) that affected performance in cuing procedures also affected IOR. Given that the mechanism underlying cuing effects is generally accepted to be attentional, they argued that the mechanism underlying IOR was also likely attentional.

Despite numerous findings of IOR in detection tasks (e.g., Pratt, 1995), early failures to find IOR in discrimination tasks (e.g., Terry, Valdes, & Neill, 1994) suggested that perceptual sensitivity at the cued location was not inhibited. This led to a preference for response bias accounts over

perceptual and attentional inhibition accounts. For example, Klein and Taylor (1994) proposed that IOR is due to a bias against responding to a stimulus presented at a cued location. Support came from Abrams and Dobkins (1994). Using the standard display containing two peripheral boxes, they presented a peripheral cue in one box followed by an arrow signal at fixation that directed the participant to make a saccade to one of the boxes. If IOR resulted only from perceptual inhibition at the cued location, then it should not manifest itself because interpretation of the arrow required no perceptual processing at the cued location. Abrams and Dobkins (1994) did find IOR in the central arrow condition, leading them to argue that there must be a response component underlying IOR. Furthermore, because they found even greater IOR for a condition with a peripheral signal that required perceptual processing at the cued location, they suggested that IOR contained both a perceptual and a response component.

Other research suggested that inhibitory tags can be attached not only to cued locations but also to cued objects (Tipper, Driver, & Weaver, 1991; Tipper, Weaver, Jerreat, & Burak, 1994), a system that may be more useful in dynamic real-world situations (see Klein, 1988, 2000). Regardless of the particular instantiation, however, the inhibitory response tag account seems unable to account for Maylor and Hockey's (1985) finding of IOR in a continuous target-target procedure. In this procedure, target 1 functioned as the cue for target 2, which functioned as the cue for target 3, and so on. Consequently, there were no cues to which to attach a "target absent" tag and so IOR would not be expected according to the inhibitory tagging account.

We turn now to an account of IOR that does not rely on inhibition. Although the name IOR clearly calls for an inhibitory explanation, an attentional account does not in fact necessitate invoking inhibition. This is most obvious in the attentional momentum account proposed by our colleagues at the University of Toronto, Jay Pratt and Thomas Spalek, together with their collaborator, Frederick Bradshaw. Pratt et al. (1999, p. 732) proposed "that attention has something like momentum associated with it that allows it to be oriented to locations along the direction of orientation faster than to locations that require a change in the direction of orientation" and that attentional momentum "may best be thought of as the bias for attention to continue moving in the direction in which it most recently traveled."

Under their attentional momentum hypothesis, the cue causes an initial reflexive movement of attention to the cued location. Attention then moves back toward the central fixation cue, where the eyes remain fixated. Because attention is now oriented toward the uncued location, it is biased to move in

that direction, thereby speeding responding to the uncued location and slowing responding to the cued location. Attentional momentum is thus a noninhibitory mechanism that can explain IOR.

In a four-location IOR experiment, Pratt et al. (1999, experiment 1) provided evidence for attentional momentum by examining target detection latencies to the cued location and to each of the three uncued locations. All were equidistant from fixation, forming a plus sign. As usual, detection latencies were slowest at the cued location. The attentional momentum account made the further prediction that because attention last moved toward the uncued location *opposite* the cued location, attention should be biased toward the opposite uncued location. As expected, latencies to the uncued location opposite the cued location were faster than latencies to either of the two uncued locations that were orthogonal to the cued location.

In prototypical IOR experiments, the attentional path is toward the uncued location and therefore attentional momentum theory produces the same primary prediction as the other theories—slower responding at the cued than at the uncued location—but without invoking inhibition. To disentangle these theories, Pratt et al. (1999, experiments 4 and 5) used an additional cue to manipulate the orientation of the attentional path independent of the cued location. This extra cue could lead attention either further along the path away from the initially cued location (continue cue condition) or back toward the initially cued location (reverse cue condition). For the continue cue condition, they found IOR for the initially cued location and facilitation for the uncued location; for the reverse cue condition, IOR was eliminated, again supporting the attentional momentum hypothesis.

In his dissertation, Thomas Spalek (2002) extended the attentional momentum account, linking it to the representational momentum idea of Freyd and Finke (1984) in which objects in motion are remembered as being further along the path of motion than they actually were. If these two ideas are related, then attentional momentum might be expected to have some of the same properties as representational momentum. Spalek focused on two biases in particular: left to right as in reading (Halpern & Kelly, 1993) and top to bottom as in gravity (Hubbard, 1990). His question was whether these same biases would be evident in the IOR paradigm. Using X-configured IOR displays, Spalek showed in a series of experiments that indeed both biases operate in IOR just as they do in representational momentum studies. Moreover, his ongoing work (e.g., Spalek, Hammad, Betancourt, & Joordens, 2002) suggests that the left-to-right bias due to reading is not present—and may even be reversed—in individuals from Egypt, whose language is Arabic, which is read right to left. The inhibition accounts make no directionality predictions, whereas the

attentional momentum account is fundamentally a directional account and accommodates these biases readily.

Inhibition of return is, therefore, another example of a phenomenon in which quite compelling inhibition-based theories were initially proposed and then widely supported; indeed, inhibition remains the dominant explanation. Again, though, as was the case with negative priming, we see in recent research the emergence of an alternative theory. Attentional momentum is based on a noninhibitory mechanism yet seems able to account for the phenomenon. The theoretical debate, however, remains heated (for a counterargument, see, e.g., Snyder, Schmidt, & Kingstone, 2001) and we cannot settle it here. Inhibition of return is an especially good case in point because it actually invokes inhibition as the explanatory process in the name of the phenomenon. It is our view that tasks are best named after the observable elements of the task rather than after the theory initially proposed to explain performance of the task, a point to which we will return later.

For the present, we simply wish to note that the two attentional tasks cited most widely as requiring explanations in terms of inhibition can both be explained successfully without invoking inhibitory mechanisms. We now more briefly consider three additional cases of attentional situations where initial inhibition accounts have been challenged.

C. OTHER ATTENTION ILLUSTRATIONS

1. *The Stroop Effect*

The most venerable of all interference situations is the *Stroop task* (Stroop, 1935; for a review, see MacLeod, 1991), in which participants are required to name the color of the stimulus while ignoring its identity. This seemingly simple task turns out, in fact, to be notoriously difficult. The two basic conditions are the incongruent conditions, in which the word and the color in which it is printed are incompatible (e.g., the word BLUE printed in red, say “red”), and the neutral condition, in which a noncolor word or letter string is colored (e.g., the word TABLE or the string XXXX printed in red, say “red”). The typical finding is that response times for incongruent stimuli are substantially slower than those for neutral stimuli, evidence that processing of the word in the incongruent condition impedes color naming.

This “Stroop interference” is often referred to in the literature as “Stroop inhibition,” conflating phenomenon and explanation. In such cases, the term inhibition is used as a synonym for the term interference (Bibi, Tzelgov, & Henik, 2000; Sugg & McDonald, 1994; Tzelgov, Henik, & Berger, 1992), despite inhibition being an explanatory idea and interference being an observed data pattern. It is an interesting footnote that Stroop

himself was well aware of this confusion, as the first sentence of his famous article clearly indicates: "Interference or inhibition (the terms seem to have been used almost indiscriminately) has been given a large place in experimental literature" (Stroop, 1935, p. 643).

What exactly is meant by inhibition in the Stroop task is not clear. It could be seen as indicating the failure of attention to block processing of the word because word processing is automatic (e.g., Logan, 1988; Posner & Snyder, 1975a,b) it could imply an interaction: that processing of the word disrupts processing of the color (e.g., Cohen, Dunbar, & McClelland, 1990). Regardless, under an inhibition account, some representation is inhibited, either in terms of its activation or the ability to retrieve it. If a representation is required for inhibition to take place, then inhibition should be absent when no representation exists, and interference should be reduced or even eliminated. In conflict with this prediction, data collected in our laboratory by Bibi and MacLeod (2002) confirm findings reported by Monsell, Taylor, and Murphy (2001), indicating that response times for words and for pronounceable nonwords do not differ, both showing equivalent, reliable interference relative to a nonlexical neutral condition (asterisks). Because pronounceable nonwords have no representations, no inhibition should have occurred. Indeed, the fact that interference is roughly equivalent whether measured against a noncolor word baseline (e.g., HORSE in red) or a nonword baseline (e.g., DRAL in red) is further evidence that the effect is not simply a function of existing representations.

It is also instructive to consider how formal models handle Stroop interference. Cohen and colleagues (1990; see also Cohen, Usher, & McClelland, 1998) proposed a parallel distributed processing account of the Stroop effect according to which congruent stimuli (e.g., RED in red, say "red") result in faster responses because processing of the word dimension produces "excitatory input to the response unit." In contrast, for incongruent stimuli, processing of the word "contributes inhibition, decreasing the response unit's net input" (p. 343). According to this model, processing of the word and of the color dimensions occurs in parallel, and the influence of one dimension on the other is restricted to the response units. Thus, processing of the word does not slow processing of the color; rather, it inhibits response execution. Therefore, what Cohen et al. (1990) refer to as inhibition is a type of response competition, although realized in the model via inhibitory links.

Although the Cohen et al. (1990, 1998) models provide good fits of the Stroop data pattern, it would appear that inhibitory links are not necessary to produce such a good fit. Roelofs (2003) has presented a new model for the Stroop task. His model succeeds in accounting for most of the results that MacLeod (1991) cited as critical findings in the Stroop literature, more

so than does the Cohen et al. (1990) model. Roelofs uses a variation on the WEAVER++ model of word production in which processing is based on spread of activation that allows the network to retrieve information and production rules, which enable selection of nodes. In such a model, production rules supply (among other things) the network bias that would be implemented in other models by the use of inhibition. Hence, what would appear to be the best current model for the Stroop task is an inhibition-free model.

As we have argued, the term inhibition has had several meanings, even within this one task. If inhibition simply means that one process slows another, then the term has no real theoretical value and is simply a synonym of interference. Like Stroop (1935), we see this as confusing and we would urge researchers to distinguish between interference, an empirical result, and inhibition, a possible mechanism to explain that result. The conclusion that inhibition is involved should be made after eliminating alternative accounts that can be argued to be the cause of interference. This is especially salient given the negative priming that occurs in the Stroop task (Dalrymple-Alford & Budayr, 1966), which Neill and Mathis (1998) have suggested results from automatic memory retrieval. On the basis of our review, we intended to make two points in this section: that distinguishing between interference and inhibition is important generally across paradigms and that Stroop interference, which might appear to be a prototypical case of inhibition, need not involve inhibition at all.

2. Task Switching

To orchestrate cognition, we must use executive processes to flexibly combine or to switch between tasks, directing our attention appropriately. Over the last decade, this ability has been studied using the *task-switching paradigm* (e.g., Allport, Styles, & Hsieh, 1994). In this situation, the task changes from trial to trial either predictably (no task cue is required) or unpredictably (a cue to the task must precede each trial). An example of a predictable sequence would be switching from word reading to color naming, or the reverse, in a variant of the Stroop paradigm (e.g., Allport et al., 1994; Wylie & Allport, 2000). The main finding is that it takes longer to respond on a trial when the task switches from the previous trial than when it remains the same. This lengthened response time is referred to as the task-switching cost.

The prevalent view (e.g., Allport et al., 1994; Rogers & Monsell, 1995) is that on each trial the participant uses a task set composed of the rules or processes defining the task for that trial. In their task-set inertia hypothesis, for example, Allport et al. (1994) claimed that there was persisting

suppression of competing task sets, or of competing task processing pathways, and that the switching cost stemmed from this ongoing inhibition. In line with this, Mayr and Keele (2000) had participants evaluate the stimulus along one of three dimensions (movement, orientation, or color—A, B, or C). While constantly switching between task sets, Mayr and Keele (2000) presented critical trial sequences that included C-B-A and A-B-A. Responses to the third trial in the sequence were slower if the same task set was used on the first trial in the sequence (i.e., A-B-A) compared to having a completely unrepeatable task sequence (i.e., C-B-A). According to Mayr and Keele (2000; see also Mayr, 2002), this result could be explained only by inhibition of the first task set, which had a persisting effect into the third trial of the sequence.

Mayr and Kliegl (2000) actually argued for a memory retrieval account of the task-switching cost, based on the finding that costs are greater when the task to which the switch occurs involves greater retrieval demands. It would seem that they see this retrieval operation as coordinated with inhibition. Meanwhile, Allport has moved away from an inhibition account, preferring a retrieval account. Wylie and Allport (2000, p. 231) suggest, on the basis of long-lasting interference from the switched-from task, that “a new hypothesis, based on the learned associations between stimulus representations and response representations, does very much better. This hypothesis is similar to learning and retrieval-based theories of negative priming.” Essentially, the stimulus on any trial drives retrieval of responses related to that stimulus, with stimulus–response connections having been built up from previous trials in which both tasks have been encountered. The more prior experience with one stimulus–response mapping, the more that mapping will dominate in retrieval (cf. “binding” in Allport & Wylie, 2000) and, if it mismatches the currently dictated response, will cause enhanced interference. Once again, memory retrieval has the potential to unseat inhibition. It is increasingly clear that just as attention strongly influences memory, memory strongly influences attention.

3. *Visual Marking*

Like inhibition of return, other skills may also help to narrow visual search. Watson and Humphreys (1997) demonstrated that when a subset of the distractors (the old items) in a visual search task appeared earlier than and remained visible when the rest of the distractors and the target appeared (the new items), search time through the new items was unaffected by the presence of the old items. Yet the preview of the old items was too brief to have permitted an extensive search of them. It was as if the second part of the display received priority for search. Watson and Humphreys (1997)

argued that this *visual marking* of the old items—a *preview effect*—was accomplished via top-down inhibition based on a “template” that operates across the entire visual field, preventing the old items from competing for selection (compare to Houghton & Tipper, 1994). Subsequent studies have replicated and extended the basic phenomenon (e.g., Olivers & Humphreys, 2002; Watson & Humphreys, 2000) and have dissociated it from an inhibition of return mechanism that is more sequential than simultaneous (Olivers, Humphreys, Heinke, & Cooper, 2002).

Donk and Theeuwes (2001) showed that without luminance onsets for the new items, the preview effect does not occur. Across their experiments, by varying the relative luminance of the items and the background, they had the old items, the new items, or neither stand out from the background. Only when the new items stood out did they obtain the visual marking effect. There is nothing in the inhibition account that should make inhibition contingent on abrupt onsets of the new items—indeed, Olivers et al. (2002) explicitly claimed that the inhibitory mechanism is in addition to any effect of onset—so Donk and Theeuwes argued against the inhibition account, maintaining that the visual marking effect is in fact the result of abrupt onsets, which provide clear discriminative cues for the new items.

The grouping explanation put forth by Humphreys, Watson, and Jolicoeur (2002) has been couched in terms of inhibition but could, we believe, just as readily be seen as consistent with an abrupt onset account. This is a quite engaging phenomenon, and the debate about how to explain it will continue. We simply note that the evidence for an inhibition account is not conclusive and that there is a viable alternative in the well-established abrupt onset effect (see Yantis & Jonides, 1984).

IV. Memory Case Studies

A. DIRECTED FORGETTING

Our second set of case studies is taken from the domain of memory. Consider the perennial observation that the successful use of memory requires not only remembering but also forgetting. As Ribot (1882, p. 61) said, “Forgetfulness, except in certain cases, is not a disease of memory, but a condition of its health and life.” We must update our memories so that no longer relevant information (e.g., an old address, the name of a former significant other) is not retrieved mistakenly. Forgetting is desirable, and the idea that it can be controlled has gained favor over recent decades. This situation seems especially amenable to an inhibition account of memory—and indeed such an account has been invoked. The paradigm used most often to simulate this situation in the laboratory is called *directed forgetting*,

<i>Item Method</i>	<i>List Method</i>
...	...
table	table
FFF	cheese
friend	friend
RRR	FFF
apple	apple
RRR	horse
horse	truck
FFF	...
...	RRR

Fig. 5. The two standard procedures in directed forgetting (for a review, see MacLeod, 1998). In the item method, each item is followed by an instruction pertaining to that item only; in the list method, there is an instruction to forget the first sublist at the middle of the list and an instruction to remember the second sublist at the end of the list.

where the participant is instructed to forget some recently acquired information, typically in a list-learning procedure.

There are two ways to implement these instructions: Cues are presented either immediately following each item (the item method; e.g., MacLeod, 1975) or only at the middle and end of the list (the list method; e.g., Elmes, Adams, & Roediger, 1970). Fig. 5 illustrates the two study procedures. Subsequent attempts to retrieve both the to-be-remembered (R) and the to-be-forgotten (F) items consistently reveal an advantage of R items over F items. This difference—the directed forgetting effect—has been the subject of considerable study over the past four decades (for reviews, see MacLeod, 1998; Golding, 1998).

Directed forgetting research began in earnest with a study by Muther (1965). Only a couple of years later, the inhibition account first appeared. Weiner (1968; Weiner & Reed, 1969) suggested that F items were inhibited from being retrieved, providing what he saw as a memory-based analog to repression. This inhibition of F items served to reduce their interference with the processing of R items. However, early accounts of directed forgetting quickly came to favor set differentiation (differential tagging of R and F items) and selective rehearsal (rehearsing mainly R items) as explanations (e.g., Bjork, 1970; Bjork, LaBerge, & Legrand, 1968), and the inhibition explanation was largely mothballed for about 15 years.

The return of the inhibition account of directed forgetting was championed by Bjork, Geiselman, and their colleagues (e.g., Bjork & Geiselman, 1978; Geiselman, Bjork, & Fishman, 1983). Originally advocates of selective rehearsal accounts of directed forgetting, but clearly influenced by early repression theories, both Geiselman and Bjork moved progressively toward a retrieval inhibition explanation through the 1980s (for a review of this switch, see MacLeod, 1998). Initially, this account was applied to both item and list methods, as was the selective rehearsal account before it. But because he found that a final free recall test showed no directed forgetting after a recognition test had been administered, Bjork (1989) then suggested that different mechanisms could underlie the two methods. The idea was that selective rehearsal provides the best account of item method directed forgetting, but that retrieval inhibition offers the best account of list method directed forgetting. Retrieval inhibition would be lifted in a recognition test by presentation of an F item, explaining the absence of directed forgetting on a recognition test under the list method. By manipulating the study method, Basden, Basden, and Gargano (1993; for a review, see Basden & Basden, 1998) provided further empirical support for this “two methods, two explanations” view. As a result, the most widely subscribed position at present is that separate mechanisms underlie list and item method directed forgetting (see MacLeod, 1998).

Under the item method, participants fail to adequately encode the F items because they terminate rehearsal at the onset of the F cue. As a consequence, F items receive less rehearsal than R items, accounting for the better recall and recognition of R items compared to F items. Thus, the effect is due to selective rehearsal at encoding.⁴ In contrast, under the list method, in which a forget cue is presented partway through the list and a remember cue at the end of a list, the participant does not know that the F items are in fact to be forgotten until they have already been encoded and rehearsed, so selective rehearsal would appear not to be possible. Instead, the F items are assumed to be inhibited subsequent to encoding, and this inhibition diminished retrieval at the time of recall.

The most frequently cited piece of evidence for inhibition in the list method comes from the failure to find a directed forgetting effect on a recognition test (e.g., Geiselman & Bagheri, 1985). Under the inhibition view, the ability to recognize items that could not be recalled indicates that they were inaccessible during recall rather than not learned. A simple reexposure to the inhibited items is enough to release the inhibition and to

⁴ MacLeod and Daniels (2000) showed that on both explicit and implicit tests of memory, it is only when the encoding is nonoptimal that selective rehearsal can operate to produce a directed forgetting effect.

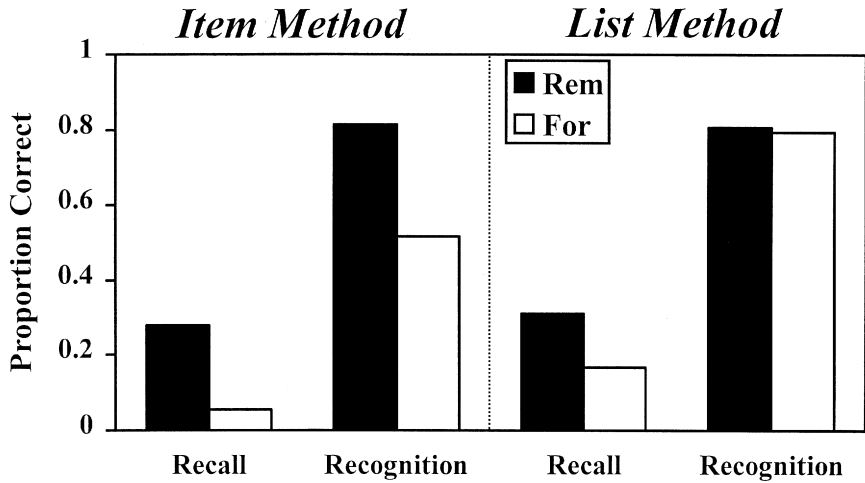


Fig. 6. The standard pattern of directed forgetting effects for the two methods. In the item method (left), the remember–forget difference appears in both recall and recognition; in the list method (right), the remember–forget difference is restricted to recall. Data are from MacLeod (1999).

produce recognition at comparable rates to never forgotten (i.e., R) items. This release does not occur in item method directed forgetting, indicating that the F items are not inhibited there but are simply not very well learned in the first place, a result of diminished rehearsal and encoding of the F items. MacLeod (1999) demonstrated the complete pattern in one study, the data of which are displayed in Fig. 6.

Although the evidence in support of inhibition may seem persuasive, by now the reader will not be shocked to learn that we are not persuaded. Rather, we have been gathering evidence that suggests that selective rehearsal may, after all, provide an adequate inhibition-free account of directed forgetting findings under both methods. This would be much more parsimonious, eliminating the need for two mechanisms to explain the two versions of this one task. The rest of this section briefly sketches out two recent series of experiments in our laboratory that suggest that rehearsal does in fact play a crucial role in list method directed forgetting.

In the first series—Sheard, Dodd, Wilson, and MacLeod (2002)—we explored the situation that Basden and Basden (1998; see also Gilliland, McLaughlin, Wright, Basden, & Basden, 1996, experiment 2) have referred to as the “warning effect” in list method directed forgetting. When, prior to a delay, Basden and Basden informed participants that both R and F words were to be recalled after the delay (the *delay–warning* condition), directed forgetting was eliminated. In contrast, providing a delay without a prior

warning (the *delay-no warning* condition) yielded a normal directed forgetting effect, like that in the standard situation without delay (the *no delay* condition). They explained their warning effect findings in terms of retrieval inhibition: With or without a delay, at recall, participants adopt a retrieval strategy that favors the R items and so the F items are inaccessible or inhibited. If a warning is given prior to a delay, however, they suggest that there is time to switch to a retrieval strategy that allows recall of both R and F words. Changing retrieval strategy presumably takes some time, otherwise participants would switch strategy in the standard condition when the usual instruction to recall all words is given immediately prior to the recall test. Why such a change would require minutes, not seconds, is not clear.

We do not see Basden and Basden's (1998) results as demanding an inhibition account; indeed, we see a selective rehearsal account as accommodating the warning effect findings quite comfortably. Assume that, during a delay with a prior warning, participants might actually selectively rehearse the F words, realizing that these are the words that they are most likely to have trouble recalling. This shift to rehearsing the F words would be detrimental to the R words, the result being a decrease in recall of R, an increase in recall of F, and hence an overall reduction in the directed forgetting effect. Furthermore, although inconsistent with Basden and Basden's results, during a delay with no prior warning, we would expect participants to selectively rehearse the R words, anticipating that only these words would be tested (as they had been told at the outset). This would be detrimental to rehearsal of the F words, therefore resulting in a larger directed forgetting effect than in the usual no-delay situation. Although Basden and Basden did not find an increased directed forgetting effect, this may have been due to their use of related words that caused less forgetting of the F words (cf. Golding, Long, & MacLeod, 1994).

To investigate these predictions from a selective rehearsal perspective, we first replicated Basden and Basden's (1998) pattern of results. We found a typical directed forgetting effect in the standard *no delay* condition and a slightly reduced directed forgetting effect in the *delay-warning* condition. Further, as we had predicted, we found an enhanced directed forgetting effect in the *delay-no warning* condition. To determine whether rehearsal played a role in the directed forgetting effect, we performed a median split based on overall recall performance (R+F). We anticipated that high-memory participants likely would have rehearsed considerably more than low-memory participants.

An interesting pattern of results emerged. Consider first the low-memory group, shown in the left-hand side of Fig. 7. They showed equivalent directed forgetting in the *delay-warning* condition and in the *delay-no warning* condition. Not surprisingly, total recall performance in both of

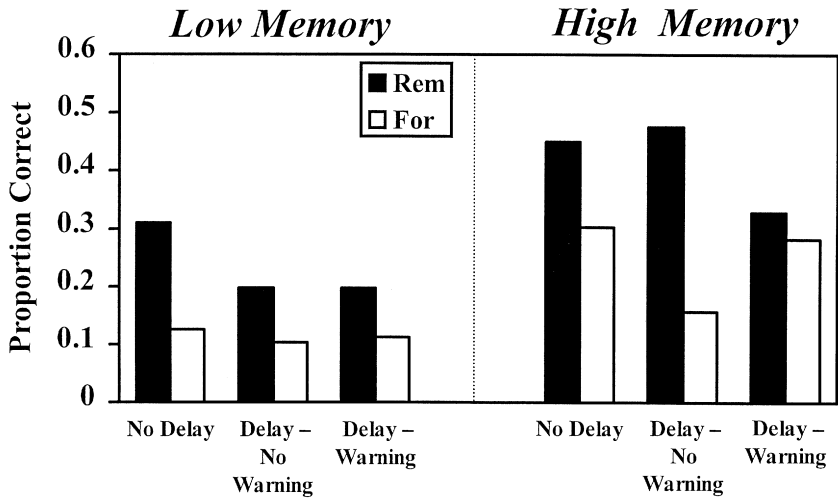


Fig. 7. Recall for two groups of participants who were (*delay-warning*) or were not (*delay-no warning*) warned about being tested on F items following a delay, and for a group with neither delay nor warning (*no delay*). Low-memory participants and (left) high-memory participants (right). Data are from Sheard, Dodd, Wilson, and MacLeod (2002).

these delay groups was reduced relative to the *no delay* condition, but the reduction derived only from reduced recall of R words. The implication is that low-memory participants were not selectively rehearsing any words (R or F) during the delay.

In contrast, the high-memory group (shown in the right-hand side of Fig. 7) demonstrated a modest directed forgetting effect in the *no delay* condition, a substantially increased effect in the *delay-no warning* condition, and a reduced effect in the *delay-warning* condition. We see this pattern as entirely consistent with these participants engaging in differential rehearsal. In the *delay-no warning* condition, R words were selectively rehearsed, resulting in an actual increase in R word recall and a decrease in F word recall, and a consequent increase in the directed forgetting effect relative to the *no delay* group. In the *delay-warning* condition, diverting more rehearsal to F words resulted in a smaller loss in F words but led to a decrease in the recall of R words, producing a diminished overall directed forgetting effect relative to the *no delay* condition. In our view, high-memory participants clearly tailored their rehearsal as a function of the warning condition. Unlike the selective rehearsal account, the inhibition view would not predict directed forgetting differences between low-memory and high-memory individuals.

In a follow-up experiment, we set out to manipulate rehearsal directly by either increasing or decreasing opportunity and motivation to rehearse

during the delay. To reduce the likelihood of rehearsal, we filled the delay with an effortful task; to increase the likelihood of rehearsal, we announced, prior to the delay, that there would be a financial incentive to recall as many words as possible. We predicted that the pattern of results for participants with a filled delay—and therefore discouraged from rehearsing—would match those of our low-memory group and that the pattern of results for participants with a financial incentive—and therefore encouraged to rehearse—would match those of our high-memory group. The findings supported these predictions. Taken together, the experiments in this series suggest that selective rehearsal makes an important contribution to list method directed forgetting under conditions of delayed recall; it remains to be determined whether this is also the case in immediate recall.

In a second series of experiments ongoing in our laboratory, Sheard and MacLeod (2002) have taken a different tack but have been led to the same conclusion that selective rehearsal underlies list method directed forgetting. In an extended set of serial position analyses, we have found that differences between F and R items in list method directed forgetting stem not from poorer *overall* recall of F items, but from impaired recall of only portions of the F sublist. Using the standard list method comparison—a within-subject comparison of the F (first) sublist to the R (second) sublist—we have observed diminished primacy and recency for the F sublist relative to the R sublist. The asymptotic positions were quite equivalent. Fig. 8 shows the serial position pattern.

This finding fits with the rehearsal perspective because the F sublist is presented before the R sublist so that the F sublist should suffer retroactive interference that should particularly minimize recency. However, it is less intuitive from an inhibition perspective, which has always been cast as if retrieval of the entire F sublist is inhibited (see, e.g., Basden & Basden, 1998). Of course, the “reactive inhibition” idea (Houghton & Tipper, 1994; Wundt, 1902; see the “negative priming” section) could be used to argue that it is these beginning and end positions that most require inhibition, but this argument amounts to claiming that inhibition is selective in the same way as rehearsal.

That, however, is not the end of the serial position story. In further experiments, Sheard and MacLeod (2002) have used the more appropriate (but less standard in the literature) comparison between the first sublist from a forget–remember (F-R) group and the first sublist from a remember–remember (R-R) group. This eliminates the usual confound of the F sublist always preceding the R sublist. Because serial position data in this comparison show considerably more primacy for the first sublist in the R-R group than in the F-R group, the directed forgetting effect remains specific to certain serial positions. We then added a new R-R group given

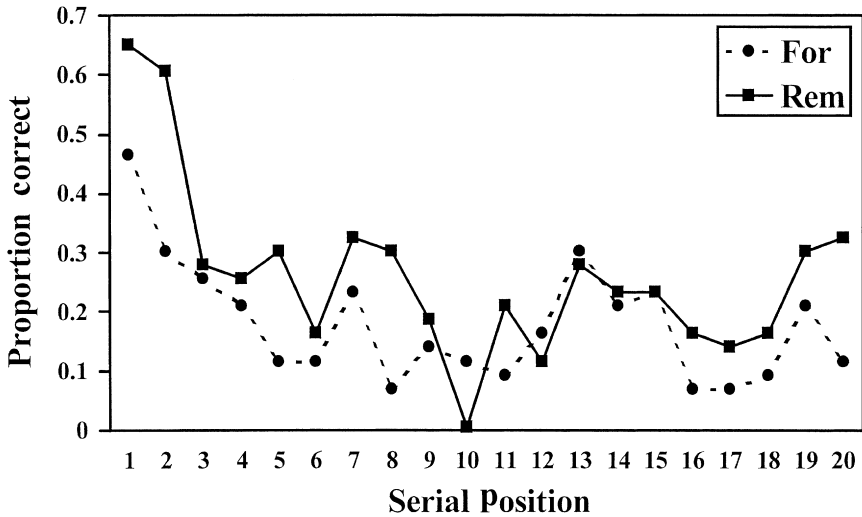


Fig. 8. Free recall serial position functions for the F (first) sublist and the R (second) sublist from a standard F-R list in a within-subject directed forgetting study. The F sublist shows diminished primacy and recency with respect to the R sublist. The instruction to forget the first half of the list clearly does not influence all items in the F sublist equally, which implicates rehearsal as critical to the difference between F and R items. Data are from Sheard and MacLeod (2002).

instructions (between the sublists) to stop rehearsing the first R sublist, hoping to mimic what the F group presumably does when they are instructed to forget. We assumed that this “stop rehearsal” R-R group would be more analogous to the F-R group if rehearsal was the crucial mechanism operating. Performance in the F-R and stop rehearsal R-R groups was almost the same across the serial position curve: Both showed modest primacy and no recency, and there was no reliable overall directed forgetting effect (see Fig. 9). Because the inhibition account makes no prediction concerning such an instruction not to rehearse, this result is decidedly more consistent with a selective rehearsal account.

Retrieval inhibition is still the dominant explanation of list method directed forgetting (for a review, see MacLeod, 1998). What we have tried to demonstrate in this section is that there is a likely role for selective rehearsal even in the list method. We hasten to note that we are not alone in this initiative (see, e.g., Kimball & Metcalfe, 2001) to provide a common selective rehearsal account for the list and item methods. This approach is certainly more parsimonious than having two separate mechanisms for two such similar procedures. The flexibility of the inhibition account makes it rather difficult to put to a stringent direct test, but we believe that the

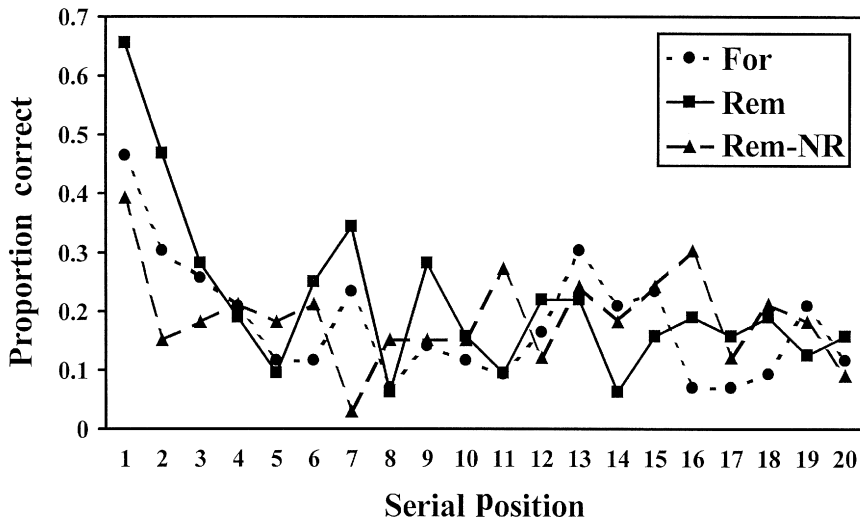


Fig. 9. Free recall serial position functions for the F sublist versus the R sublist in a between-subjects directed forgetting study. Three groups—an F-R group (For), an R-R group (Rem), and an R-R group told not to rehearse after the first sublist (Rem-NR)—are contrasted, with comparisons made on only their first sublists. The first R sublist of the R-R group shows more primacy than the F sublist of the F-R group. However, the first R sublist of the R-R group told not to rehearse behaves much like the F sublist of the F-R group. This implicates rehearsal as critical to the difference between F and R items. Data are from Sheard and MacLeod (2002).

convergence across the lines of research that we have described provides support for a general selective rehearsal account of directed forgetting. Once again, routine memory operations can handle the data without augmentation by an inhibitory mechanism.⁵

B. RETRIEVAL-INDUCED FORGETTING

In the memory domain, directed forgetting is probably the most visible and long-standing phenomenon where inhibition has been invoked as explanatory, but there certainly are others. Another example is a

⁵ There is a remaining puzzle: How can the selective rehearsal account explain the apparent absence of a directed forgetting effect on a recognition test under the list method? We suggest two possible answers. First, the size of the effect ordinarily seems to diminish from recall to recognition under the item method. Given the larger effect in recall under the item method than under the list method, a corresponding reduction from recall to recognition may drive the effect size in list method recognition to the floor. Second, because recognition may not show serial position effects as strongly as recall (see, e.g., Cohen, 1970; Kintsch, 1968), if the list method effects are serial position effects, they may not be visible in recognition.

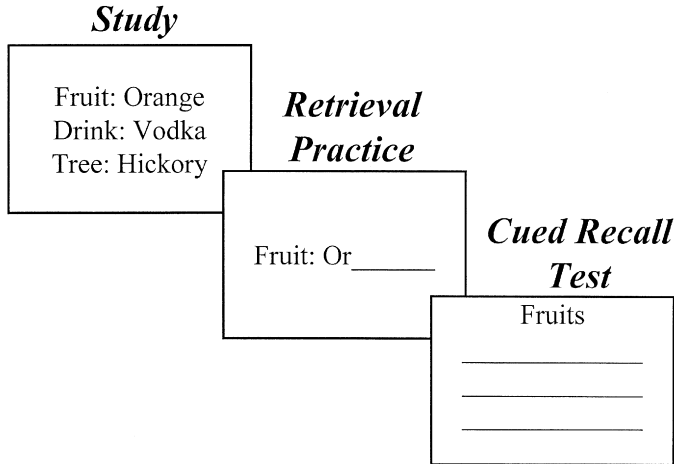


Fig. 10. Procedure used by Anderson et al. (1994, experiment 1) to produce the retrieval-induced forgetting data pattern. *Fruit: Orange* is an example of a strong exemplar; *Tree: Hickory* is an example of a weak exemplar. In the first phase, a list of 48 category–exemplar pairs was studied. This was made up of 8 categories, 4 containing strong and 4 containing weak exemplars, with 6 exemplars per category. In the second phase, half of the exemplars (3) from half of the categories (2 weak and 2 strong) were retrieved repeatedly with a stem cue, such as *Fruit: Or___*. In the final phase, category cues were presented for recall of all items from all categories.

paradoxical situation in which the act of remembering some material disrupts the retrieval of other related material. Labeled *retrieval-induced forgetting*, this phenomenon has been explored by Anderson and colleagues (e.g., Anderson, Bjork, & Bjork, 1994; Anderson, Bjork, & Bjork, 2000; Anderson, Green, & McCulloch, 2000) and others (e.g., MacLeod & Macrae, 2001; Williams & Zacks, 2001). Although the term retrieval-induced forgetting is relatively new, it is worth noting that related findings had been reported earlier (e.g., Blaxton & Neely, 1983; Roediger & Schmidt, 1980; Smith, 1971).

Anderson et al. (1994) first observed retrieval-induced forgetting using lists of words consisting of category–exemplar pairs. Their method is illustrated, using their experiment 1, in Fig. 10. Typically, six exemplars, e.g., *Fruit-Orange* or *Fruit-Nectarine*, were used in each of eight categories (e.g., *Fruit*, *Drink*, etc.). Four of the categories contained only strong exemplars and four contained only weak exemplars. Participants were instructed to learn the pairs for a later memory test. After the study session, there was a practice session in which participants were cued repeatedly (e.g., *Fruit-Or___*) for half of the words from half of each of the strong-exemplar

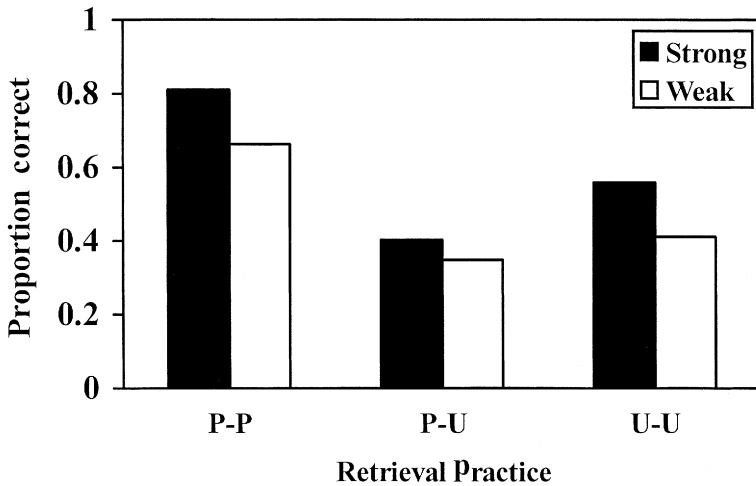


Fig. 11. Mean proportions of items recalled correctly on a category-cued recall test as a function of (1) whether the items were strong or weak exemplars within their categories and (2) whether they were from a practiced category and received retrieval practice (P-P), were from a practiced category and did not receive retrieval practice (P-U), or were from an unpracticed category (U-U). Data are from experiment 1 of Anderson et al. (1994).

and weak-exemplar categories. At test, participants were provided with category cues and asked to recall all of the studied words.

Results from their experiment 1 are summarized in Fig. 11. Not surprisingly, recall was best for the practiced pairs from practiced categories (P-P). Interestingly, though, recall was poorer for unpracticed items from practiced categories (P-U) than for (unpracticed) items from entirely unpracticed categories (U-U). Anderson et al. (1994) argued that this detriment was indicative of inhibitory processes that suppress related material when practiced material is recalled correctly. Under their account, during the practice session, studied words compete with each other while a search for the correct stem completion is ongoing. This competition necessitates a suppression/inhibition of competing words, which in turn makes them less accessible at a later time. More specifically, though, they reported that retrieval impairment occurred for strong categorical exemplars (e.g., *Fruit-Orange*) but not for weak categorical exemplars (e.g., *Tree-Hickory*). They hypothesized that strong categorical exemplars are more likely to interfere during retrieval practice due to their greater associative strength, which causes them to require more inhibition. Weak categorical exemplars are less likely to interfere and may not need to be inhibited during practice. (Once again, this idea is similar to the idea of “reactive inhibition,” where inhibition

is greater to the extent that a distractor might be expected to intrude.) This was the first piece of evidence that led them to an inhibition account.

The second piece of evidence that fit with an inhibition account had to do with the nature of the final retrieval cue and is referred to as the cue-independent effect. To understand this, we turn to a study by Anderson and Spellman (1995; see also Anderson & Green, 2001). Because members of the same category had to be recalled together, it could be argued that the practiced exemplars interfere with the unpracticed exemplars within a category, which clearly cannot occur across categories. To demonstrate that retrieval-induced forgetting is due to inhibition, not simply interference at recall, Anderson and Spellman (1995) used different cues on the final test. To illustrate, participants might learn *Green-Emerald*, *Green-Lettuce*, *Soups-Chicken*, and *Soups-Mushroom* during the study phase. Note that *Mushroom* and *Lettuce* both belong to the shared category *Vegetables*, a category not learned during study. They would then practice *Green-Emerald* in the practice phase. This would lead to the inhibition of *Green-Lettuce* (because *Emerald* and *Lettuce* are both *Green*) as well as *Soups-Mushroom* (because *Mushroom* and *Lettuce* are both *Vegetables*) on a later recall test. Moreover, relative to an unrelated control condition, both *Lettuce* and *Mushroom* would be impaired when the independent cue *Vegetable* was used as a cue on another recall test. Anderson and Spellman saw this as evidence that the items were truly inhibited in memory and not just interfered with at test.

But all is not well in the land of inhibition. More recently, Williams and Zacks (2001) attempted to replicate the Anderson et al. (1994) and Anderson and Spellman (1995) studies, homing in on both of these linchpins of the inhibition account. Put simply, although they readily replicated retrieval-induced forgetting itself in their experiments, they could not replicate either the category strength effect or the cue-independent effect. These were the two legs upon which the inhibition explanation stood. On this basis, Williams and Zacks (2001) argued that the inhibition account of retrieval-induced forgetting was seriously undermined. They preferred an account in terms of retrieval interference, with practice exerting its influence not at the time of practice but at the time of retrieval. Once again, memory retrieval plays the key role.

Continuing research on retrieval-induced forgetting has demonstrated boundary conditions on the effect (Anderson et al., 2000; Anderson & McCulloch, 1999; Butler, Williams, Zacks, & Maki, 2001). A number of studies have also provided evidence for greater generality of the effect, extending it to the realms of social cognition (e.g., MacLeod & Macrae, 2001; Macrae & MacLeod, 1999), eyewitness memory (e.g., Shaw, Bjork, & Handal, 1995), and perception (e.g., Ciranni & Shimamura, 1999). In all of these, the prevailing explanation for the effect derives from the one suggested

by Anderson et al., (1994) and Anderson and Spellman (1995), albeit expressed in more general terms: Retrieving a studied item during practice is now thought to suppress/inhibit other studied items, thus accounting for the later reduction in recall of these items relative to items from unpracticed sets.

As it happens, there is an older phenomenon that appears to be closely related to retrieval-induced forgetting [a fact that Anderson et al. (1994) recognized]. The *part-list cuing effect* grew out of the work of Norman Slamecka (1968, 1969), a colleague at the University of Toronto for many years. Here, after learning a list at study, a few of the studied items are presented at retrieval ostensibly to “aid” recall. Yet presentation of this subset actually reduces the proportion of correctly recalled words from the rest of the list, relative to not presenting this subset (e.g., Todres & Watkins, 1981; Basden, Basden, & Galloway, 1977). Researchers have gone on to examine the interfering effects, as well as those conditions under which the effects can be facilitating, of presenting a subset of studied words as cues during recall (e.g., Penney, 1988; Roediger, 1974; Sloman, Bower, & Rohrer, 1991).

A full review of the part-list cuing literature is beyond the scope of this chapter, but this effect deserves mention because it, too, was initially accounted for in terms of inhibitory processes. Presenting the “cue” list was seen as strengthening the memory of cued items and blocking (inhibiting) the remainder of the studied items: “In other words, cuing may facilitate category recall but usually inhibits instance recall” (Basden et al., 1977, p. 100). Part-list cuing studies have even been conducted using category cues in a manner similar to that used in retrieval-induced forgetting studies.

Basden et al. (1977; see also Basden & Basden, 1995) specifically tested the inhibition explanation of part-list cuing. They showed that extra-list cues (i.e., cues not actually studied) did not reduce recall and that a final free recall test (without cues) showed no residual impact of the part-list cues having been presented on the prior recall test. They saw the inhibition account as predicting a larger part-list cuing effect for strong than for weak items, but did not obtain this result, coinciding with the Williams and Zacks (2001) finding for retrieval-induced forgetting. Basden et al. (1977) concluded that inhibition was an inadequate account of the interference due to part-list cuing. Instead, they put forth a retrieval strategy disruption account: “editing cue words from recall disrupts that recall, perhaps by forcing a recall order inconsistent with intracategory organization” (p. 107), an account that they have continued to support (Basden & Basden, 1995). Although the plausibility of this strategy disruption hypothesis has been debated (e.g., Peynircioglu, 1989), this account has endured and is now considered a viable alternative to the inhibition view. Indeed, the retrieval interference account offered by Williams and Zacks (2001) for retrieval-induced forgetting would appear to be a direct descendent.

Part-list cuing can be accounted for without inhibitory processes, which raises the possibility that retrieval-induced forgetting can be accounted for in the same way. It could be that the practice session, which requires participants to recall a subset of words, disrupts the original organization of studied words in practiced categories, making the unpracticed words from the practiced categories more difficult to recall. Words from the unpracticed categories, however, are easier to recall because the organization of these items has not been disrupted by the practice session.

A number of findings from the literature can be aligned with this view. Although Anderson et al. (1994) observed a retrieval-induced forgetting effect up to 20 min after the practice session, the effect had dissipated by 24 h after the practice session (MacLeod & Macrae, 2001). This could mean that once participants are far enough removed from the disruptive practice session they are able to return to their original retrieval strategies or organization. Anderson and McCulloch (1999) reported that making multiple connections between list items at study created an immunity to retrieval-induced forgetting, reminiscent of a similar finding in directed forgetting (Golding et al., 1994). Relatedly, Smith and Hunt (2000) demonstrated that retrieval-induced forgetting could be reduced when individuals were encouraged to engage in further “distinctive” processing for each presented word. Under the retrieval strategy disruption hypothesis, even if the practice session disrupts the organization of some items in memory, the greater durability afforded by multiple or distinctive representations can ward off the detrimental effect of this disruption.

Anderson and McCulloch (1999) acknowledged the strategy disruption account but did not see it as a viable explanation of the existing retrieval-induced forgetting data. Currently, no study exists in the literature that explicitly tests the strategy disruption hypothesis as it may relate to retrieval-induced forgetting. This leads us to conclude that the dismissal of retrieval strategy disruption as an alternative account for retrieval-induced forgetting effects would be premature. How we orchestrate retrieval of information from memory is a powerful influence on our likelihood of success, so disruption of a retrieval scheme could be very damaging. Despite the provocative demonstrations of Anderson and colleagues, the need to invoke an inhibition account in this setting remains to be established.

C. OTHER MEMORY ILLUSTRATIONS

1. Aging and Memory

Another University of Toronto colleague, Lynn Hasher, with her colleague, Rose Zacks, has championed an inhibition-based account of the cognitive decline seen in aging, particularly in memory. Beginning with Hasher and

Zacks (1988), they have argued that cognitive control involves the tandem processes of excitation and inhibition, with a loss in inhibitory control being the primary factor underlying the change with age. Zacks and Hasher (1997) and Hasher, Zacks, and May (1999) maintained that there are three inhibitory processes that diminish with age: (1) processes that control what information enters working memory, (2) processes that control the unloading or deletion of no longer needed information from working memory, and (3) processes that reduce the probability of incorrect but possibly relevant responses being made.

We do not dispute the cognitive decline data, but we do question their interpretation in terms of inhibition. That older adults are more susceptible to distraction from information not relevant to their current task is an empirical observation, one that we prefer to call, more neutrally, a performance cost. Older people suffer greater interference from to-be-ignored text surrounding to-be-attended text (Carlson, Hasher, Connelly, & Zacks, 1995). They also are more likely to remember information that they need not remember (Hasher, Quig, & May, 1997) or even that they are explicitly instructed to forget (Zacks, Radvansky, & Hasher, 1996). Better memory for to-be-ignored information could be due to the failure to inhibit that information, but do we have to appeal to inhibition to account for these cognitive effects of aging?

Older people could fail to prioritize processing of relevant information either by failing to inhibit irrelevant information or by failing to promote or enhance relevant information. Both mechanisms could explain inefficient selection. We suggest that the greater distractor interference suffered by older people does not result from them failing to inhibit the irrelevant but from them failing to enhance the relevant. We believe that this is a less cumbersome account, obviating the need for inhibition or its failure.⁶

In a related vein, using the process dissociation procedure (Jacoby, 1991), Jacoby, Debner, and Hay (2001) argued that the greater interference often seen in older adults is "caused by a deficit in recollection rather than a deficit in the ability to inhibit a preponderant response" (p. 697). Essentially, as recollection worsens with age, a habitual response is made because recollection cannot be used as successfully to countermand that response at the time of test. In this situation, then, a failure in episodic memory results in the expression of a response that would otherwise be avoided. (Indeed, it may be that older individuals come to rely on their memory of

⁶ Recent work is calling into question whether, indeed, age-related declines are related to increased inhibition or to some other factor correlated with aging. Shilling, Chetwynd, and Rabbitt (2002) argued that other factors, such as speed and intelligence, may not have been as well ruled out as would be desired in studies of aging that have pointed to poorer inhibitory control.

recent or habitual events more, given their knowledge that their memory is poorer than it once was, which presents them with more responses that require countermanding.) Once again, episodic retrieval and the resolution of response conflict would appear to be involved, without need for any inhibitory process(es) at all.

2. *Lexical Decision*

We will consider just two more memory-related instances where inhibition has been proposed. Both occur in the *lexical decision task*, the classic semantic memory task, where the participant must determine whether each string of letters is a word. Since the pioneering work of Meyer and Schvaneveldt (1976), this has become, without question, one of the most frequently employed word identification tasks of the last 30 years. Although early work using this paradigm emphasized the benefits of priming—faster responding to a word following a related word—recent explanations have increasingly added inhibitory components as well.

In the first instance, Ratcliff and McKoon (1995) demonstrated what they referred to as nonword prime inhibition in which the response to the target word of a prime–target pair was slower when preceded by a nonword prime than when preceded by a word prime. McNamara (1994) failed to obtain this effect. Zeelenberg, Pecher, de Kok, and Raaijmakers (1998) suggested that whether this effect was obtained depended on the type of instruction: Instructions that called attention to prime–target relatedness (e.g., Ratcliff & McKoon, 1995), might produce the effect, whereas instructions that did not mention this possibility (e.g., McNamara, 1994), might not. This is precisely the pattern that Zeelenberg et al. (1998) observed when they manipulated instructions.

What is particularly interesting to us about the Zeelenberg et al. (1998) study is that rather than explaining the effect in terms of nonword prime inhibition, they offered a compelling alternative. They suggested that participants made a covert lexical decision response to the prime, although no overt response was required. The consequence was that the response mismatched between a nonword prime and a word target but matched for a word prime followed by a word target. Perhaps, they reasoned, the cost associated with a nonword prime did not involve inhibition but rather the resolution of the mismatch. That calling attention to the relation between prime and target increased the effect is entirely consistent with this explanation. Once again, episodic retrieval and the resolution of response conflict provide a plausible account of an empirical phenomenon seen previously as evidence of inhibition.

The second instance involves an inhibitory idea that has its roots in Ribot (1889): center-surround inhibition. Ribot had suggested that when we excite one representation, we simultaneously inhibit potentially competing ones. Dagenbach, Carr, and Barnhardt (1990) suggested that when an individual tries but fails to extract the meaning from a briefly presented masked prime word, there should be positive repetition priming for that word but negative semantic priming for a related word. The idea is that in the case of failed extraction of meaning for the masked prime word, the word itself receives small semantic activation but related words are inhibited: the center (the word itself) is activated but the surround (related words) is inhibited. Dagenbach et al. (1990) reported data thoroughly consistent with this account.

Kahan (2000) challenged this interpretation of the phenomenon. His theoretical position is called retrospective prime clarification and rests on the idea that when identification of the prime has just failed and the target then appears, we are compelled to resolve, or clarify, the prime before handling the target. It is memory retrieval, not inhibition, that produces the “center-surround” type of data pattern. Kahan varied the proportion of related prime–target pairs, a manipulation that he reasoned should be influential only if his retrospective clarification idea was correct, and found that this indeed did have a powerful influence. In likening his account to the episodic retrieval account of negative priming proposed by Neill and Mathis (1998), he clearly allied himself with the memory retrieval and conflict resolution account advocated in this chapter.

V. The “Big Picture”

A. THE CONCEPT OF INHIBITION

Running through the history of “inhibition,” as with some other key concepts in science, such as “force” in mechanics, was an ambivalence amounting to a philosophical problem. The word referred to a causal process or to a functional relationship. Both usages were common. Sometimes scientists sought to understand inhibition as a specific physical mechanism. At other times, they used the word to describe the function of particular nerves or parts of the brain. On yet other occasions, the word characterized relations within the mind or between the brain and the mind. (Smith, 1992, p. 13)

Our presentation of several case studies in inhibition has necessarily been limited even with respect to the evidence for the tasks and phenomena that we did discuss; space constraints have meant that we have had to leave out a great many more possible cases altogether. Nevertheless, across these examples, we have seen several different senses of and nuances of inhibition.

As we come to the close of the chapter, we wish to characterize what has been meant by inhibition more explicitly and then to make our own theoretical position more concrete as well. We will first indicate how attention and memory theorists have viewed inhibition.

In the domain of attention, Rafal and Henik (1994) have distinguished three inhibitory processes: inhibition of responding to signals at unattended locations, endogenous inhibition of reflexes, and reflexive inhibition of the detection of subsequent signals. In the domain of memory, as outlined previously, Hasher and Zacks (1988) have also distinguished three inhibitory processes: control of what information enters working memory, control of the unloading or deletion of information from working memory, and prevention of incorrect but possibly relevant responses from being made. More broadly, Nigg (2000) suggested three kinds of inhibition: executive inhibition, automatic inhibition of attention, and motivational inhibition. (We will not discuss Nigg's third category, which has more to do with the clinical domain.) His "executive inhibition" includes the control of inhibition arising from competition, the suppression of irrelevant information, the suppression of highly likely responses, and the suppression of reflexive saccades. The first three of these are quite analogous to those of Hasher and Zacks. Nigg's "automatic inhibition of attention" includes attentional suppression of recently examined stimuli and the suppression of unattended information while attention is directed elsewhere. These two and the last one listed under "executive inhibition" closely resemble those of Rafal and Henik.

It is clear, then, that there is some consensus on the conceptual components of inhibition in cognition and that there are also quite a few of these components, harking back to the three senses—suppression, restraint, and blocking—laid out by English and English (1958) and described at the outset of this chapter. It is often difficult to ascertain which one or more of these meanings is intended in existing inhibition-based accounts of cognitive processing. Unlike the meaning of inhibition in the nervous system, the meaning in the mind is much more diffuse. As Breese (1899, p. 14) put it over a century ago: "Inhibition is a term which has been used to designate all kinds of mental conflict, hesitation and arrest."

B. THE PROBLEM OF TERMINOLOGY

When we began working on this chapter, we wanted to illustrate the circularity problem with labeling any negative deviation from baseline as inhibition and then taking this negative deviation as *de facto* evidence for inhibition. We had planned to use *interference* as the label for the empirical finding of below-baseline performance and *inhibition* as the term for a

particular theoretical account of that interference. We wanted to make very clear the point that *interference is not inhibition*. We have come to realize, however, that the term interference also has some degree of theoretical baggage, implying how a negative deviation from baseline occurs.

To describe negative and positive deviations from baseline, we now prefer the terms cost and benefit (Jonides & Mack, 1984; Posner & Snyder, 1975a,b).⁷ A *cost* can be defined as a performance decrement relative to some baseline; a *benefit* can be defined as a performance increment relative to some baseline. If, as cognitive psychologists, we could agree to use these as nonloaded empirical terms, we could then go on to theorize about what mental processes underlie these costs and benefits. Terms such as interference and inhibition would then be seen as theoretical terms at different levels of explanation. A performance cost might be due to interference, which in turn might involve a process(es) of inhibition—although we would not take this second step. A principal advantage of this scheme would be the avoidance of the reflexive equation of inhibition with cost (or interference).

C. AN INHIBITION-FREE EXPLANATION

Many of these inhibitory mechanisms have been suggested by, and based on, metaphors of inhibition that have come to cognitive psychology through the neural sciences. Unlike in the neural sciences, however, where inhibitory mechanisms can be observed in the hardware, in cognitive models inhibition must be inferred on the basis of overt behavior. As such, there is a danger of circularity whereby investigators attribute interference effects to inhibition and subsequently define inhibition on the basis of behavioral interference. For this reason, the terms inhibition and interference are often confused in the literature. (Klein & Taylor, 1994, p. 146)

The variations on inhibition that currently exist are rather like additional free parameters in a model: They certainly make it easier to fit the data, but they are not the preferred way to accomplish the goal. We believe that in most cases where inhibitory mechanisms have been offered to explain cognitive performance, noninhibitory mechanisms can accomplish the same goal without needing to summon reinforcements in the form of inhibition. We have emphasized two such mechanisms—automatic memory retrieval and conflict resolution—that we now wish to consider in greater depth. We should note that these do not originate with us, but have been applied

⁷ It has not escaped our attention that any discrimination of an improvement or a decrement in performance is necessarily with respect to some baseline. This, in turn, places a huge weight on choosing a suitable baseline from the outset, and we realize that this is a very complex problem that deserves a considerably more thorough discussion than undertaken here.

successfully by others in explaining performance in a variety of cognitive tasks, including some of those described here. Our most direct intellectual debts are to Logan (1988, 2002) and Neill and Mathis (1998).

Logan (1988, 2002) proposed that automaticity results when the algorithmic processes required to perform a task lose the race against memory “instances” laid down by previous performances of the task. Each time the task is performed, relevant memory instances are recovered to assist with performance, so the probability of an instance beating the algorithm increases with each performance of the task until a memory instance virtually always beats the algorithm. Consistent with this view, Huettel and Lockhead (1999) showed that sequence effects are very powerful in individual-trial tasks, with the most recent trial exerting a very strong influence on the current trial, whether in the form of a cost or a benefit. It is really quite intuitive that we should look back for help from recent experience, and the evidence is strongly in accord with this intuition. Very often, what we are doing now involves a good deal of what we were doing a moment ago, so routinely querying memory about the recent past can be most helpful in avoiding the need to reanalyze our task and recompute our responses. Jacoby (1978) and Anderson and Milson (1989) have made this point nicely. In particular, routine, possibly automatic, retrieval reduces the need for frequent decisions, and decision making is perhaps the most demanding of cognitive operations (cf. Posner & Boies, 1971).

Cognitive psychologists are, however, expert at creating situations where the recent past (or even the irrelevant present) conflicts with the present. A great deal has been learned about the normal operation of cognition from performance costs; in fact, we would argue that situations involving performance costs are among our most useful cognitive tools. When the past conflicts with the present, we must resolve that conflict before we can respond, or risk making an error. Automaticity, habit, and familiarity—related concepts that recognize the powerful influence of the past—are extremely difficult to deny. Indeed, Anderson and Milson (1989) have argued elegantly that memory is tuned to the statistical analysis of the past, with a particularly heavy weight assigned to the very recent past. When our ongoing processing turns up two paths that we might follow, we must choose. It is interesting, in this regard, that in their excellent book on the subject of inhibition, Diamond et al. (1963) characterized inhibition as what the nervous system does and choice as the behavioral analog: The title of the book is *Inhibition and choice*. When memory points to the same path that our ongoing analysis points to, there is no conflict and no need for choice; when they diverge, then choice—a process that takes considerable time and effort—becomes essential to resolve conflict.

At the risk of redundancy, our candidate to replace the suppression, restraint, or blocking that constitutes inhibition in cognitive theory is a combination of routine memory retrieval coupled with choosing between two (or more) routes when there is conflict. This second stage has often been referred to as “response competition,” although “conflict resolution” (without resort to inhibition) might better capture our intended meaning. Memory retrieval is usually helpful and will speed performance relative to an entirely new analysis (see Jacoby, 1978). When, in a minority of situations, retrieval is not helpful, it still occurs, but now we are forced to choose—to resolve the conflict between memory and the present—and this choice adds to our processing time and may even lead to errors. The result is a performance cost. We would argue that other memory processes also play a role in what might otherwise appear to be inhibition, processes such as selective rehearsal and the implementation of schemas or the use of organizational strategies. All of these are noninhibitory processes that bring the relevant experience of the past to bear on interpreting and acting on the present.

A critic might say that this entire chapter has simply been railing about an ill-defined word and attempting to define it better. We would agree that this is part of our mission and would further argue that we do need to be careful about our terminology.⁸ Yet the reification of inhibition from the neural to the mental is not what we see as meant by linking neural to mental because the meaning of the word differs in the two domains. Our intention certainly has been more than merely to clarify a word. Our goal has been to challenge the concept of cognitive inhibition, proposing instead that processing records in memory are not truly suppressed. In fact, we maintain that the opposite is the case: Recent processing records are retrieved routinely to assist with current processing, but they have the potential to conflict with that processing, producing a cost instead of a benefit. One implication of these ideas (cf. Huettel & Lockhead, 1999) is that cognitive psychologists should be paying more attention to sequence effects across trials in their supposedly “discrete trials” experiments.

We cannot assert that cognitive inhibition is impossible, now and forever. Rather, we hope to have presented a challenge to the invocation of inhibitory explanations whenever performance is poorer than in some baseline condition. We have tried to show that other noninhibitory processes can produce the same behavioral cost. That cost is something to be explained, not to be renamed. As Klein and Taylor (1994, p. 146) put it:

⁸ In this regard, we recommend not naming phenomena after theories that are proposed to explain them. If, for example, it turns out that there is no inhibition in inhibition of return, this name becomes anachronistic and rather misleading. A better name might have been something like the “location repetition cost” to avoid grafting theory to phenomenon.

“There is as yet no established method for distinguishing between those forms of interference which are likely to depend on inhibitory mechanisms and those which reflect processes such as response competition or fatigue.” Cognitive psychologists must define what they mean by inhibition and establish criteria for its occurrence—and its nonoccurrence. At the same time, we must consider how to differentiate possible inhibitory processes from alternative noninhibitory processes. We hope that this chapter provides some measure of motivation for taking up this challenge.

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EVOLUTION OF HUMAN COGNITIVE ARCHITECTURE

John Sweller

Human cognitive architecture is peculiar. A dominant structure, working memory, is minute in its ability to process new material but massive in its ability to process very extensive and complex, previously learned information. An immeasurable quantity of that previously learned information is held in schematic form in a long-term memory that is so closely associated with working memory that it directs and, indeed, can misdirect the manner in which working memory processes information. Together, these two systems (along with a sensory memory system that is not considered in this chapter) permit us to engage in cognitive activities that can vary from simple and routine at one extreme to the intellectual heights that humans have scaled at the other extreme.

The chapter is concerned primarily with why human cognitive architecture evolved in this manner. Specifically, what are the evolutionary advantages of a working memory that requires a large long-term memory to become maximally effective in processing information but has difficulty processing new information not held in long-term memory? In answering this question, it will be suggested that working memory is very limited when handling new information because there is no central executive to coordinate novel information; working memory only becomes fully effective when handling previously learned material held in long-term memory because that previously learned material can act as a central executive; and long-term memory is very large in order to

maximize the circumstances under which a central executive function will be available.

In order to throw light on these and other topics, the following are considered: (1) Relations between the structure of information and cognitive architecture leading to how and why some characteristic types of information impelled the evolutionary development of human cognitive architecture; (2) common information structures underlying human information processing and evolution by natural selection; and (3) consequences of the particular evolutionary directions that our cognitive architecture has taken for learning in general and for modes of presenting information.

I. How Information Structures Have Impelled the Evolution of Human Cognitive Architecture

A. INFORMATION STRUCTURES

While considerable work by many researchers over several decades has been devoted to the organization of human cognitive architecture, far less effort has gone into investigating the information structures that must have driven the evolution of that architecture. Some work has been carried out by Sweller (1994) and Halford, Wilson, and Phillips (1998). Sweller (1994) suggested that all information can be placed on a continuum according to the extent to which the elements that constitute the information interact. At one extreme, there is no interaction between the elements that need to be learned. They are independent. Element interactivity is low or, indeed, nonexistent, which means that each element can be considered and learned serially without reference to any other element. Because elements at the low element interactivity end of the continuum do not interact with each other, there is no loss of understanding despite each element being learned individually and in isolation. Understanding is defined as the ability to process all elements that necessarily interact simultaneously in working memory. Learning such material imposes a low cognitive load because each element can be learned without reference to other elements.

At the other extreme of the continuum, there is close interaction between the various elements that need to be learned. Element interactivity is high, which means that if the material is to be understood, all of the information with its multiple elements must be processed simultaneously, imposing a heavy cognitive load. Elements that interact can be processed individually, in serial fashion, but not with a high degree of understanding. Processing high element interactivity material without learning necessary relations between elements will result in rote learning. The reason rote learning occurs

frequently is because learning individual elements without learning important relations and interactions between elements can reduce cognitive load dramatically. When rote learning, only one, or at most, a very limited number of elements need to be held or processed simultaneously. In effect, during rote learning, high element interactivity material is treated by the cognitive system as though it is low element interactivity material.

In contrast, learning high element interactivity material with understanding imposes very heavy cognitive demands, especially if there are many interacting elements. For understanding to occur, all interacting elements must be processed simultaneously, and for some extensive, high element interactivity material, processing all of the interacting element simultaneously may be very difficult or even impossible (Pollock, Chandler, & Sweller, 2002). Learning such material by rote reduces cognitive load, but at the cost of understanding. Examples of very low and very high element interactivity material are discussed next.

1. Low Element Interactivity Material

Laboratory-based paired associate learning tasks provide one example of learning low element interactivity material. Each paired associate can be learned without consciously considering any of the other paired associates that require learning. In that sense, the elements of the task do not interact. They can be learned in isolation without imposing a heavy cognitive load and without any loss of understanding of the task at hand.

Many realistic tasks resemble paired associate learning. Learning the names of any set of entities such as people's names, the vocabulary of a second language, or chemical symbols provide examples. Such material may be difficult to learn because there may be many elements that require learning, but the difficulty is unrelated to cognitive load. The elements can be learned in serial fashion without loss of understanding. Indeed, the concept of understanding is not normally applied to the learning of such material. One may have not learned or forgotten a particular foreign word, such as the translation of the word "cat," but one does not fail to "understand" the word. The distinction between rote learning and learning with understanding does not apply to such material. Failure to understand is reserved exclusively for high element interactivity material for which there is a heavy load if it is to be learned with understanding (Marcus, Cooper, & Sweller, 1996).

2. High Element Interactivity Material

Modern examples of high element interactivity material include learning the syntax of a second language, deriving meaning from words or symbols,

balancing chemical equations, or most areas of mathematics. Examples of high element interactivity information that our ancestors had to process at a time when the human cognitive system evolved to its present point include learning a spatial layout, such as a route from point A to point B, learning to find food and shelter, learning to avoid danger, or learning complex social relations. To demonstrate the concept, the element interactivity associated with learning some of these areas is considered next.

While much of the vocabulary of a second language can be learned element by independent element with little or no interactivity, syntax cannot be learned in this manner. Elements interact and must be processed simultaneously for understanding and learning to occur. For example, word order is important in English, and word order cannot be learned without considering several words simultaneously. Consider the two sentences: "Word order is important in English" and "English in important is order word." One cannot learn that the first is grammatical but the second is not by considering each word in isolation. Learning the appropriate order of words in English requires the learner to consider all of the relevant words simultaneously. Each word and its interaction with at least some and, in some cases, all of the other words must be considered. Element interactivity is high and, as a consequence, cognitive load is high because at least at some point, all of the elements and their relations must be processed simultaneously.

Understanding and learning the structure of any mathematical process that incorporates an equation invariably involve a high degree of element interactivity. Assume a student is learning how to make a the subject of the equation $a/b = c$. In order to understand and learn the procedure, the structure of the initial equation must be considered, the numerator on the left side must be multiplied by b , which means the numerator on the right side must be multiplied by b in order to retain the equality, and the b in both the numerator and the denominator must be canceled, leaving the solution $a = cb$. While this procedure can be memorized step by step, understanding only occurs when the entire procedure can be processed simultaneously. Multiplying the left side by b without multiplying the right side by b simultaneously reflects a lack of understanding of the procedure. The entire procedure needs to be processed simultaneously if it is to be learned with understanding rather than by rote because all of the elements that need learning interact. Rote learning will reduce cognitive load substantially, but at the cost of understanding. Learning with understanding imposes a heavy cognitive load because the elements that require learning interact and so must be processed simultaneously if appropriate meaning is to be derived.

3. *An Alternative Conceptualization of Element Interactivity*

Halford, Wilson, and Phillips (1998) have provided a formal model of what they term “relational complexity” that provides an alternative to the concept of element interactivity. The model was intended primarily to provide a metric measuring individual differences, including developmental differences, in working memory. Nevertheless, it can equally provide a measure of the working memory load imposed by various tasks, especially problems that require solution. The model assumes that any task or problem can be characterized by the number of dimensions that need to be related. A unary dimension relates constants: *The cat walked*, provides an example. A binary dimension relates two variables, ternary dimension three variables, quaternary four variables, etc. The proportion $a/b = c/d$ is an example of a quaternary relation with its four variables. The number of dimensions that must be related provides the relational complexity of a task or problem, and the number of dimensions that a person can process in working memory provides a measure of working memory capacity.

Relational complexity and element interactivity may well be different terms for the same concept. Because element interactivity was devised specifically to measure differences in working memory load imposed by different tasks has been applied experimentally to a very wide variety of tasks (e.g., see Marcus et al., 1996; Sweller & Chandler, 1994; Tindall-Ford, Chandler, & Sweller, 1997) and, as shown later, has been closely related to schema-based knowledge held in long-term memory, it is used in this chapter. Nevertheless, the similarity and perhaps identity of element interactivity and relational complexity need to be kept in mind.

How has human cognitive architecture evolved to handle these information structures? In particular, how do we handle intellectually difficult, high element interactivity material? Finding one's way around new locations, understanding relations between the environment and food sources or the environment and danger, and establishing social relations and interactions with friends and enemies have been part of human life for a very long time and, along with a myriad of other activities, can all involve high element interactivity information. The nature of the mechanisms required to deal with these situations is discussed next.

B. HUMAN COGNITIVE ARCHITECTURE

Much more work has been carried out on human cognitive architecture than on information structures. The term “cognitive architecture” refers to the manner in which cognitive structures are organized. Cognitive structures and their relations were either discovered or emphasized as individual structures by various researchers since the early 1930s and have been

conceptualized into a unified architecture since the early 1970s. While there are many active research areas and controversies associated with that architecture, there is also a substantial degree of consensus concerning its basic outline. This section describes those aspects of human cognitive architecture around which there is broad agreement, including a brief history of our developing understanding of the topic.

1. Working Memory

Initially designated short-term memory (e.g., Miller, 1956), it is now more commonly referred to as working memory (e.g., Baddeley & Hitch, 1974) to reflect the change in emphasis from a holding store to the processing engine of the cognitive system. Working memory is the seat of consciousness and, indeed, can be equated with consciousness in that the characteristics of our conscious lives are the characteristics of working memory. The most commonly expressed attributes of working memory are its extremely limited capacity, discussed by Miller (1956), and its extremely limited duration, discussed by Peterson and Peterson (1959). In fact, both of these limitations apply only to novel information that needs to be processed in a novel way. Well-learned material, held in long-term memory suffers from neither of these limitations when brought into working memory (Ericsson & Kintsch, 1995).

While initially conceptualized as a unitary concept, working memory is now more commonly assumed to consist of multiple streams, channels, or processors. For example, Baddeley (e.g., Baddeley, 1992; Baddeley & Hitch, 1974) divided working memory into a visuospatial sketch pad for dealing with two-dimensional diagrams or three-dimensional information, a phonological loop for dealing with verbal information, and a central executive as a coordinating processor.

A major consequence of the limitations of working memory is that when faced with new, high element interactivity material, we cannot process it adequately. We invariably fail to understand new material if it is sufficiently complex. In order to understand such material, other structures and other mechanisms must be used. Processing high element interactivity material requires the use of long-term memory and learning mechanisms.

2. Long-Term Memory

Because we are not conscious of the contents of long-term memory except when they are brought into working memory, the importance of this store and the extent to which it dominates our cognitive activity tend to be hidden from us. Given this hidden nature of long-term memory, it is not surprising that modern research into long-term memory postdated research into

working memory. It took some time for researchers to realize that long-term memory is not just used to recognize or recall information but rather is an integral component of all cognitive activity, including activities such as high-level problem solving. When solving a problem, it was previously assumed that knowledge stored in long-term memory was of peripheral rather than central importance. De Groot's (1965) work on chess (first published in 1946) demonstrated the critical importance of long-term memory to higher cognitive functioning. He demonstrated that memory of board configurations taken from real games was critical to the performance of chess masters. The significance of this finding became fully apparent with Chase and Simon's (1973) paper on the same topic.

3. *Schemas*

Knowledge is stored in long-term memory in schematic form, and schema theory describes a major learning mechanism. Schemas allow elements of information to be categorized according to the manner in which they will be used. Thus, for example, we have a schema for the letter *a* that allows us to treat each of the infinite number of printed and hand-written variants of the letter in an identical fashion. Schemas first became important cognitive constructs following the work of Piaget (1928) and Bartlett (1932). They became central to modern cognitive theory, especially theories of problem solving, in the 1980s. As well as the work of de Groot (1965) and Chase and Simon (1973), Gick and Holyoak (1980, 1983) demonstrated the importance of schemas during general problem solving, and Larkin, McDermott, Simon, and Simon (1980) and Chi, Glaser, and Rees (1982) demonstrated the critical role of schemas in expert problem solving. As a consequence of this work, most researchers now accept that problem-solving expertise in complex areas demands the acquisition of tens of thousands of domain-specific schemas. These schemas allow expert problem solvers to recognize problem states according to the appropriate moves associated with them. Schema theory assumes that skill in any area is dependent on the acquisition of specific schemas stored in long-term memory.

Schemas, stored in long-term memory, permit the processing of high element interactivity material in working memory by permitting working memory to treat the many interacting elements as a single element. In effect, the interacting elements are buried within the schema that, as discussed in more detail later, can act as a central executive by appropriately coordinating those interacting elements. As an example, anyone reading this chapter has schemas for the complex squiggles that represent a word. Those schemas, stored in long-term memory, allow us to reproduce and manipulate the squiggles that constitute writing, in working memory,

without strain. However, we are only able to do so after several years of learning.

4. *Automation*

Everything that is learned can, with practice, become automated. After practice, specific categories of information can be processed with decreasing conscious effort. In other words, processing can occur with decreasing working memory load. As an example, schemas that permit us to read letters and words must initially be processed consciously in working memory. With practice they can be processed with decreasing conscious effort until eventually, reading individual letters and words becomes an unconscious activity that does not require working memory capacity. Schneider and Shiffrin (1977) and Shiffrin and Schneider (1977) demonstrated the contrast between conscious and automated processing. In his versions of the ACT architecture, Anderson places a heavy emphasis on automation (e.g., Anderson & Lebiere, 1998). Kotovsky, Hayes, and Simon (1985) demonstrated the enormous benefits of automated processing to problem-solving skill. A problem isomorph that could be solved using automated rules was solved 16 times more rapidly than an isomorph that required the rules to be processed consciously. Thus, high element interactivity material that has been incorporated into an automated schema after extensive learning episodes can be manipulated easily in working memory to solve problems and engage in other complex activities.

5. *Coalescing of Isolated Cognitive Structures and Functions into a Unified Cognitive Architecture*

While these cognitive structures and functions are studied frequently in isolation, they can be combined into a unified cognitive architecture. Atkinson and Shiffrin (1968) elucidated relations between working or short-term memory and long-term memory. In depicting the flow of information between memory stores, they presented a cognitive architecture that is at the core of most subsequent treatments. The cognitive architecture described here incorporates the Atkinson and Shiffrin (1968) model along with the two learning mechanisms, schema acquisition and automation.

All conscious processing of information consists of the manipulation of schemas, which can act as interacting elements, in working memory. That manipulation can result in learning, which consists of the creation of new, higher order schemas and automation. Schemas are stored in long-term memory. They can only be brought into working memory if they are held in long-term memory. The primary, possibly sole, function of long-term memory is to hold hierarchically organized schemas. The limitations of

working memory refer to its limited ability to process separate schemas that have not been incorporated into a higher level schema. Only a very small number of schemas can be processed and they can only be held in working memory for a few seconds. Some schemas can consist of a huge number of interacting elements. These interacting elements are lower level schemas. When brought into working memory, a schema, no matter what its size, is treated as a single element. Thus, schemas have a dual function of organizing information in long-term memory and reducing working memory load. Automation has a similar function of reducing working memory load. On this analysis, the two learning mechanisms of schema acquisition and automation both have a primary function of reducing working memory load and so allowing a limited working memory to process large amounts of information, providing that information has, after learning, been stored in long-term memory in the form of automated schemas. This configuration of cognitive structures and functions has evolved to handle the information humans must deal with.

C. COORDINATION OF INFORMATION STRUCTURES AND COGNITIVE ARCHITECTURE

The information structures and cognitive architecture described in the previous sections can be assumed to be closely coordinated. Biological evolution could be expected to ensure that coordination. The particular information structures that the cognitive configuration has to deal with can be expected to have been a major governing factor in the direction of the evolution of that configuration. Accordingly, it is appropriate to establish links between information structures and cognitive structures and, in the process, attempt to answer questions concerning aspects of human cognitive architecture. An important consideration is how human cognitive architecture evolved to deal with high element interactivity material.

1. Schemas, Working Memory, and High Element Interactivity Material

High element interactivity material, by its very nature, must be processed simultaneously in working memory. It cannot be processed element by individual element and still retain its meaning. One might assume that the obvious way human cognitive architecture would evolve to handle such material would be to develop a sufficiently large working memory to handle many interacting elements simultaneously. Our cognitive architecture did not, of course, follow this route. For reasons discussed later, humans have not developed a large working memory when dealing with new information. As a consequence of our limited capacity working memory, we are not able

to process novel, high element interactivity material. When faced with novel information that contains many interacting elements, we inevitably fail to understand it. Understanding requires all interacting elements to be processed simultaneously, at least at some point, and when confronted with many interacting elements, processing all of them simultaneously in working memory is impossible. As indicated earlier, if we feel impelled or motivated to process such information, the best that can be done is to rote learn some aspects of the material.

Rather than develop a large working memory to handle novel, information-rich, high element interactivity material, our cognitive architecture has evolved to deal with such information by first integrating it into schemas held in long-term memory. Interacting elements can be incorporated within a schema and that schema can then be treated as a single element within working memory. Because those schemas can be processed in working memory as a single element, they eliminate the problem of a limited working memory. Our cognitive architecture has evolved so that very high element interactivity material encompassing large amounts of information can *only* be handled when incorporated in schemas. It follows that such material can only be fully processed in working memory after extensive learning has occurred, sometimes over very long periods of time. Until learning through schema acquisition and automation has taken place, the human cognitive system cannot adequately deal with very complex, high element interactivity material. After learning, such information rich material is handled easily and smoothly.

2. When Working Memory Is Unlimited

A limited capacity working memory is a central concept in cognitive psychology. Since Miller (1956) and Atkinson and Shiffrin (1968), most discussions of human cognitive architecture have incorporated a limited capacity short-term or working memory. It is appropriate that they should do so because working memory is limited when dealing with new information. Nevertheless, capacity limitations only apply when dealing with new, not old information. When dealing with previously learned material, the only discernible limit on working memory is the amount that has been learned and stored in long-term memory. Massive, seemingly unlimited amounts of information can be processed by working memory providing they have previously been incorporated in schemas. A schema may contain a large amount of information but will be processed in working memory as a single element.

The tension between a very limited working memory when dealing with new information and an unlimited working memory when dealing with

learned material can be seen as far back as Miller's (1956) paper. Miller's concept of "chunking," which today can be incorporated in the more sophisticated conception of schema construction, altered the amount of information that short-term memory could hold. By chunking together elements of information, the amount of information held by short-term memory could be increased. In that sense, learning could be used to increase the effective capacity of short-term memory. Similarly, while working memory can only process a limited number of schematically based elements, what constitutes an element is entirely dependent on what has been learned. If much has been learned, an element can incorporate a massive amount of information. Indeed, there may be no limit to the amount of information incorporated in a schema that acts as a single element in working memory. In that sense, there is no limit to the amount of information that can be processed by working memory. The capacity limitations of working memory appear only when new, unorganized information that has not yet been organized into schemas must be processed.

Empirically, de Groot (1965) and Chase and Simon (1973) provided the strongest early evidence for this phenomenon. Chess experts with their appropriate schemas can hold an entire board of chess pieces taken from a real game in working memory because they have a schema for that configuration. Novices have to remember each piece individually, which is beyond working memory capacity, as are random configurations for experts. This result has been obtained in a wide variety of areas (e.g., Egan & Schwartz, 1979; Jeffries, Turner, Polson, & Atwood, 1981; Sweller & Cooper, 1985).

The ability of working memory to hold and process large amounts of learned information for long periods of time was recognized by Ericsson and Kintsch (1995). Their concept of "long-term working memory" applies to very well-learned material. For such material, the capacity limitations of "short-term working memory" disappear. Large amounts of domain-specific, well-learned material in complex areas such as text comprehension, chess, and music can be held and processed in working memory for long periods. The usual capacity and duration limits associated with working memory are not in evidence for such well-learned material.

In effect, we are dealing with two continua: A learning continuum and a working memory limitations continuum. At one extreme, when dealing with yet-to-be-learned or unlearned material, well-known working memory limitations are relevant to processing. At the other extreme, when dealing with well-learned material, the usual working memory limitations are irrelevant and working memory can best be described in terms of Ericsson and Kintsch's (1995) long-term working memory. Thus, in this chapter, long-term working memory is incorporated at one end of a working memory continuum rather than as a discrete structure. Rows 1 and 5 of a cognitive

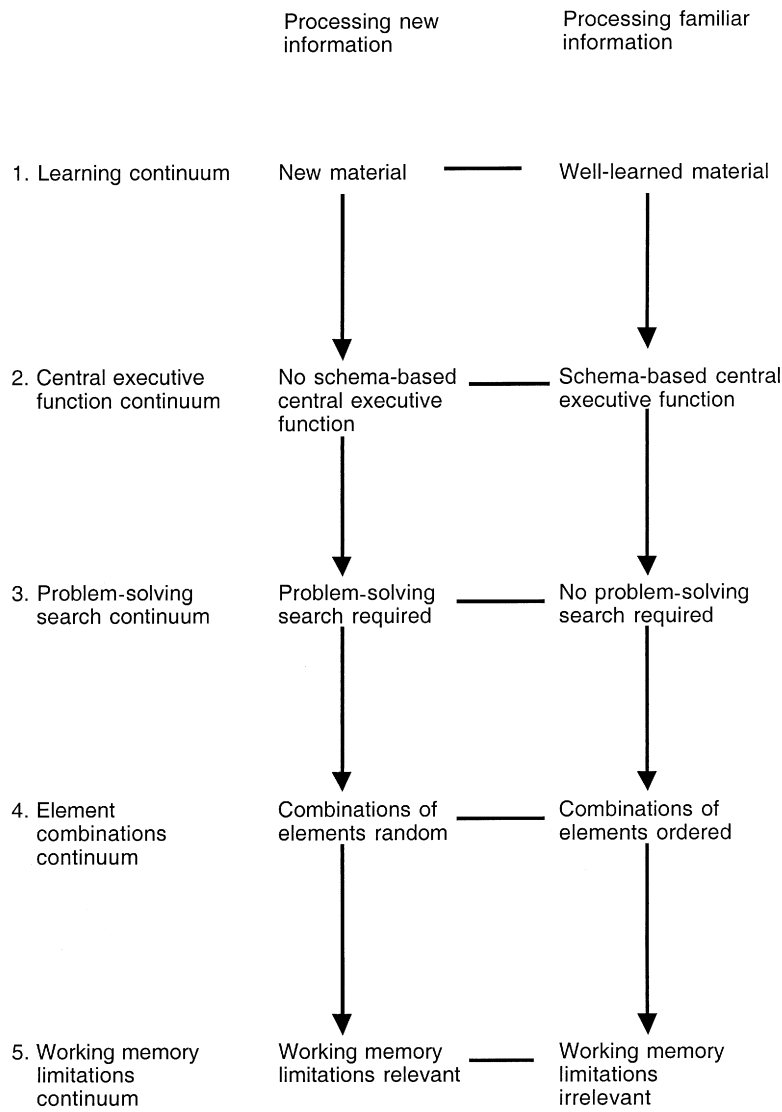


Fig. 1. A cognitive matrix of continua.

matrix of continua (see Fig. 1) depict the learning and working memory continua, respectively.

This chapter is concerned primarily with the intervening constructs relating unlearned material and a limited working memory at one extreme of

the matrix of continua and relating well-learned material and an unlimited working memory at the other extreme. While learning through schema acquisition eliminates the problem of a limited working memory having to handle large numbers of interacting elements (the right side of the matrix of continua), the question remains why human cognitive architecture evolved in this manner rather than following the apparently more straightforward route of a larger working memory, either as an adjunct to or even as a substitute for some learning mechanisms. That route of a larger working memory would have permitted larger amounts of new material to be processed. There should be evolutionary reasons why that route was not followed.

D. A COGNITIVE MATRIX OF CONTINUA

Information we deal with can be placed on a learning continuum extending from new material for which there are very limited schemas available to well-learned material with its elements incorporated into an extensive schematic framework. The first row of Fig. 1 indicates the two extremes of this learning continuum.

The second row is concerned with schemas. While the characteristics and functions of schemas were discussed previously, they have one additional function that is less commonly considered: Schemas held in long-term memory provide working memory with a central executive. Furthermore, they may be the only structure available to provide a central executive for working memory. The second row of Fig. 2 indicates the two extremes of the schema-based, central executive function continuum.

A schema, acting as a central executive, coordinates information. It indicates which information can be ignored, which information is significant, and how the elements of significant information relate to each other. A well-established, automated schema acts exactly as we would expect an effective central executive to act. Both incoming information and the responses to that information can be governed and coordinated by schemas. Provided schemas are available, no other central executive function is required for humans to process information. Of course, schemas must be learned and activated and so are not always available.

Evidence for the central executive function of schemas comes from one of the conditions under which problem solving fails. If a problem solver learns to solve a class of problems using a particular technique, he or she will continue to attempt to use the technique even when presented a problem with a similar surface structure for which it is inappropriate. This mental set, or *Einstellung*, was demonstrated by Luchins (1942) using his well-known water jar problems (see also Ben-Zeev & Star, 2001; Fingerman

& Levine, 1974; Levine, 1971; Ross & Kilbane, 1997; Sweller, 1980a,b; Sweller & Gee, 1978.) The effect occurs because a schema is acquired when learning to solve an initial set of structurally similar problems. That schema then directs the solution of all subsequent similar problems in exactly the manner to be expected of a central executive. On the one hand, it permits the solution of problems that would be quite insoluble without an appropriate schema. On the other hand, it continues to organize the elements and solution procedures of other, structurally dissimilar problems that have similar surface features even when the solution procedures are quite inappropriate. As a consequence, the solution will either be delayed or fail entirely. In contrast, a person presented such a target problem without first having acquired the inappropriate schemas will have no difficulty solving it. The frequently spectacular contrast between the performance of people with and without inappropriate problem solving schemas demonstrates *Einstellung*. In the process, the central executive function of schemas is revealed graphically.

While schemas held in long-term memory provide a central executive for working memory at the well-learned end of the learning continuum, it can be argued that there is no available central executive at the other end of the continuum when dealing with new, yet-to-be-learned material. Two arguments can be put forward against the notion of a coordinating central executive when dealing with new, yet-to-be-learned information for which no schema is available. The weaker argument simply states that the characteristics of a central executive have not been sufficiently well specified to be assured that it exists and, in any case, there is no real empirical evidence for any possible central executive-type construct. This argument is not pursued further because it is overridden by the stronger argument, which is that the very concept of a central executive dealing with yet-to-be-learned material in a nonrandom manner leads to an infinite regress and so is logically impossible.

Consider a central executive coordinating new information in a nonrandom manner. The executive must make decisions on how information is to be dealt with in that it must decide which elements will be combined, coordinated, or related in some fashion. In other words, it must decide on how the information will be processed. That information is both new and infinite in scope. It is new in the sense that the executive has not dealt with such information before and it is infinite in that there is no limit on the types of information or how that information will have to be combined or processed. Other than randomly, how does the central executive decide how to deal with this potentially infinite range of new information? It cannot draw on previous knowledge because the material is new. It could use biologically programmed or "hardwired" procedures for a

limited number of activities but not for the infinite range of information that humans can potentially deal with. (It will be assumed that we are not hardwired to deal with each of the procedures of complex mathematics, for example.) If these assumptions are correct, there is only one other way a nonrandom central executive can arrive at a decision. If the information is to be dealt with in an orderly fashion, it must have another executive function available to direct it. However, the logic of a second executive will, of course, be identical to the logic of the first, requiring a third executive, etc. This infinite regress indicates that the entire concept is flawed and requires replacing. Mechanisms other than a schema-based central executive are required to coordinate new, unlearned information.

If there is no central executive available to coordinate new, yet-to-be-learned elements, how are these elements dealt with? Research into problem solving provides an answer and also provides the third row, the problem-solving search continuum of the matrix of continua. Problem solving search is required precisely when we are faced with new information for which we have yet to acquire appropriate schemas. Critical research in the early 1980s on expert–novice distinctions (e.g., Chi et al., 1982; Larkin et al., 1980) clearly established that when faced with a novel problem for which a learned solution is not available (i.e., a problem being dealt with by a novice with respect to that class of problems), people engage in problem-solving search using a weak strategy such as means-ends analysis (Newell & Simon, 1972). Using this strategy, problem-solving moves are generated by attempting to find operators that will reduce differences between each problem state attained and the goal or a subgoal. In other words, faced with a novel situation, people use general problem-solving search strategies in an attempt to impose some order and choose between various element combinations. The purpose of those search strategies is to attempt to coordinate yet-to-be-learned elements with the external environment. This process of matching is only required when faced with new material for which adequate schemas have yet to be acquired. With respect to the cognitive matrix of continua of Fig. 1, problem-solving search flows directly from the left side of the first two rows of the matrix of continua. That is, it occurs because a person is dealing with new, unlearned material for which there is no schema-based central executive.

At the well-learned end of the continuum, problem-solving search is unnecessary. On the right side of the matrix, when dealing with well-learned material for which well-established schemas are available, the schemas themselves generate problem-solving moves (Larkin et al., 1980). Problem-solving search to coordinate and establish relations between elements is unnecessary because schemas provide all of the necessary relations. In between the two extremes of the third row of the matrix, search becomes less

and less important, moving from the point where moves are generated by problem-solving search to the point where they are generated by schemas. Thus, the third continuum, the problem-solving continuum, has been established and related to the learning and central executive continua.

The first three continua lead to the critical fourth continuum that provides a direct explanation for working memory characteristics when dealing with both new and well-learned material. On the left side of the matrix, operators and problem states must be chosen during problem-solving search in the absence of schemas and their executive function. A major function of problem-solving search is to impose a degree of order on otherwise disordered, more or less random, combinations of elements. This order is imposed by attempting, as far as possible, to use the environment to provide appropriate relations between elements. Random combinations of elements are held in working memory, and attempts are made by problem-solving search to order them in a manner that reflects the environment. Once an appropriate set of relations has been established, the goal of the problem has been attained.

It is frequently forgotten that by necessity, problem-solving search conducted without solution knowledge of moves or element combinations must include a random component. Consider means-ends analysis as an example of a strategy that does not rely on a heavy knowledge base. This strategy requires considerable control and has a relatively small random component. Nevertheless, a random component cannot be fully eliminated. The strategy involves first choosing a move and then testing it to see whether it reduces differences between a current problem state and the goal or a subgoal state. Checking whether a move reduces differences between the current problem state and the goal state cannot occur before the move has been chosen. It must occur after the move has been chosen. If there is no prior knowledge concerning the effect of the move (in the form of schemas or partial schemas), it must be chosen randomly. Only after it has been chosen can it be assessed for effectiveness. There is a high degree of control in that differences between current and goal states are extracted before moves are chosen and moves that do not reduce differences between the current and goal states are rejected. Nevertheless, in the absence of prior knowledge, which moves are chosen for testing using the means-ends heuristic must be random. In the absence of a central executive, there is no other technique available. Other than a random mechanism, there can be no knowledge-free procedure for initially choosing moves to test to see if they reduce differences between current and goal states. As a consequence, on the left extreme of the element combinations continuum, random combinations of elements are necessarily the norm.

With random choice, the greater the number of alternative subgoals and operators from which to choose while problem solving, the less likelihood

that an appropriate choice will be made. As the number of choices available increases, the probability of a choice leading to a dead end also increases. With increased choice, problem-solving search becomes decreasingly effective and, indeed, with even a moderately large number of choices, search becomes pointless. Making an appropriate choice out of two or three at each choice point is feasible. Choosing out of several dozen or more alternatives at each choice point would render the process futile. Problem-solving search is more likely to be effective if it can be limited, and our cognitive architecture had to evolve to ensure that it is always limited because anything beyond a small search space reduces the probability of arriving at a solution to almost zero.

With increasing knowledge, the random choice of elements decreases. At the right extreme of the element combinations continuum, well-learned material has schemas to coordinate elements, and problem-solving search is unnecessary with all element combinations ordered by previously acquired schemas. It is only after learning has occurred that problem-solving search is not needed to order elements because they are ordered by schemas.

We are now in a position to consider the last continuum, the working memory limitations continuum (the fifth row of the cognitive matrix of continua), and to indicate why working memory must be limited when dealing with new, yet-to-be-learned material. The need for a random component when combining elements through problem-solving search leads directly to a requirement for working memory to have a severely limited capacity. Consider someone dealing with two new elements. While the manner in which elements should be combined will vary depending on the material being dealt with, assume that they must be combined using the logic of permutations. There are two ($2!$) unique ordered permutations possible for two elements (ab or ba). As the number of elements increases, the number of permutations rapidly becomes very large ($5! = 120$). The way in which these elements should be combined can be handled easily by a system with a schema-based central executive determining the appropriate combination, as occurs on the right side of the matrix of continua, dealing with well-learned material. Without a central executive, on the left side of the matrix dealing with new material requiring problem-solving search and its attendant need to combine elements randomly, no more than two or three elements can be handled because any more elements would result in more potential combinations than could be tested realistically.

It may be for this reason that we have evolved with a limited working memory. When dealing with new, interacting elements that have not been learned (i.e., have not been formed into schemas), there is no structure that can indicate the manner in which the elements should be combined and so

the need to combine any more than two or three elements can result in a huge number of possible combinations that could not be tested properly against reality. A limited working memory ensures that combining a large number of elements in the absence of a controlling schema cannot occur. Such combinations of many elements would rarely reflect reality. The proposal that working memory is limited in order to limit the number of element combinations that require testing constitutes a central core of this chapter.

The suggestion that a limited working memory may have advantages when processing information under some conditions has been made previously. Both Dirlam (1972) and MacGregor (1987) provided a formal analysis indicating that search is most efficient when the number of items being dealt with closely approximates the number of items that can be held in working memory. Elman (1993) and Newport (1990) suggested that by constraining the search space for grammatical forms, a limited working memory is an advantage when learning a language. Kareev (1995) indicated that when dealing with correlations, a smaller sampling size increases the probability of the sample having a correlation stronger than the population. Thus, if a relation exists, a limited capacity working memory could have the effect of increasing the probability of its being detected. Kareev, Lieberman, and Lev (1997) provided data indicating that people with smaller working memories were more likely to perceive a correlation than people with larger working memories. Taken together, these suggestions all indicate that there may be advantages to a limited working memory when dealing with new material, and the commonsense view that a larger working memory should be advantageous may be erroneous.

In summary, the manner in which our cognitive architecture interacts with information can be represented by a matrix that incorporates five parallel continua: (1) a yet-to-be-learned to well-learned continuum in which the extent that individuals have learned the material (i.e. acquired schemas) that they are faced with increases; (2) an uncontrolled to schematically controlled central executive function continuum in which the degree to which schemas control working memory processing increases; (3) a problem-solving search continuum in which the need to solve problems by problem-solving search varies from essential to unnecessary; (4) a random to ordered combination of elements continuum in which the manner in which elements combine varies from random to ordered; and (5) a working memory limitations continuum with working memory limitations critical at one end and irrelevant at the other.

These five continua are linked causally providing a matrix. On the left side of the matrix, new material that is still to be learned has no central executive coordinating high interactivity elements. Some degree of coordination only

can be provided by problem-solving search that incorporates testing the effectiveness of random combinations of elements. When dealing with these element combinations, a limited capacity working memory is essential to prevent a combinatorial explosion. In contrast, on the right side of the matrix, well-learned material has schemas providing a central executive function. Problem-solving search is not required because schemas provide ordered combinations of elements. Interacting elements are incorporated within schemas, resulting in no effective working memory limits when dealing with such well-learned material. Examples demonstrating the relations incorporated in the matrix are discussed in detail in the next two sections.

1. Processing Well-Learned Material

Assume a person is faced with a high element interactivity task such as navigating from one location to another in a city. How the person deals with that task depends on the learning continuum. The right side of the matrix of continua of Fig. 1 is considered in this section. At this extreme, the person will have learned all that is needed to handle the information using automated schemas. Where to turn, the consequences of being in one traffic lane rather than another, and even where there are bumps or potholes in the road are all incorporated in appropriate schemas. At this extreme of the matrix of continua, schemas act as a central executive when brought into working memory. They coordinate the huge number of sensory inputs and motor outputs with virtually no load on working memory. All the myriad of elements associated with driving from point *a* to point *b* are ordered and organized by the appropriate schemas. The driver will not engage in problem-solving search and may arrive at the destination with almost no conscious effort. Working memory limitations do not impinge on performance at this end of the continuum because the automated schemas generating actions do not impose an appreciable working memory load. Other activities requiring working memory, such as holding a conversation or thinking about an unrelated activity, can be carried out easily because little working memory capacity is required for navigation.

Similarly, for any well-learned activity, such as reading a book, using a computer, going for a walk, and listening to music, schemas tell us what to listen or look at, what to do, and when to do it. For such material, the well-learned nature of the information permits schemas to govern and coordinate the various elements; this central executive function of schemas allows huge amounts of information to be both held and processed in working memory. Problem-solving search to establish appropriate relations between elements does not occur. It has no function because suitable schemas determine all

relations between elements. Under these conditions, working memory limitations are not in evidence (Ericsson & Kintsch, 1995), providing we do not come across new, unfamiliar material for which we have not acquired schemas. When faced with new, unlearned material (i.e., material for which a schema is not available to act as a central executive) different processes are required.

2. *Processing Novel, Yet-to-be-Learned Material*

In contrast to a traveler at the highly learned end of the learning continuum, consider someone at the other end of the continuum, represented by the left side of the matrix of continua of Fig. 1. This person is traversing the route for the first time and so has few or no schemas to coordinate the elements of information. There is no well-defined, schema-based central executive to deal with the information. In the complete absence of a schema-based central executive, problem-solving search to ascertain a suitable route will be required. As indicated earlier, when engaged in problem-solving search, at certain points there is no choice but to combine and test elements randomly. In this particular case, that requires choosing roads on a random basis and testing the consequences of the choice either mentally or physically. That means while we can consider the consequences of choosing a particular direction, we can only do so after deciding to consider that direction, not before. In the absence of knowledge, the decision to choose a particular direction for consideration must be random. More frequently, partial executive functions can be provided by other sources (e.g., a map) and, indeed, precise, ongoing instructions from someone else can provide full executive functions. Nevertheless, in the absence of suitable domain-specific schemas to coordinate elements of information, the person normally will need to engage in problem-solving search using a general problem-solving strategy such as means-ends analysis. Using this problem-solving strategy, the problem solver must attempt to find problem-solving operators that will reduce the differences between the current problem state and a goal or subgoal state. These operators must be chosen randomly but can be tested mentally for their consequences using means-ends analysis, a process that is very expensive in terms of the limited working memory resources available at this extreme of the matrix of continua (Sweller, 1988).

The left side of the matrix of continua applies to a wide variety of intellectual tasks. When listening to or reading unfamiliar, high element interactivity material, various aspects of the material need to be related in order to derive meaning. If the relations are not incorporated in schemas, they will need to be processed in working memory, which will require a

problem-solving process to determine which relations are appropriate. Initial attempts to establish connections between referents, for example, will contain random components and so some attempted relations will be inappropriate and fail, resulting in a comprehension failure. To understand the statement “Initial attempts to establish connections between referents will contain random components,” the listener or reader must establish that “random components” refer to the “attempts” and not the “connections” or “referents” directly. To understand text, the number of such attempted relations must be limited in order to prevent a numerical explosion of possible relations that would permanently prevent comprehension. A limited working memory reduces the number of possible relations allowing the prospect of comprehension. Nevertheless, if there are too many possible relations not previously incorporated in schemas, comprehension will fail (e.g., Britton & Gulgoz, 1991). In contrast, schematic control determines which relations between interacting elements are appropriate and embeds them within schemas. A schema for a statement includes all of the interacting elements within it and can be processed readily in working memory. As a consequence, large amounts of information can be processed with a limited working memory load, allowing very complex relations to exist and thus ensuring comprehension.

II. Human Information Processing Recapitulates Evolution by Natural Selection

The manner in which information is processed by the human cognitive system, as described earlier, recapitulates the manner in which natural selection handles information of the genetic code that results in the perpetuation and evolution of species. Both systems consist of very large bodies of information that control the activities of natural entities that must continually adapt their behavior to a complex environment. It can be argued that the structure of such information systems happens to have certain fixed characteristics irrespective of the particular entity they control or the specific activities of that entity. As a consequence, both natural selection controlling the adaptation of organisms to their environment and the cognitive structures that control human behavior incorporate a single, natural system of information that underlies both processes.

There are several features of such a natural system of information.

- (1) Natural information systems consist of an information store sufficiently massive to permit them to behave appropriately in a complex environment.
- (2) Any alteration or variation to the information store is tested against the environment for effectiveness with effective alterations added to the store

while ineffective alterations are deleted. (3) All natural variations to the store are necessarily random. (4) Because large random variations will almost certainly destroy the functionality of the store, mechanisms must exist to ensure that most variations are small. The validity of each of these propositions is considered in more detail.

A. THE SIZE OF INFORMATION STORES

Information stores that coordinate activity with a complex, natural environment over extended periods of time are necessarily massive. Many natural environments are complex in the sense that they can be characterized by a large variety of states. While any single, simple physical attribute of an environment, such as temperature, pressure, radiation, or chemical composition, may have narrow limits under some circumstances, combinations of attributes frequently result in a constantly altering environment. Information stores governing the activity of an entity must be capable of coordinating that activity with its variable environment. In general, the more variable an environment, the greater the size of the information store required to coordinate activity with that environment. The complexity of an environment must be matched by a commensurately complex information store.

The genome of a species provides an example of the required size of a natural information store. The genetic information contained within the genomes of organisms surviving in complex environments must be massive in order to permit survival. The human genome consists of about 3 billion base pairs. While much of this information appears not to be used in genes, humans still have an estimated 30,000 or more genes. This enormous store of information is required to coordinate complex human activity with our environment. In contrast, the much simpler activity of yeast requires about 1/200th of the number of base pairs and approximately 1/5th of the number of genes of a human. The simpler activity of yeast requires a much smaller store of information. Nevertheless, in an absolute sense, even information stored in the genome of yeast is very large. (It also needs to be noted that there may be no simple numerical contrast that can be used to correlate genetic factors and species complexity. While there may be some correlation between the number of base pairs in the DNA of species and their complexity, some very simple species have many more base pairs than humans. Furthermore, the recent consensus that humans have about 100,000 genes has been broken since the successful mapping of the human genome. The estimated number of genes now varies from 30,000 to 40,000 with the lower number more probable. That number is only marginally larger than for a plant. Complexity may be incorporated in each gene rather

than expressed by the number of genes. It appears that human genes are more complex than that of simpler organisms, with human genes generating more protein products. See Aparicio, 2000; International Human Genome Sequencing Consortium, 2001.)

The large store of information contained within a species' genome is mirrored by the large store of information held in human long-term memory. Information held in long-term memory governs human behavior in an analogous manner to a genetic code governing the behavior of a species. Rows 1 and 2 (the learning and central executive function continua) of the cognitive matrix of continua depicted in Fig. 1 can be used to substantiate the analogy. On the right side, a very large store of well-learned material determines much human behavior. Similarly, a large store of genetic information determines the characteristics of a species. Human behavior is not permanently fixed, and the left side of the learning and central executive continua reflects the fact that common patterns of behavior must alter to reflect a changing environment. Because genetic characteristics of a species must also change to reflect a changing environment, mechanisms to affect genetic change are built into the genetic system.

B. TESTING THE EFFECTIVENESS OF VARIATIONS IN AN INFORMATION STORE AGAINST AN ENVIRONMENT

The manner in which variations to natural information stores are tested for effectiveness can be described by rules. The general rule is that a variation that more closely coordinates activity with an environment will tend to persist, whereas a variation that decreases the coordination of activity with an environment will disappear. This rule is referred to as the environmental coordination rule. Particular versions of this general rule can be described for both evolutionary biology and the manner in which human cognitive architecture handles information.

The mechanism of natural selection is well known. Offspring retain many of the characteristics of their parents, and individuals with more advantageous variations leave more offspring than individuals with less advantageous variations. Natural selection is an example of the environmental coordination rule. Information contained in a genetic code will persist if that code results in activity that is well coordinated with an environment. Information will disappear if activity is poorly coordinated with an environment. An alteration that increases coordination of activity with an environment will result in permanent changes to the genetic code. An alteration that decreases coordination with an environment will result in no permanent changes to the genetic code.

The environmental coordination rule applies equally to humans processing information. The rule is reflected in the third row of the matrix of continua, the problem-solving search continuum. Humans will generally use information in long-term memory to govern their activity (on the right of the problem-solving continuum). Any departures from the use of that information will be tested for effectiveness against the environment using problem-solving strategies such as means-ends analysis. Novel procedures that coordinate activity with the environment more accurately are likely to be retained in long-term memory and used again. The long-term memory store is altered by successful procedures. Procedures that fail to coordinate with the environment will not be retained in long-term memory and tend not to be used again. The long-term memory store is left largely unchanged by unsuccessful procedures. This mechanism is closely analogous to evolution by natural selection.

C. RANDOM VARIATIONS TO NATURAL INFORMATION STORES

Variations to natural information stores occur randomly. Random genetic variation mechanisms are well known. Mutation and sexual recombination result in random variations and without these mechanisms, no natural alterations to a genetic code would occur. Barring deliberate human action, there is no other mechanism available. Similarly, and as indicated earlier, barring knowledge held in long-term memory indicating which moves to make when faced with a problem, moves can only be generated randomly as indicated on the left side of the elements combinations continuum of the matrix of continua. Until the knowledge base can be brought into play allowing movement to the right side of the elements combinations continuum, move generation is necessarily random, just as mutation and genetic recombination are random. Material deliberately intended to have an educative function provides the only exception to these mechanisms. Education techniques can reduce or eliminate the random generation of problem-solving moves (see later), just as the deliberate alteration of a genetic code substitutes for the random variations due to mutation and genetic recombination.

Both the historical reasons for and the consequences of the concept of random variations to natural information stores need to be carefully noted. Random variation was required to explain the evolution of species through natural selection without a guiding intelligence and provides one of the major functions of the theory of evolution. In other words, evolution by natural selection does not have a "central executive" to guide the process. Indeed, in the many theologically motivated debates concerning the theory of evolution, there appears to have been a tacit consensus that no

natural, as opposed to supernatural, candidate for an intelligence guiding the evolution of species was available. All of the “intelligence” of the system resides in genes. A requirement for a second intelligence to guide the manner in which genes evolve would require a third to guide the second and so on, resulting in an infinite regress. Random mutation and natural selection act as substitutes for an additional intelligence.

One purpose of this chapter is to suggest that human cognitive architecture similarly has no natural intelligence in the form of a central executive guiding the generation of novel procedures. There is a natural intelligence in the form of schemas held in long-term memory that guide previously learned procedures that have been established as effective. Those schemas govern the vast bulk of human behavior, including determining what new material should and should not be learned. As indicated previously and as is the case for evolution by natural selection, that stored information incorporates intelligence. An additional intelligence (or central executive) would require an infinite regress to function. When schematic knowledge held in long-term memory is not available or when guidance from other humans who hold such knowledge is not available, only random selection of mental actions is possible. Of course, knowledge gained from those randomly selected mental actions can be retained in long-term memory, which ensures that subsequent actions are intelligent rather than random. Analogously, genetic codes provide a natural intelligence to guide the continuation of a successful species. When suitable codes are not available, random mutations determine which codes will be offered to the environment for testing as part of the processes of natural selection.

D. THE SIZE OF RANDOM VARIATIONS TO A NATURAL INFORMATION STORE

Natural information stores have mechanisms to ensure that variations to the store are small. If, in order to deal with a very complex, variable environment, a store is very large, then relative to its size, any usable alterations will constitute a minute proportion of the total store. A large variation in the store will almost certainly disrupt essential functions and so is incompatible with the continuation of a natural store in a natural environment.

Individual mutations and genetic recombination that permit continuation of a species constitute a very small proportion of a genetic code. A substantial genetic shift will take many thousands or even millions of years. The huge overlap in the genetic code of species that separated millions of years ago is a testament to the stability of genetic codes. Changes over short periods are minute. Only such small variations are viable. Large variations do not survive. Similarly, as indicated by the working memory limitations

continuum, human working memory ensures that alterations to the long-term memory store are relatively slow and small.

In summary, mutation and sexual recombination result in quite random variations analogous to the random choice of moves faced by a person solving a problem for which schema-based solutions are not available. The usefulness or otherwise of a genetic variation can only be assessed after it has occurred. If it is successful, information in the genetic code will be passed on to subsequent generations, whereas a failure will result in a genetic dead end with the information not passed to subsequent generations. Similarly, when limited or no knowledge is available to a problem solver, moves must be chosen randomly. Successful moves may be incorporated in schemas that then can be used indefinitely when faced with similar circumstances. Unsuccessful moves result in dead ends with information not incorporated in schemas and not used subsequently.

Under this formula, a schema encapsulates psychological information in the same way that a gene encapsulates genetic information. Both can be reproduced indefinitely, providing the environment supports the use of that information. Nevertheless, alternative schemas/genes may be more appropriate for environmental conditions. If inappropriate, the structure of the information encapsulated in schemas or genes must change. Changes or variations are generated randomly and tested against the environment. If successful, a new schema or gene will be constructed and used in future. Thus, natural selection and the processing of information by human cognitive architecture can be characterized as identical ways of handling very complex information.

E. GENERATING ADDITIONAL MATRICES OF CONTINUA

This analysis suggests that the cognitive matrix of continua depicted in Fig. 1 is a specific example of a more general matrix from which examples such as that of Fig. 1 can be generated. If so, that more general matrix should be capable of generating not only the psychological example of Fig. 1, but also a specific example applicable to evolutionary biology. The ability to generate a general matrix from Fig. 1 and to generate, in turn, an example applicable to evolution would provide evidence for the argument that common information structures underlie human cognitive architecture and evolution by natural selection. Figure 2 depicts a general matrix of continua that can be used to generate specific matrices applicable to particular areas that may have the same underlying information structures. Figure 3 depicts the evolutionary example that can be derived from Fig. 2.

The first continuum of Fig. 1 deals with learning. On the left side of this continuum, we need to learn (or adapt) when we do not have knowledge

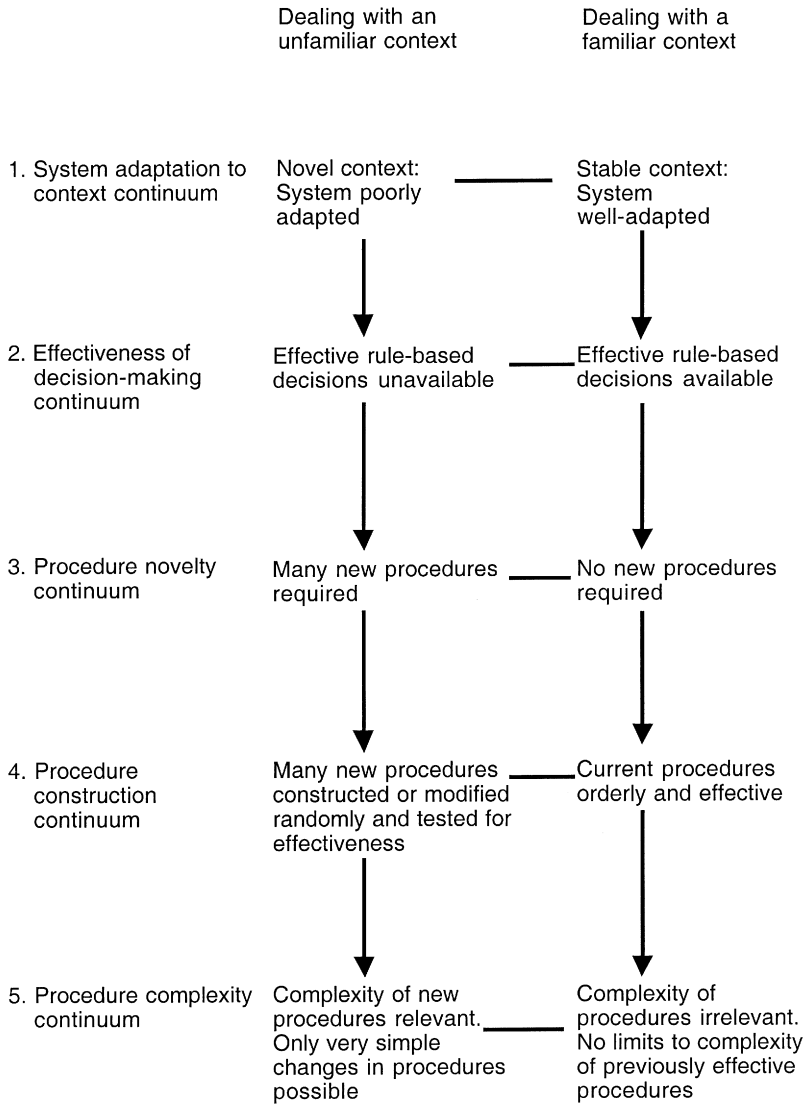


Fig. 2. A generalized matrix of continua.

needed to function in a particular environment. On the right side, essential knowledge has been acquired. In the more general terms of Fig. 2, on the left side, the first continuum deals with an information system that is operating in a novel context for which it is poorly adapted. It needs to adapt or

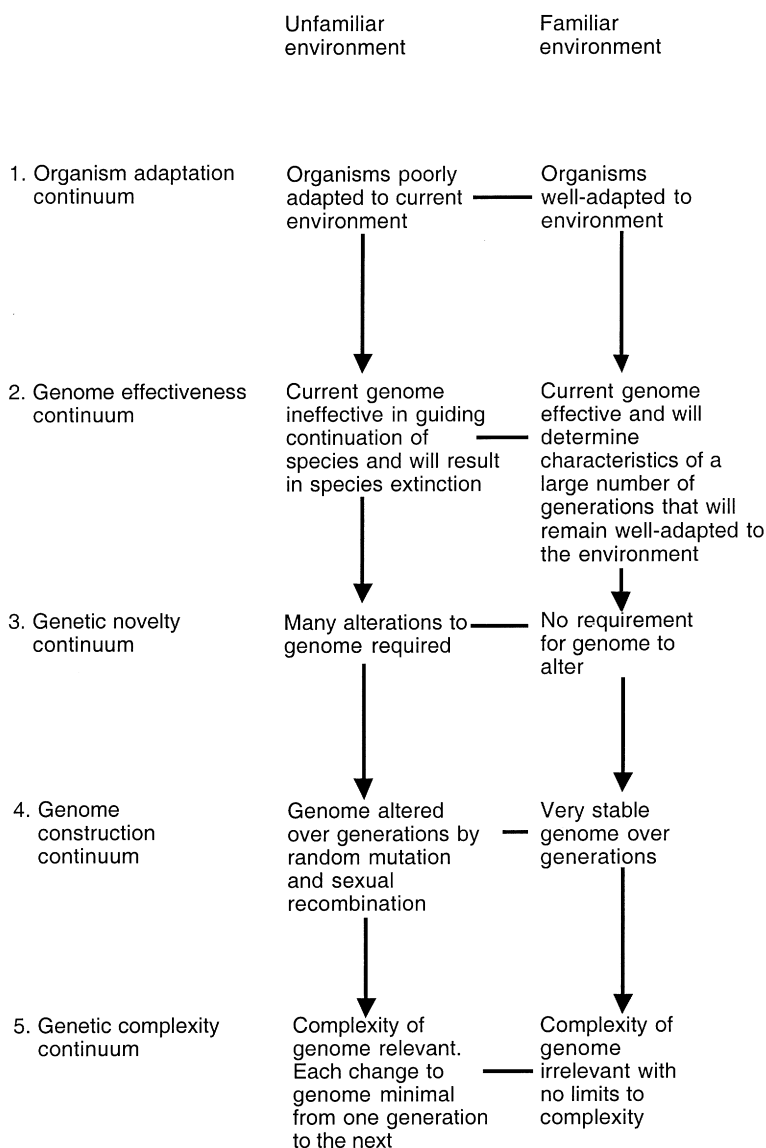


Fig. 3. A matrix of continua for evolution by natural selection.

“learn.” On the right side, the system has already adapted or “learned” what is needed to operate in its environment. The first continuum of the specific evolution by the natural selection continuum of Fig. 3 varies from

organisms that are poorly adapted to their current environment and so need to adapt to organisms that are well adapted to their environment.

The second continuum of each of the three figures is concerned with the extent to which performance is guided by established rules. In the case of Fig. 1, dealing with cognitive architecture, on the left side when faced with new material, there are no schemas to guide performance. On the right side, when dealing with familiar material, schemas determine actions. Thus, in the general terms of Fig. 2, on the left there are no available rules to govern the way the system should operate in its environment, whereas on the right there are well-established rules. This general continuum is the second continuum of Fig. 2. Translated into evolutionary terms, on the left we have a genetic endowment that will not permit a species to survive without change, whereas on the right we have a species with a genetic endowment that is well adapted to the current environment.

If a system is not adequately adapted to its environment, it needs to alter. The left side of the third continuum of Fig. 1 indicates that humans engage in problem solving when faced with such a situation. On the right, where material is well learned, adaptation or problem-solving search is unnecessary. The third continuum of Fig. 2 describes a general continuum in which at one extreme, many new procedures are required to permit the system to operate in the prevailing environment to a situation at the other extreme where no new procedures are required because the system is well adapted to the current circumstances. Similarly, in the genetic terms of the third continuum of Fig. 3, many alterations to the genome are required for survival on the left side of the continuum as opposed to no requirement for alterations to the genome on the right side.

If change is required, what are the mechanisms of change? For human cognitive architecture, the left side of the fourth continuum indicates that change occurs randomly. (Recall that while the generation of possible changes is random, assessment of the effectiveness of possible changes is not random.) On the right side of the continuum, change is not required because previously acquired schemas indicate what actions to take faced with a problem. In other words, we have a system that must generate new procedures randomly and test them for effectiveness at one extreme of the fourth continuum of Fig. 2 or is able to use currently established procedures at the other end of the continuum. In evolutionary terms, as depicted in the fourth continuum of Fig. 3, random mutation and sexual recombination are needed to generate changes to the genome and perhaps new species if a line is to survive. Alternatively, at the other end of the continuum, the current genome is satisfactory for survival without substantial alteration.

Finally, if elements are combined randomly, there must be mechanisms that ensure combinatorial explosions are kept in check. The limited working

memory on the left side of the fifth continuum of Fig. 1 provides such a mechanism. In contrast, on the right side of the continuum, working memory limitations are not needed and do not occur because previous learning has ensured orderly and appropriate sets of elements irrespective of the size of those sets. In general terms of the fifth continuum of Fig. 2, if new procedures are being generated randomly, there must be mechanisms to limit their complexity. Changes must be relatively small and simple to reduce the number of possible changes and to reduce the probability that any change will result in a breakdown of the system. On the right side of the fifth continuum, procedures that are effective need have no limits to their complexity. In other words, while changes to the system must be small and incremental, there are no limits to the complexity of the resulting system. From the perspective of evolution by natural selection, while alterations to the genome from one generation to the next are minimal, as indicated on the left side of the fifth continuum of Fig. 3, that process, if permitted to continue for a sufficiently long period, can result in the immensely complex genome referred to on the right of the fifth continuum. There may be no limit to genetic complexity under such circumstances.

The isomorphism of Figs. 1, 2, and 3 provides evidence for the suggestion that human information processing recapitulates evolution by natural selection. They both share common information structures. It is understandable that the management of information by human cognitive architecture and evolution by natural selection should be similar. Evolution by natural selection is possibly the most efficient, natural system for transmitting, altering where necessary, and perpetuating information. It might be expected that human cognitive architecture, which must also manage information, would evolve to mimic the information processing procedures of evolution by natural selection because both systems are based on the general information processing procedures of Fig. 2.

III. Instructional Consequences

A. GENERAL INSTRUCTIONAL CONSEQUENCES

Instruction is only necessary toward the unlearned end of the learning continuum of the cognitive matrix of continua (Fig. 1), and one of its primary functions is to provide a partial substitute for the missing central executive at this end of the continuum. Consider again someone wishing to learn the road route from point A to point B. They can have someone explain the route, use a road map, or use a combination of prior knowledge with a problem-solving search to fill in the gaps. These activities function as a central executive in

different ways and have different instructional consequences. Both an explanation and a map are two different forms of direct instruction, whereas problem solving provides an example of exploratory learning.

An explanation provides a strong substitute for a cognitive central executive. As one would expect from a central executive, it provides an overarching set of instructions for the critical processes that must be taken. Furthermore, the instructions can be followed with a minimum of additional learning, such as learning to use a map. If the explanations are adequate, all random processes are eliminated because the explanation, as a central executive, tells the learner precisely what needs to be done. Once a road route is learned, the learner moves to the right side of the matrix of continua, and the schemas acquired take over from the explanation and act as the central executive, rendering an explanation redundant.

A map, while it also acts as a substitute for a cognitive central executive, requires more intermediate learning than an explanation before it can be used. People need to learn to use a map before they can use it to learn a particular route. Thus, learning to use a map has its own set of learning continua, and until a person has acquired the map-reading schemas that allow movement to the right side of the matrix of continua for map reading, learning a route by using a map will be difficult or even impossible. Nevertheless, if map-reading skills have been acquired, a map, like explanations, can provide a powerful central executive substitute. Used properly the need to consider the consequences of random actions can be totally obviated and can continue to be avoided until the schema-based central executive on the right of the matrix of continua takes over the executive functions.

Problem solving provides the least effective substitute for a cognitive central executive. There is no choice but to propose actions randomly and then use the environment or prior knowledge to test the effectiveness of those actions as far as they can be tested. The learner is likely to move to the right of the matrix of continua very slowly, and so for much of the learning process, there is no effective central executive function. Only toward the end of the learning process, when schemas have been acquired, is an effective central executive available. Using this reasoning, problem solving may be considered as a last resort instructional technique when other more direct forms of instruction are unavailable.

The inadequate central executive function provided by problem solving has other ramifications. Combining elements randomly and testing the effectiveness of combinations against reality require substantial working memory resources (Sweller, 1988). The activity imposes a heavy working memory load just at the point where working memory resources are at their weakest because problem-solving search occurs at the new, yet-to-be-learned

end of the learning continuum where working memory limitations are relevant. The heavy working memory load associated with problem solving can interfere with learning. Direct, fully guided instruction alternatives to problem solving circumvent both the lack of a central executive and the heavy cognitive load associated with search. On this analysis, direct guided instruction, rather than problem solving, should be used as a means of acquiring schemas. Substantial empirical evidence exists for this suggestion (see Sweller, 1999; Sweller, van Merriënboer, & Paas, 1998; Tuovinen & Sweller, 1999).

The contrast between direct guided instruction and exploration applies to all material that needs to be learned, including material covered in educational institutions. Learning to solve classes of mathematical problems, write essays in history, run scientific experiments, or learning to read and write must all be affected without an adequate cognitive central executive provided by schemas. Showing students how to solve mathematical problems, write particular types of essays, run experiments, or providing direct instruction in how to read and write can all provide an effective central executive substitute and reduce the cognitive load associated with problem solving, although care must be taken to ensure that the instruction itself does not impose a heavy working memory load (e.g., Sweller, Chandler, Tierney, & Cooper, 1990; Sweller, Mawer, & Ward, 1983). In all cases, direct guided instruction can provide a temporary replacement for schemas until they are acquired.

Indirect instruction provided by various discovery/exploratory techniques offers a less effective central executive substitute with an inevitably high random component. Direct guided instruction is effective because it reduces the number of random element combinations that must be tested. It is likely to be essential for very high element interactivity material for which the number of random combinations that must be tested will be unacceptably high. The knowledge that lies behind such material could only be derived by scholars engaged in the very lengthy, working memory-taxing activities inevitably required when dealing with a multitude of interacting elements that are not appropriately organized by a central executive. Such problem-solving activity is unavoidable when neither schemas nor direct instruction are available to act as a central executive that indicates appropriate relations between elements. Humans learn through problem solving not because it is effective (empirical evidence indicates unambiguously that it is not effective as a learning device, see Sweller, 1999; Sweller et al., 1998) but because they are forced to by the environment and the lack of a central executive. Direct guided instruction acts as a substitute for a central executive and should always be used if available.

B. CREATIVITY

Creativity has always been a difficult concept to deal with or even to define. Nevertheless, most definitions of creativity incorporate the generation of new ideas and, under such definitions, it is easy to assume that the general instructional consequences discussed in the previous section leave no room for human creativity or may even stifle creativity. In fact, the common information processing structures of human cognitive architecture and evolution by natural selection can provide a solution to the problem of human creativity.

Evolution by natural selection has created innumerable functions, procedures, and outcomes that vastly exceed the capability of human cognition. We are not only unable to create what evolution by natural selection has created, to this point we are unable to even understand many of the products of evolution, with massive scientific enterprises being devoted to precisely this cause. Given the much shorter time frame in which human cognitive activity operates, it is not surprising that our creative endeavors are unable to match those of evolution by natural selection. Nevertheless, humans are and have been creative and that creativity can be explained by the current theoretical framework. Based on the perspective of this chapter, human creativity and the creativity exhibited by evolution by natural selection are generated by the same mechanisms. Those mechanisms are reflected on the left side of the matrices of continua. A knowledge base in long-term memory or as part of a genetic code may become inadequate and is altered by random processes; the knowledge base requires procedures for testing the effectiveness of alterations and only incorporating those that are effective; and the knowledge base must have mechanisms to protect it from large random alterations that may destroy it. Using these mechanisms, both evolution by natural selection and human cognition have been able to create new and effective structures.

It needs to be noted that on this analysis, random processes provide the initial impetus for human creativity just as random mutation is critical for the creativity of evolution by natural selection. There is no central executive determining what is creative (left-hand side of the second continuum of Figs. 1 and 3). Nevertheless, despite the initiating random processes, creativity is critically determined by the current knowledge base, as it is from that base that new creative actions are taken, just as it is the information encapsulated in a genome from which random mutations can determine new biological procedures and functions (fourth continuum of Figs. 1 and 3).

Langley, Simon, Bradshaw, and Zytkow (1987) also suggested that creativity depends on an appropriate knowledge base associated with

conventional problem-solving search mechanisms. Some evidence for the validity of their proposal comes from a production system that they constructed that rediscovered some of the early laws of physics. That system only had the knowledge base required to generate particular laws and so has not been able to discover new scientific laws. If the theoretical suggestions made in the current chapter are valid, no computational system is likely to discover, as opposed to rediscover, new scientific laws unless it incorporates a massive knowledge base with the mechanisms for small random alterations of that base over long periods of time along with procedures for testing the effectiveness of those alterations. Such a system is currently not available.

Suggested procedures for “teaching” creativity arise periodically in both psychology and education. None of these attempts has been able to obtain widespread, empirical support. The current proposals imply that teaching creativity is likely to be difficult or impossible but that humans may no more need to be taught how to “explore,” “investigate,” “discover,” or “create” than does evolution by natural selection. Only a knowledge base can be taught and learned and that knowledge base will determine what can and cannot be created.

It is, of course, possible that life on earth includes multiple mechanisms that have creativity as one of their end results and that the creativity exhibited by evolution by natural selection and by humans uses different mechanisms. Nevertheless, the thesis outlined in this chapter suggests a single rather than multiple mechanism.

C. SPECIFIC INSTRUCTIONAL DESIGN PRINCIPLES AND EFFECTS

There are a range of specific instructional design principles and effects that flow from the considerations outlined in this chapter. Cognitive load theory, an instructional theory based on the combination of information structures and cognitive architecture described earlier, has been used to generate those instructional effects.

1. The Goal-Free Effect

This effect occurs when learners presented a conventional, goal-specific problem in which the goal might be “calculate the value of angle ABC” in the case of a geometry problem or “calculate the final velocity of the vehicle” in the case of a kinematics problem learn less than learners presented a nonspecific or goal-free problem. Examples of nonspecific goal problems are “calculate the value of as many angles as you can” or “calculate the value of as many variables as you can.” The goal-free effect was obtained by Sweller and Levine (1982) and has been demonstrated on many occasions (Ayres, 1993; Sweller, & Cooper, 1985; Burns & Vollmeyer,

2002; Geddes & Stevenson, 1997; Miller, Lehman, & Koedinger, 1999; Owen & Sweller, 1985; Paas, Camp, & Rikers, 2001; Sweller, 1988; Sweller et al., 1983; Tarmizi & Sweller, 1988; Vollmeyer, Burns, & Holyoak, 1996). It can be explained using the cognitive matrix of continua of Fig.1.

Assume a novice problem solver solving conventional problems by means-ends analysis. As a novice, he or she will be on the left side of the matrix of continua. To make moves, differences between the current state and the goal state will need to be established, a potential move will need to be chosen randomly (assuming prior knowledge concerning the effects of particular moves is unavailable), and each potential move will need to be assessed to establish whether it reduces differences between the current problem state and the goal state. Because working memory limitations are relevant on the left side of the matrix of continua, this complex procedure may leave few or no resources available to attend to schema acquisition. When acquiring a schema, learners must engage in the quite different activity of learning to classify problems and problem states according to their moves. As a consequence, learning may be inhibited.

In contrast, assume a problem solver who is presented goal-free problems. The only activity that needs to be engaged in is to choose any potential moves randomly and determine whether they can be made. Working memory load is minimal. Furthermore, learning which moves can be made given a particular problem state is central to schema acquisition. Sweller (1988) suggested that this interpretation explains the goal-free effect.

Presenting learners with goal-free problems may appear unusual if the aim is to present learners with direct, fully guided instruction. Goal-free problems reduce the guidance provided by a specific goal. For this reason, the procedure is effective, but only if all moves made under goal-free conditions are useful in the sense that they need to be learned and practiced. Not all problems have this characteristic. Some problems have a large or even infinite number of moves that could be made with most moves serving no function. For example, asking learners to make as many manipulations as possible of the equation $(a + b)/c = d$ can result in an infinite number of manipulations, as one can legitimately add an infinite number of constants to each side. Goal-free problems should not be used with such material and so an alternative is required.

2. The Worked Example Effect

The use of worked examples can overcome the problem of goal-free problems only being useful for a limited class of problems. There are probably no classes of problems for which worked examples are not potentially effective.

The worked example effect occurs when learners who are presented with a large number of worked examples to study learn more than learners presented an equivalent number of problems to solve. The effect has been studied extensively (Carroll, 1994; Cooper & Sweller, 1987; Miller et al., 1999; Paas, 1992; Paas & van Merriënboer, 1994; Pillay, 1994; Quilici & Mayer, 1996; Sweller & Cooper, 1985; Trafton & Reiser, 1993).

Worked examples provide problem-solving guidance that can act as a substitute for schemas that are unavailable to novices. They are the ultimate form of direct instruction. Rather than engaging in the means-ends problem-solving search process described earlier, learners can be guided by a worked example acting as a substitute schema-based central executive. The lack of such a central executive necessitates problem-solving search, with its inevitable random components and working memory load found on the left side of the matrix of continua. While psychologically the learner is on the left side of the matrix of continua, a worked example allows him or her to perform as though they are on the right side of the matrix. A good example acts as a substitute for a schema-based central executive, eliminates the problem-solving search with its random base, and reduces difficulties imposed by a limited working memory because all necessary information is incorporated within the example (see later sections on split-attention, modality, and redundancy effects). As a consequence, learning can be facilitated by an emphasis on worked examples resulting in the worked example effect.

3. The Problem Completion Effect

Most demonstrations of the worked example effect involve presenting worked examples paired with very similar problems. Learners are presented a worked example and are then immediately presented a very similar problem to solve. This procedure ensures that learners are motivated to study the worked example in order to ensure that they can solve the following problem. The extent to which they can solve the following problem also provides them with some feedback concerning their ability to solve problems of that type.

Completion problems were invented as an alternative to this procedure. Rather than presenting learners with full worked examples followed by similar problems, they are presented with partial worked examples that require completion. The partial worked example provides sufficient guidance to reduce the problem-solving search and cognitive load, whereas problem completion ensures that learners are motivated and receive feedback concerning their knowledge of relevant problem types. Paas (1992), Paas and van Merriënboer (1994), van Merriënboer (1990), van Merriënboer and

de Croock (1992), van Merriënboer and Krammer (1987), and van Merriënboer, Schuurman, de Croock, and Paas (2002) provided evidence that completion problems have a positive effect similar to that of worked examples when compared to full problems. It is reasonable to assume that the theoretical reasons for the problem completion effect are identical to those used to explain the worked example effect.

4. *The Split-Attention Effect*

Not all worked examples are effective. A worked example that is structured in a manner that ignores working memory limitations may be no more or even less effective than solving the equivalent problem. Some worked examples in some areas are conventionally structured in a manner that requires learners to split their attention between multiple sources of mutually referring information before mentally integrating those sources of information. A conventional geometry worked example consisting of a diagram and statements provides an instance. The diagram in isolation provides no instruction. The associated statements, such as *angle ABC = angle XYZ*, are unintelligible without a diagram. Meaning can only be derived from the worked example by mentally integrating the diagram and the statements. Mental integration requires working memory resources because learners must search for referents. When a geometry statement refers to *angle ABC*, learners must search the diagram for *angle ABC* in order to understand the statement. In effect, the learner is not only on the left side of the matrix of continua for geometry, but is on the left side of the matrix for the particular example being studied. An act of problem solving must be engaged in simply to locate appropriate referents. Locating referents requires working memory resources that are unavailable for learning geometry.

Because we do not normally have schemas for the labeling of particular geometry diagrams, providing guidance in locating referents can be just as beneficial as guidance in the more general terms discussed previously. Such guidance can be provided by physically integrating diagrams and statements. Rather than placing the statement *angle ABC = Angle XYZ* below or next to the diagram as normally occurs, the relevant statements can be incorporated within the diagram so that a search for referents is eliminated. If conventionally structured worked examples are compared with physically integrated examples, results normally demonstrate an advantage for the integrated versions, resulting in the split-attention effect. Various versions of the effect have been demonstrated using a wide variety of materials under a wide variety of conditions. Furthermore, as might be expected, it is not restricted to worked examples but applies to any

instructional material (Bobis et al., 1993; Cerpa, Chandler, & Sweller, 1996; Chandler & Sweller, 1992, 1996; Mayer & Anderson, 1991, 1992; Mwangi & Sweller, 1998; Sweller et al., 1990; Tarmizi & Sweller, 1988; Ward & Sweller, 1990).

5. *The Modality Effect*

While physical integration of multiple sources of information can be highly effective, there is an alternative that is equally effective and, under some circumstances, may be preferable. The split-attention effect relies on visual modality with visual search being reduced by the use of physical integration. Visual search means that the visual channel only (the visuospatial sketch pad of Baddeley, 1992; Baddeley & Hitch, 1974) is being used and overloaded under split-attention conditions. Considerable evidence, shows that effective working memory can be increased by using dual rather than a single modality (e.g., Penney, 1989). While the visual and auditory processors of working memory are not fully separate in the sense that one does not obtain a simple additive increase in processing capacity by presenting some material visually and some in auditory mode, there is considerable empirical evidence of a measurable increase in working memory capacity when using both modalities (Allport, Antonis, & Reynolds, 1972; Brooks, 1967; Frick, 1984; Levin & Divine-Hawkins, 1974). From a theoretical perspective, capacity should increase to the extent that visual and auditory processors can function autonomously without sharing other cognitive structures that limit capacity. Some empirical evidence of an increase in working memory capacity when using both modalities also provides evidence for partial autonomy of the auditory and visual channels.

The possibility of increasing working memory capacity using dual rather than a single modality should have instructional consequences. For example, under split-attention conditions, rather than presenting a diagram and written text that should be integrated physically, it may be possible to present a diagram and spoken text. Because the diagram uses visual modality while speech uses auditory modality, the total available working memory capacity should be increased, resulting in enhanced learning.

The instructional modality effect occurs when learners, faced with two sources of information that refer to each other and are unintelligible in isolation, learn more when presented with one source in visual mode and the other in auditory mode rather than both in visual mode. This effect has been demonstrated on a number of occasions (Jeung, Chandler, & Sweller, 1997; Mayer & Moreno, 1998; Moreno & Mayer, 1999; Mousavi, Low, & Sweller, 1995; Tindall-Ford et al., 1997).

6. *The Redundancy Effect*

Both split-attention and modality effects occur under very specific conditions. They are only obtainable when multiple sources of information refer to each other and are unintelligible in isolation. For example, a diagram and text will not yield either split-attention or modality effects if the diagram is fully intelligible and fully provides the information needed, with the text merely recapitulating the information contained in the diagram in a different form. Under such circumstances, the text is redundant. The redundancy effect occurs when additional information, rather than having a positive or neutral effect, interferes with learning. For example, instead of integrating a diagram with redundant text or presenting the text in auditory form, learning is enhanced by eliminating the text.

There are many different forms of redundancy. The previous diagram/text redundancy occurs when a self-explanatory diagram has additional text redescribing the diagram (Chandler & Sweller, 1991). Mental activity/physical activity redundancy occurs when, for example, learning how to use a computer application by reading a text has the added physical activity of using the computer (Cerpa et al., 1996; Chandler & Sweller, 1996; Sweller & Chandler, 1994). Either reading the text in a manual or, surprisingly, physically using a computer can be redundant and interfere with learning. Summary/detailed exposition redundancy occurs when a summary alone results in enhanced learning compared to a full exposition (Mayer, Bove, Bryman, Mars, & Tapangco, 1996; Reder & Anderson, 1980, 1982). Finally, auditory/visual redundancy occurs when the same material, presented simultaneously in written and spoken form, results in a learning decrement compared to the material presented in written or auditory form alone (Craig, Gholson, & Driscoll, 2002; Kalyuga, Chandler, & Sweller, 1999, 2000; Mayer, Heiser, & Lonn, 2001).

The redundancy effect is one of the more surprising cognitive load effects, with many people finding it quite counterintuitive. Most of us feel that even if additional explanatory material is not beneficial, at the very least it should be neutral. In fact, the addition of redundant information can have strong, negative consequences. The effect can be understood in cognitive load theory terms. If one form of instruction is intelligible and adequate, providing the same information in a different form will impose an extraneous cognitive load. Working memory resources will need to be used to process the additional material and possibly relate it to the initial information. It is likely to be only after the learner has processed the additional information that he or she will be aware that the activity was unnecessary. At that point, the damage may have been done.

7. The Element Interactivity Effect

Split-attention, modality, and redundancy effects all occur as a consequence of instructional procedures designed to reduce working memory load. It might be expected that the instructional procedures would only be effective where the material being learned imposed an intrinsically high cognitive load. If material does not impose a high cognitive load, the additional load due to inadequate instructional procedures may not matter a great deal because working memory capacity may not be exceeded. An extraneous cognitive load due to inadequate instructional procedures may be irrelevant if the intrinsic cognitive load imposed by the structure of the information is low. Because low element interactivity material has a low intrinsic cognitive load, we can predict that cognitive load effects may disappear when learning such material. The effects may only be obtainable using high element interactivity material. Chandler and Sweller (1996) and Sweller and Chandler (1994) demonstrated that split-attention and redundancy effects could be demonstrated readily using high element interactivity material but disappeared when low element interactivity material was used. Tindall-Ford et al. (1997) similarly found that the modality effect could only be obtained using high element interactivity material. Marcus et al. (1996) found that diagrams for which we have schemas facilitated understanding when compared to text but only under conditions of high element interactivity.

The finding that cognitive load effects can only be obtained using high element interactivity material demonstrates the element interactivity effect. It consists of an interaction between the split-attention, redundancy, and modality effects and the complexity (as measured by element interactivity) of the material being learned. While it has not been tested using other cognitive load effects, there is every reason to suppose that it could be obtained with all other effects based on a limited working memory.

It has been suggested in this chapter that the particular interaction between a limited working memory and a very large long-term memory had to evolve in order to handle high element interactivity material. High element interactivity material must be imbedded in schemas before it can be handled by a limited working memory. The element interactivity effect indicates that when instruction deals with high element interactivity material, then the characteristics of human cognitive architecture, such as a limited working memory, become critical.

8. The Isolated Interacting Elements Effect

Consider a learner faced with new material. That learner is on the left side of the cognitive matrix of continua. Consider further that element interactivity of the information that must be assimilated is sufficiently high to

substantially exceed working memory capacity. Understanding cannot occur because understanding requires all interacting elements to be processed simultaneously in working memory. All the interacting elements cannot be processed simultaneously in working memory until schemas have been formed, but schemas will not be formed until the learner has moved toward the right of the matrix of continua. Because the learner cannot possibly understand the material until those schemas have been formed, understanding and learning may appear impossible at first sight. When the material is presented with all of its interacting elements, as it needs to be if understanding is to occur, it cannot be processed in working memory because it vastly exceeds working memory capacity. How does learning occur under such circumstances?

One possibility (perhaps the only possibility) is that initially the elements must be learned as though they are isolated, noninteracting elements. Once sufficiently sophisticated schemas have been constructed, understanding will occur because the interacting elements can now be processed in working memory. On this analysis, learning must precede understanding.

If this analysis is valid, it is reasonable to hypothesize that learning might be facilitated by initially presenting very complex information to students in isolated elements form without emphasizing or even indicating the interactions between elements. Understanding of such instruction will be limited, but once it has been learned, presentation of the full information may permit understanding to occur. In contrast, presentation of the complete information that potentially could be understood during initial instruction may result in very little learning or understanding. Pollock et al. (2002) obtained precisely this effect. Learners presented isolated elements to learn followed by the full set of interacting elements learned more than learners presented the full set of interacting elements twice, demonstrating the isolated interacting elements effect.

9. The Imagination Effect

Assume a novice on the left of the cognitive matrix of continua has acquired some schemas and is beginning to move toward the right of the continua. To attain relatively high levels of expertise, further learning will need to include automation of the previously acquired schemas that normally includes continuing to study the material until desired levels of performance have been attained. An alternative is to attempt to imagine the procedures that have been learned. Imagining requires the learner to mentally “run through” the procedures in working memory. For high element interactivity material, processing information in working memory is impossible until schemas have been acquired. Once they have been

acquired and the learner has moved toward the right of the matrix of continua, imagination techniques should be feasible and practice through imagination should assist in automation. Continuing to study the material should be unnecessary because studying high element interactivity material is designed to provide the guidance necessary to reduce search while acquiring schemas, as occurs on the left side of the matrix of continua. If schemas have already been acquired, there is no longer any need to provide instructional guidance to reduce search because, on the right of the matrix of continua, the central executive function of schemas is now able to operate. Using those schemas to imagine the procedures learned should facilitate further learning through automation in a manner that studying the instructions may not.

Cooper, Tindall-Ford, Chandler, and Sweller (2001) tested this hypothesis and found that learners given instructions to “imagine” a set of procedures that needed to be learned performed better than learners given conventional “study” instructions. This imagination effect was only obtained using learners with sufficient knowledge to be able to process all of the required information in working memory. For complete novices who were unable to process the high element interactivity material in working memory, a reverse imagination or “study” effect was obtained with “study” instructions proving superior to “imagination” instructions. In other words, the effect obtained depended on the levels of expertise of the learners. Higher levels of expertise could reverse the effect obtained. The ideal form of instruction depended on the expertise of the learners. This reversal effect with expertise, as it happens, is general. As described in the next section, most, perhaps all, of the cognitive load effects described earlier depend on the use of novices.

10. The Expertise Reversal Effect

With the exception of the imagination effect, all of the previously described effects were intended to provide new instructional procedures for novices who were on the far left of the cognitive matrix of continua. Learners, of course, continue to learn and may require instructional procedures after they have moved beyond the left of the matrix of continua. It turns out that frequently, once learners have acquired some knowledge, many of the effects described previously reverse. With increased experience, conventional instructional procedures, such as practice at solving problems, are better than cognitive load procedures, such as studying worked examples. The imagination effect differs from the other effects discussed in that the imagination technique is intended for more knowledgeable learners rather than complete novices and so reverses when the imagination technique is

presented to novices rather than the more experienced learners. In all other cases, the effects shown using novices are reversed when using more experienced learners. The reversal is due to the redundancy effect and is called the expertise reversal effect. It is due to an interaction between simpler cognitive load effects and levels of expertise and can be contrasted with the element interactivity effect, discussed earlier, which consists of an interaction between simpler cognitive load effects and task complexity.

Using diagrams and text, Kalyuga, Chandler, and Sweller (1998) obtained the normal split-attention effect with integrated diagrams and text proving superior to a split-attention format. A group presented the diagrams alone performed poorly because the text was essential in helping understand the diagram, a necessary condition for the split-attention effect. The learners used were novices on the left side of the cognitive matrix of continua. Over several months training in the relevant, engineering area, they moved toward the right of the matrix of continua. The necessary guidance provided by the text became less and less essential as schemas were acquired to take over from the text. The superiority of the integrated format decreased with increased expertise. A point was reached where there was no difference between groups. Eventually, with additional training, the text became redundant. Learners could understand and learn from a diagram alone. Having to process unnecessary text increased the cognitive load. The presence of redundant text, especially in integrated form where it is difficult to ignore, interfered with rather than facilitated learning. A redundancy effect was obtained with the diagram-alone condition providing the best learning environment.

Yeung, Jin, and Sweller (1998) obtained a similar effect using textual materials. Learners with low levels of language competence were assisted by explanatory notes integrated into the primary text. Integrated notes retarded learning for learners with higher levels of language competence because the notes were redundant but were difficult to ignore when integrated into the primary text.

Other cognitive load effects also disappear and then reverse with increased expertise. A modality effect obtained with novices disappeared and then reversed (Kalyuga, Chandler, & Sweller, 2000) as expertise increased. Novices required textual material to assist them understand visually presented material; that textual material was best presented in spoken rather than written form, demonstrating the modality effect. As expertise increased, that modality effect disappeared and eventually, presenting the visual material alone was superior to an audiovisual presentation or, indeed, any presentation that included the text. Guidance provided by textual material, essential to students on the left of the cognitive matrix of continua, was provided by the schemas now available after students had moved to the right side of the matrix.

Similarly, Kalyuga, Chandler, Tuovinen, and Sweller (2001) found that the worked example effect reversed with increased expertise. Novices require worked examples to provide them with guidance. Schemas, once they have been acquired, provide guidance, and worked examples become redundant. Kalyuga, Chandler, and Sweller (2001) and Tuovinen and Sweller (1999), using novices, found that direct instruction is superior to discovery learning. That difference disappeared if learners with more experience in the domain were used.

These results can be used to explain other findings. McNamara, Kintsch, Songer, and Kintsch (1996) found that when learners were presented a textual passage to read and assimilate, those who were relatively expert in the area learned more from reduced passages that had segments omitted than the full passage. Learners with less experience in the area learned most using the full passage. On the present interpretation, novices required the full passage to allow understanding and so the full passage condition was superior. With increased experience, the added material was redundant and merely served to obscure critical points. Working memory resources were required to extract those critical points from the surrounding, redundant material, reducing learning and resulting in the superiority of the reduced passage.

11. The Guidance Fading Effect

From an instructional perspective, the expertise reversal effect suggests that as learners move from the left of the cognitive matrix of continua to the right, schemas increasingly provide guidance and so the guidance provided by instruction should be faded out. Unnecessary guidance has negative, not simply neutral effects. Renkl and associates (Renkl, 1997; Renkl, Atkinson, & Maier, 2000) obtained precisely this result using combinations of worked examples, completion problems, and full problems. Using novices, they found that guidance provided by worked examples was the best form of instruction. With increasing expertise, it was desirable for those worked examples to be replaced with completion problems and, ultimately, with full unguided problems.

It was indicated earlier that for novices, instruction should replace the missing central executive but that with increased levels of expertise, schemas play the role of a central executive. A guidance fading technique accords closely with this suggestion. Initially, with no central executive available, worked examples indicate relations between elements of information. As rudimentary schemas begin to form, they can take over some of the central executive function from worked examples and so complete worked examples are no longer necessary. Completion problems can be used as a substitute

for worked examples. Once full schemas have been constructed, they can act as a central executive and so full problem solving with no other guidance can be instituted. Additional learning through schema automation should occur during problem-solving practice.

Renkl, Atkinson, Maier, and Staley (2002) found guidance fading as levels of expertise increase to be demonstrably superior to using a single instructional procedure. They compared the presentation of conventional worked examples with guidance fading. The worked example procedure incorporated the presentation of several pairs consisting of a worked example followed by a very similar problem to solve. This pairing of a worked example followed by a problem was used throughout the learning period, irrespective of changing levels of expertise. Results indicated that the guidance fading procedure was superior. The superiority of fading over a single design procedure (e.g., worked examples alone or problems alone) as expertise increases constitutes the guidance fading effect.

The guidance fading effect, along with the expertise reversal effect, indicates that individual differences, specifically differences in levels of expertise, are a critical consideration when choosing an instructional design. A design that is ideal for a person located toward the left of the cognitive matrix of continua may be quite inappropriate for someone further to the right of the matrix. Ignoring levels of expertise can result in the use of quite inappropriate instructional procedures.

The instructional designs described in this section differ from most instructional designs in that they are very closely tied to our knowledge of information structures and human cognitive architecture. Indeed, they were generated directly from that knowledge. It can be argued that they provide a degree of validity to the cognitive theories discussed. In any scientific area, it is difficult or impossible to generate applications from substantially faulty theories.

IV. Conclusions

Human cognitive architecture has evolved to permit humans to engage in activities that range from prosaic to awe inspiring. There are logical structures that determine the way in which cognitive architecture deals with information. Those logical structures, along with the structure of information itself, must have determined the course of the evolution of human cognitive architecture. The basic information structures that underlie human cognitive architecture consist of a very large information store with limitations to ensure that any changes to that store do not destroy its functionality. The end result is an architecture designed to store immeasurable

amounts of information in a long-term memory but a very limited ability to deal with novel information in working memory. Information held in long-term memory guides most of our activities. Novel information in working memory can feed information into long-term memory and so alter long-term memory, but the logic of the governing information systems ensures that the alterations are relatively small to circumvent the unavoidable random components.

As might be expected, this system logic is universal. It not only applies to the manner in which human cognitive architecture has evolved, it applies to the manner in which information is handled by the processes of evolution themselves. Evolution by natural selection can be characterized as an effective and efficient system for managing and adapting very complex, natural information to changing circumstances. Human cognitive architecture must also manage complex information. Accordingly, it would not be surprising if human cognitive architecture evolved to handle information in the same way as evolution by natural selection. Similarities in the way that the two systems function suggest that human cognitive architecture, by the processes of evolution by natural selection, has itself evolved to duplicate the manner in which evolution by natural selection deals with information.

The logic of these systems places both restrictions on and generates opportunities for the manner in which information is presented and the activities in which learners should engage. Our cognitive architecture is structured with schemas providing an executive function guiding our mental activities. Instruction is required when those schemas are unavailable and must be acquired. Ideally, that instruction should provide an executive function that mimics the missing schemas as closely as possible in order to avoid random activities and reduce working memory load. Many instructional procedures that meet these requirements have now been devised. The successful generation of instructional procedures from theoretical principles provides a degree of validity for those principles.

While the logic of the information systems discussed in this chapter places immense barriers to their alteration, their adaptability to new circumstances, even if slow and frequently ineffective, is their crowning glory. Evolution may occur over eons but its whole point is change and adaptability, resulting in the creation of new functions, processes, and entities. Similarly, learning is the adaptive engine of human cognitive architecture. It may take many years, especially if creativity is required because instruction from and imitation of other humans is unavailable, but it is the foundation function of human cognitive architecture. Only through learning does the ability to efficiently process high element interactivity material become possible, and processing high element interactivity material is characteristic of humans. Prior to learning, such material can be dealt with but only in an unguided,

partially random manner with all complex interactions ignored. Furthermore, there is an inevitability about this limitation. There can be no mechanism to coordinate the very large number of possible combinations that can occur when dealing with even a relatively small number of elements that have not been learned. Because knowledge acquired through learning provides the only coordinating function, it is essential that our cognitive architecture evolved to ensure that only a limited amount of uncoordinated information is considered at any given time prior to learning. This limitation creates an immediate tension when dealing with high element interactivity information that cannot be limited or reduced in size without compromising understanding. Because high element interactivity material must be coordinated, a mechanism for coordinating such information had to evolve if it was to be processed. Schematic knowledge acquired through learning is that mechanism. There are very wide or perhaps no limits to the amount of previously learned information that humans can process.

On this analysis, long-term memory is the source of human intellectual skill because long-term memory holds learned material. It may be this structure that took millions of years to evolve, and at least on earth, is unique to humans in terms of size. Our huge knowledge base is shared neither by other living creatures nor, to this point, by artificial devices created by humans. It may only be shared by the mechanisms that permit life itself to reproduce and evolve. Other cognitive structures, including ones not considered in this chapter, such as sensory systems, are both ubiquitous and frequently superior to their human equivalent. In contrast, our immense long-term memory, with its close connections to learning, has no cognitive equivalent on earth. That structure is quintessentially human.

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COGNITIVE PLASTICITY AND AGING

Arthur F. Kramer and Sherry L. Willis

I. Overview

Aging is associated with a decline in a multitude of cognitive processes and brain functions. However, a growing body of literature, which is reviewed in this chapter, suggests that age-related decline in cognition can sometimes be reduced through experience, cognitive training, and other interventions, such as fitness training. Research on training and expertise has suggested that age-related cognitive sparing is often quite narrow, only being observed on tasks and skills similar to those on which individuals have been trained. Furthermore, training and expertise benefits are often only realized after extensive deliberate practice with specific training strategies. Like cognitive training, fitness training effects on the cognitive processes of older adults are relatively narrow rather than broad, with the most substantial effects being observed for executive control processes.

II. Cognition across the Adult Life Span

One of the most ubiquitous findings in research on cognition and aging is the observation of increasing decline in a wide variety of cognitive abilities across the life span. Declines in cognitive function over the adult life span have been found in both cross-sectional and longitudinal studies across a variety of tasks, abilities, and processes, including measures of perception,

memory, abstract reasoning, and spatial orientation with the earliest and most pervasive decline occurring in speed of processing. Cross-sectional studies, which compare the performance of one age group to that of another age group (e.g., 20-to 30-year olds and 60-to 70-year olds) have, for the most part, found linear age differences in measures of a number of aspects of cognition over the adult life span (Park et al., 2001; Park, Lautenschlager, Hedden, Davidson, Smith, & Smith, 2003).

Longitudinal studies, which range in length from a few years to over 40 years, have tended to find that abilities vary in the rate and onset of decline with accelerated decline in the late seventies and eighties (Schaie, 2000; Hultsch, Hertzog, Dixon, & Small, 1998; Zelinski & Burnight, 1997; Schaie & Hofer, 2001). The ability exhibiting the most linear pattern of decline across the entire adult life span is perceptual speed with decline beginning in young adulthood and continuing into old age. Almost two standard deviations of negative change in perceptual speed has been observed across the adult life span (Schaie, 2000). While the layperson views memory as one of the first abilities to show decline, trajectories of change vary across the types of memory. Hultsch and colleagues (1998) found significant decline in word recall, a form of episodic memory, but little decline in text recall, another form of episodic memory. Hultsch hypothesized that maintenance of text recall ability may be due to its strong association with verbal ability. The stability of verbal skills may contribute to the maintenance of text recall. Zelinski and Burnight (1997) observed decline in text recall when studied over much longer intervals. Implicit memory showed no decline as has been documented in prior research. Finally, fact recall, which is said to represent semantic memory, did show an age-related decline, whereas prior cross-sectional research had shown no age differences.

Given the discussion of executive function in later parts of the chapter, findings of age-related change in cognitive flexibility, which is closely related to selective aspects of executive control, are of interest (Schaie, 2000). Psychomotor speed flexibility exhibits a trajectory of modest increment until the early sixties and then declines approximately one standard deviation by the late eighties. In contrast, motor cognitive flexibility is relatively stable across the adult life course.

One of the most striking findings from longitudinal studies is the vast individual differences in the timing and pattern of decline (Schaie, 2000). For example, Hultsch and colleagues (1998) reported strong evidence of wide individual differences in the rate of cognitive change. Individuals were becoming less alike as they aged as a function of individual differences in change. Thus, mean or average change may present a different picture of aging than that observed when individual patterns of change are examined.

Although a number of factors may be responsible for the different performance trajectories obtained in cross-sectional and longitudinal studies (e.g., differential attrition, cohort effects in cross-sectional studies, practice effects, and study length in longitudinal studies), the important common observation is a reduction in cognitive efficiency with age beginning in young adulthood for processing speed and in late middle age and old age for more complex abilities.

Interestingly, although age-related cognitive decline is quite broad, there are some notable exceptions. It has generally been observed that knowledge-based or crystallized abilities (i.e., the extent to which a person has absorbed the content of culture), such as verbal knowledge and comprehension, continue to be maintained or improve over the life span. This is in contrast to process-based or fluid abilities (i.e., reasoning, speed, and other basic abilities not dependent on experience), which display earlier age-related declines.

A. COMMON CAUSE EXPLANATIONS

An important current issue concerns the source(s) of age-related declines in process-based abilities. A large number of mostly cross-sectional studies and some longitudinal studies (Baltes & Lindenberger, 1997) have found that age-related influences on different perceptual, cognitive, and motor skills are highly related, prompting the suggestion that a common factor may be responsible for age-related declines (Salthouse, 1996). Two approaches to a common cause explanation of age-related change in cognition have been discussed in the literature. Salthouse (1996) and others have espoused a resource-based processing model suggesting that reduced processing resources explain age-related decline in cognition. Several variations of the processing model have been proposed focusing on speed of processing, working memory, inhibition, or sensory function as the key resource variable (Park, 2000). Salthouse (1996) hypothesized two important mechanisms responsible for the salience of speed as a processing resource. First, the time to perform later operations is hypothesized to be restricted greatly when a large proportion of the available time is occupied by the execution of earlier operations. Second, products of earlier processing may be lost by the time that later processing is completed. Hence, the role of speed increases in importance the more complex the task.

Working memory has been conceptualized as the amount of on-line cognitive resources available at any given moment to process information and can involve storage, retrieval, and transformation of information (Craig & Byrd, 1982). Of interest in the study of working memory as a processing resource is the finding that demands on working memory can sometimes be

reduced significantly by providing environmental support in memory tasks to the elderly (Park, 2000).

A third processing resource is inhibition defined as an increase in difficulty in focusing on target information and inhibiting attention to irrelevant material (Hasher & Zacks, 1988). Inhibition effects are most pronounced when the individual has to inhibit a prepotent response and it is in these situations where older adults are most likely to show evidence for poor inhibition.

Finally, support for sensory deficits as processing resources comes from the Berlin Aging Study (Linderberger & Baltes, 1994, 1997). Most of the age-related variance in a wide variety of cognitive tests was mediated by sensory functioning as measured by simple tests of visual and auditory acuity. Sensory measures were considered to be a more fundamental index of cognitive resource than even speed of processing. Sensory measures mediated most of the variance in speed of processing, but the reverse was not true. The Berlin group has argued that sensory function is a crude measure of brain integrity.

Alternatively, Baltes and colleagues (1994) have argued that age changes in general central nervous system integrity represent a "common cause of declines in information processing capacity." Rabbitt (1993) aptly phrased the question "Does it all go together when it goes?" According to this hypothesis, processing speed and working memory share this common influence, but do not cause it.

B. BEYOND A COMMON CAUSE

Contrary to the general decline proposals, a growing body of literature has pointed out a number of situations in which age-related effects remain after having been controlled statistically or methodologically for a general age-related factor (Hultsch et al., 1998; Verhaeghen, Kliegl, & Mayr, 1997). Such data suggest that a variety of different mechanisms may be responsible for age-related declines in information processing and that these mechanisms may be differentially sensitive to age. In examining longitudinal change in various memory functions, Hultsch and colleagues (1998) tested the resource and the global cognitive change models to account for age-related change in various forms of memory. Neither the resource nor the global cognitive change model consistently accounted for change in all aspects of memory. The global change model accounted for a significant amount of variance in change in the memory dimensions of fact recall, working memory, and comprehension speed. However, the global change model did not account for a variance in change associated with verbal fluency, reading comprehension, or semantic speed. Hultsch reported

considerable support for working memory as a processing resource that accounted for change in memory. However, neither working memory nor speed as two of the most popular resources could account for all of the variance in changes in word recall. Indeed, a subset of the competing models of general decline may, in future research, be found to account for specific age-related cognitive deficits.

In a similar vein, Kramer, Humphrey, Larish, Logan, and Strayer (1994) examined the general inhibitory account of aging (Hasher & Zacks, 1988) and found, contrary to the predictions of the model, that age-related changes in a variety of different inhibitory processes were specific rather than general in nature. Verhaeghen et al. (1997) found age equivalence in sequential numeric operations while observing age substantial and disproportionate age differences in coordinative operations (i.e., holding some products in mind while carrying out additional computations). Such data are inconsistent with a general slowing account of aging.

III. Changes in Brain Function and Structure across the Adult Life Span

Findings obtained in the study of cognitive aging are mirrored, in a number of ways, by research on brain aging (for an in-depth review of this literature, see Albert & Killiany, 2001; Raz, 2000; Vinters, 2001). For example, a body of research has documented nonspecific or global changes in brain volume across the adult life span. In most cases, these studies, which have employed computerized tomography (CT) or magnetic resonance imaging (MRI) scanning techniques, have been cross-sectional in nature and have found decreases in gray and white matter and increases in the size of ventricles across the adult life span (Coffey, Wilkinson, Parashos, Soady, Sullivan, Paterson, Figiel, Webb, Spritzer, & Djang, 1992; Pfefferbaum, Mathalon, Sullivan, Rawles, Zipursky, & Kim, 1994; Murphy, DeCarli, MvIntosh, Daly, Mentis, Pietrini, Szczepanik, Schapiro, Grady, Horwitz, & Rapoport 1996). Similar findings have been obtained in relatively short-term longitudinal studies of morphological changes in brain structure (Davatzikos & Resnick, 2002; Resnick, Goldszal, Davatzikos, Golski, Kraut, Metter, Bryan, & Zonderman, 2000; Shear, Sullivan, Mathalon, Lim, Davis, Yesavage, Tinklenberg, & Pfefferbaum, 1995).

Gray matter changes were originally thought to be the result of neuron loss. However, more recent studies, which have employed unbiased stereological techniques to enumerate neurons, suggest instead that large neurons appear to shrink in normal aging. Few neurons appear to be lost in cortical regions (Morrison & Hof, 1997; Terry, DeTeresa, & Hansen, 1987).

White matter changes appear largely to be the result in changes in the myelination of axons.

There have been a number of reports of significant statistical relationships between global age-related differences in cortical morphology and measures of cognitive function. For example, Albert, Duffy, and Naeser (1987) reported that increases in global brain atrophy resulted in decreases in performance on a battery of neuropsychological tests. More recently, MacLullich, Ferguson, Deary, Seckl, Starr, and Wardlaw (2002) reported a significant relationship between MRI-based measures of brain volume and a general cognitive factor composed of memory, attention, and decision-making tests.

A. AGE-RELATED CHANGES IN BRAIN STRUCTURE AND FUNCTION ARE NOT UNIFORM

Similar to the cognitive literature, studies have also found regional differences in the time course and magnitude of age-related differences and changes in brain structure and function. Correlations between age and cortical volume have been reported to be largest for prefrontal regions, somewhat smaller for temporal and parietal areas, and small and often nonsignificant for sensory and motor cortices (Head, Raz, Gunning-Dixon, Williamson, & Acker, 2002; Raz, 2000). In general, the disproportionate changes in brain structure across the adult life span parallel findings of age-specific changes in executive control and a subset of memory processes, which are supported in large part by prefrontal and temporal regions of the brain (Robbins, James, Owen, Shaakian, Lawrence, McInnes, & Rabbitt, 1998; Schretlen, Pearlson, Anthony, Aylward, Augustine, Davis, & Barta, 2000).

Indeed, a number of theories of cognitive and brain aging are based on the specificity of age-related changes. For example, West (1996) proposed a detailed model of the relationship between the age-related decline in the structure and function of the prefrontal regions of the brain and different aspects of executive control (e.g., interference control and inhibition, working memory, multitasking, prospective memory). More recently, Braver, Barch, Keys, Carter, Cohen, Kaye, Jahowsky, Taylor, Yesavage, Mumenthaler, Jagust, and Reed (2001) suggested that a variety of aspects of executive control decline as a result of age-related deficits in the function of the dopamine system in the prefrontal cortex. Thus, these models and others have attempted to integrate research on changes in the structure and function of the aging brain with the observation of disproportionate declines in a subset of cognitive processes, namely those that subserve aspects of executive control and memory.

B. NEUROIMAGING STUDIES OF FUNCTIONAL BRAIN AGING

Human neuroimaging studies, employing positron emission tomography (PET) and functional magnetic resonance imaging (fMRI), have provided a number of insights into age-related differences and changes in brain function (for in-depth reviews of this literature, see Cabeza, 2000; Park, 2003). Both of these techniques involve inferring changes in neuronal activity from changes in blood flow or metabolic activity in the brain (Reiman, Lane, Van Petten, & Bandettini, 2000). In PET, cerebral blood flow and metabolic activity are measured on the basis of clearance of radionuclides from cortical tissues. These radionuclides, which are either inhaled or injected, decay by the emission of positrons that combine with electrons to produce gamma rays, which are detected by a series of sensors placed around the head. Each PET image, which is acquired over an interval of anywhere from 1 to 45 minutes depending on the nature of the radionuclide employed in a study, represents all of the brain activity during the integration period. These PET images are then coregistered with structural scans, often obtained from MRIs, to indicate the location of the functional activity. fMRI is similar to PET in that it provides a map of functional activity of the brain. However, fMRI activity can be obtained more quickly (within a few seconds), does not depend on the inhalation or injection of radioactive isotopes, and can be collected in the same system as the structural information. The blood oxygen level-dependent technique (BOLD) of fMRI uses the perturbation of local magnetic fields due to changes in the oxygen content of blood during increased blood flow to image functional brain activity (Belliveau, Kennedy, McKinstry, Buchbinder, Weisskoff, Cohen, Vevea, Brady, & Rosen, 1991; Ogawa & Lee, 1990).

Although a thorough review of the human aging and neuroimaging literature is beyond the scope of this chapter, a few important observations have been made in this rapidly growing literature. First, it has often been reported that older adults show lower levels of activation, in a wide variety of tasks and brain regions, than younger adults (Logan, Sanders, Snyder, Morris, & Buckner, 2002; Madden, Turkington, Coleman, Provenzale, DeGrado, & Hoffman, 1996). Two different interpretations have been offered for such data. One is that aging is associated with an irreversible loss of neural resources. Another possibility is that resources are available but are recruited inadequately. Although the reason(s) for underrecruitment remains to be determined, some evidence points toward the second possibility. Logan et al. (2002) found that underrecruitment of prefrontal regions could be reduced when old adults were instructed to use semantic association strategies during word encoding.

Another common finding is that older adults show nonselective recruitment of brain regions. That is, relative to younger adults performing the same task, older adults often show the recruitment of different brain areas in addition to those activated in younger adults. Indeed, one variety of nonselective recruitment, the bilateral activation of homologous brain regions, has been codified into a model of neurocognitive aging by Cabeza (2002). The model, referred to as hemispheric asymmetry reduction in older adults (HAROLD), suggests that, under similar circumstances, cortical activity tends to be less lateralized in older than younger adults. An important question with regard to this asymmetry is whether the additional activity observed for older adults is compensatory or a marker of cortical decline (i.e., a failure to recruit specialized neural processors). At present, this is an open question with a few memory studies reporting that older adults who perform better on a task show bilateral recruitment of homologous areas, whereas older adults who perform more poorly show unilateral activation (Cabeza, Anderson, Locantore, & McIntosh, 2003; Reuter-Lorenz, Jonides, Smith, Hartley, Miller, Marshuetz, & Koeppel, 2000). However, other studies have either failed to find a relationship between laterality and performance (Logan et al., 2002) or have reported unilateral prefrontal activation for better performing old adults and bilateral activation for poorer performing older adults (Colcombe, Kramer, Erickson, Belopolsky, Webb, Cohen, McAuley, & Wszalek, 2002). Thus far, such studies have compared the quality of performance between subjects. Clearly, it is important to examine the relationship between patterns of cortical recruitment and performance quality within subjects in the future. Ideally, examination of this relationship should take place in studies with graded cognitive challenges, as well as in intervention studies whose goal is to enhance cognition and brain function of older adults. Evaluation of the generality of asymmetry reduction across different perceptual, cognitive, and motor processes is also an important goal for the future.

Another variant of nonselectivity that has been observed is the activation of different but nonhomologous brain regions in young and old adults. For example, in a study of focused and divided attention, Madden et al. (1997) observed that older adults showed weaker activity than young adults in occipital cortex while also showing stronger activation than young adults in the prefrontal cortex. These data were interpreted as evidence for strategic differences in the processing of task-relevant stimuli.

One additional issue is important to note regarding age-related changes in brain structure and function. That is, that a substantial amount of variability has been observed in age-related changes in the brain, with some older adults showing minimal structural and functional changes and others showing dramatic changes (but less dramatic than that observed with

Alzheimer's dementia). One potential implication of such data is that slowing deleterious changes in brain with aging may be achievable through training or other interventions.

Indeed, while human research has not yet addressed the question of whether changes in brain structure and function of older adults can be slowed or reversed through training or other interventions, such data are available in the animal literature. For example, while early research that examined the influence of enriched versus improvised environments with rats and mice was confined to young animals, given the belief that brain plasticity existed only for young organisms, later research discovered that morphological changes could also be obtained with older animals (Black, Isaacs, Anderson, Alcantara, & Greenough, 1990; Kempermann, Kuhn, & Gage, 1997; Riege, 1971; Rosenzweig & Bennett, 1996). The changes, engendered by enriched environments, include increased dendritic branching, capillary development, and the development of new neurons presumably from adult stem cells, as well as a cascade of molecular and neurochemical changes. Indeed, many of these changes have also been observed when older animals are involved in fitness training (Black et al., 1990; Cottman & Berchtold, 2002; van Praag, Kempermann, & Gage, 1999). Such data, when viewed in terms of human neuroimaging data, which argue for a close coupling between cognition and brain function and structure, suggest that it is indeed conceivable that age-related cognition decline might be modifiable through experience and training. We now turn to an examination of this issue.

IV. Does Experience Reduce Age-Related Cognitive Decline?

Over the past several decades a number of researchers have examined whether previous experience, and indeed often high levels of expertise, in content areas such as driving, flying, music, medical technology, graphic art, architectural design, typing, and complex game playing (e.g., bridge, chess, go) serves to (a) reduce age-related decline on basic perceptual, cognitive, or motor abilities that underlie the complex skill and/or (b) aid in the development of domain general or specific strategies that can offset or compensate for the impact of aging on complex skills or their component processes. An early example of such research is provided by Murrell, Powesland, and Forsaith (1966), who studied the influence of skill on age-related differences in pillar drilling. The relationship between age and skill was examined in a sample of experienced and inexperienced individuals in a variety of component tasks and measures (e.g., accuracy and time required for drill aiming) related to pillar drilling. Performance differences were

observed, as a function of age, only for the inexperienced individuals. Thus, these data appear to suggest that skill or expertise can indeed slow or abolish age-related psychomotor deficits. There are, however, some important caveats with respect to this study. First, very small samples (seven or fewer subjects per group) were employed in the study. Second, the subjects were not characterized beyond their performance on the drilling tasks. Thus, both of these factors may point to an alternative interpretation of the results, which might be referred to as the selective attrition hypothesis. This hypothesis states that older adults who remain in a profession and attain (and retain) the status of "expert" might represent only a very small proportion of the aging population, thereby substantially limiting the generalizability of such results.

A. EXPERTISE AS A MEANS TO REDUCE AGE-RELATED DECLINE IN PERFORMANCE AND COGNITION

Charness (1981a,b) described and implemented a research strategy that could address, at least in part, concerns about the representativeness of the older adult sample in studies of age and expertise. This proposal, referred to as the molar-equivalence molecular decomposition strategy, involves (1) selecting individuals who differ widely on both age and skill but for whom the correlation between these two factors is near zero and then (2) examining the influence of age, skill, and their interaction on a series of component processes of the task/skill of interest. An additional step in this procedure, implemented by a number of researchers (e.g., Masunaga & Horn, 2001; Morrow, Leirer, Altieri, & Fitzsimmons, 1994; Morrow, Menard, Stine Morrow, Teller, & Bryant, 2001), entails (3) the additional examination of age and skill effects on basic perceptual, memory, and motor processes not considered to be relevant to the skill of interest. Within such a research framework, expertise might be said to moderate an age-related decline in performance to the extent that older highly skilled individuals showed a smaller performance decrement than older less skilled individuals on the skill-based component tasks. In other words, older and younger highly skilled individuals should perform more similarly than less skilled old and young individuals. The extent to which such effects were also found for the nonskill related tasks would provide an assessment of the degree of generality of the expertise effects on age-related differences in cognition.

To preview the discussion of the literature presented here, in general these studies have found that well-learned skills and their component processes, across a variety of different domains, can be maintained at relatively high levels of proficiency, well into the 70s. However, these same studies have found that general perceptual, cognitive, and motor processes are not

preserved in these highly skilled individuals. Thus, preservation of cognitive abilities for highly skilled individuals appears to be domain specific and often compensatory in nature. Furthermore, the maintenance of proficient domain-specific skills generally requires substantial deliberate practice (i.e., practice defined as activity designed to explicitly improve performance) (Ericcson, Krampe, & Tesch-Romer, 1993).

One domain in which the question of whether skill can reduce an age-related decline on complex skills and task-relevant component processes is typing. For example, Salthouse (1984) examined the performance of young and old adult (19 to 72 years of age) typists on both domain-specific (i.e., typing tasks) and less domain-specific tasks (i.e., tapping, choice reaction time). He found a significant age-related decline in the performance of general psychomotor tasks but no age-related deficit in measures of typing proficiency. Furthermore, older typists demonstrated an interesting compensatory strategy that likely minimized the general decline in processing speed on typing speed. That is, older typists displayed a greater ability than young typists to use preview of the text to decrease their interkeystroke times, thereby enhancing their typing span. Thus, older typists were able to employ their accrued knowledge of the task domain to implement a strategy that compensated for declines in processing speed.

In a series of more recent studies, Bosman (1993, 1994) replicated Salthouse's preview benefits for older typists. However, she also found evidence for other experience-based benefits for older typists. In a series of component tasks that entailed making rapid responses to multiple sequentially presented letters, Bosman found significant age \times expertise interactions for the time it took to type the second of two responses to a stimulus pair. That is, while large age-related response time differences were found for the initial response, age-related differences were reduced substantially for the second response. A significant age \times expertise effect was also found for a multiple finger-tapping task. Bosman interpreted these results as suggesting that expertise moderates execution but not stimulus-response translation processes. Thus, it would appear that compensatory strategies (i.e., preview effects), as well as selective sparing of task-relevant component processes (i.e., execution processes), can be obtained, at least with a well-practiced psychomotor task such as typing.

Complex game playing represents another domain in which the molar-equivalence molecular-decomposition strategy has been used to examine the influence of expertise and age on performance. Charness (1981a,b) conducted a series of studies in which he examined the influence of expertise in chess on the performance of a number of task-related components, including the recognition and recall of the spatial configuration of chess pieces and the selection of moves during simulated chess games. A number

of important task components were independent of age but related to the skill level of the player. These components included the quality of the moves selected and the rapid evaluation of end game positions. Performance on recall and recognition tasks was influenced negatively by age and positively by skill. These results could be interpreted to suggest that highly skilled individuals encoded the spatial positions of the chess pieces in an elaborated representation of previously played or studied games, but that such representations could not ameliorate the influence of age. Indeed, this explanation is consistent with the observation of increases in chunk size with chess skill along with decreases in chunk size with age. An important question regarding these studies is how could it be that there are small or no age-related deficits in the game of chess and a number of its components relating to the quality of the selected move and the speed of search given the obvious memory problems exhibited by the older players? One possibility is that older adults learn to be more selective in their representation and choice of moves. Such a compensatory strategy would serve to reduce memory load while also speeding search, as was observed in the studies (Charness, 1999).

A study reported by Masunaga and Horn (2001) concerned expertise and age effects in the game of Go. Go is a game that involves two players who attempt to surround each other's stones with their own on a 19×19 grid board. The game, which involves complex problem solving, memory, and learning, takes at least 10 years to achieve expert status. In the Masunaga and Horn study, 263 Go players of widely varying age and expertise performed a variety of Go-related and more general memory, problem solving, and processing speed tasks. Subjects showed the typical age-related decline on non-GO related tasks. However a number of age \times expertise interactions were observed on Go-related tasks involving recognition, recall, and reasoning. Thus, similar to the chess studies, the acquisition of a large and well-organized body of knowledge in Go appears to offset age-related decline in more general cognitive abilities.

The results that have been discussed so far, in the domains of typing and complex gaming, are both interesting and important in that they establish that expertise can reduce or eliminate processing declines observed during the course of normal aging both through the development of compensatory strategies as well as through the maintenance of task-related basic processes. However, an important question is whether such results can be generalized to complex skills and professions that entail the acquisition and coordination of a multitude of skills that often need to be performed under time pressure and other stressful conditions.

This question has been addressed by several different research groups in the context of piloting. For example, Tsang and Shaner (1998; see also Tsang & Voss, 1996) examined whether piloting expertise would reduce

commonly observed age-related decrements in multitask processing (for a review of aging and multitask performance literature, see Kramer & Larish, 1996). Such a proposal appears plausible given the inherent multitask nature of piloting an aircraft. Ninety participants between the ages of 20 and 79, half of whom were pilots, were asked to perform a variety of different single and dual tasks. Age \times expertise interactions were observed for a number of the dual-task conditions with smaller dual-task decrements [i.e., (dual-task performance–single-task performance)/single-task performance] being observed for older pilots than for older nonpilots. Age \times expertise interactions were not obtained for any of the single tasks. Thus, these data suggest a specificity of expertise effects on the skills most related to piloting rather than a general effect on the performance of psychomotor and cognitive tasks. It is important, however, to point out that not all dual-task combinations produced expertise \times age effects. The question of why this might be the case is discussed in the next section.

Morrow and colleagues (1992, 1994, 2001) examined whether piloting expertise reduces age-related differences in a series of laboratory tasks that were designed to be similar to routine air traffic control communications. Across a series of studies, older and younger pilots and nonpilots performed a number of tasks that entailed reading back route descriptions, answering questions about route commands, and recalling route commands. Age \times expertise interactions were found on tasks that were rated to be most similar to the kinds of communication tasks performed by pilots and air traffic controllers (e.g., reading back commands concerning heading) but not for less aviation-relevant communication tasks. Interestingly, age \times expertise effects were not observed for domain-relevant communication tasks that were quite complex. These results were interpreted to suggest that older pilots could compensate for declines in processing when they were able to capitalize on their knowledge of the structure of air traffic control messages, but only when working memory demands were low or moderate. Thus, while research that focused on piloting expertise as a means to reduce age-related processing deficits has clearly found expertise-related benefits, this research has also been useful in beginning to establish some boundary conditions on such effects (see also Clancy & Hoyer, 1994; Dollinger & Hoyer, 1996).

B. EXPERTISE DOES NOT ALWAYS REDUCE AGE-RELATED DECLINE IN PERFORMANCE AND COGNITION

Research in other domains of expertise such as music has produced more limited support for the hypothesis that expertise can reduce age-related declines in cognition. Krampe and Ericsson (1996) examined the influence

of expertise, with young and old amateur and expert pianists, on measures of general processing speed as well as performance on music-related tasks (i.e., single hand and bimanual finger coordination). An age-related decrement was found on general processing speed measures, regardless of the level of the individuals' music expertise. However, no such deficit was found on music-related tasks. In this case, age effects were abolished for expert but not for amateur pianists. Furthermore, high levels of deliberate practice over the past 10 years were found to be associated with decreases in age-related differences, for the expert group, in music-related performance.

The examination of expertise effects in other music-related tasks has provided less consistent and weaker support for experience-based moderation of age-related cognitive decline. Halpern, Bartlett, and Dowling (1995) examined age and expertise effects on a series of music transposition tasks that entailed deciding whether two tunes that started in a different key were otherwise identical or not. In these studies, musical expertise was broadly characterized to include either voice training or training on any instrument, with high levels of expertise being defined as at least 8 years of lessons (with no assessment of recent experience or deliberate practice). An age \times experience interaction was obtained in only one of four experiments. Interestingly, this was the experiment that obtained the strongest relationship between experience and performance as well as between age and performance.

Meinz (2000; see also Meinz & Salthouse, 1998) examined age and expertise effects on musical and nonmusical perceptual speed (i.e., same/different judgments on chords) and memory tasks (i.e., comparison of short melodies) with a large group of pianists who ranged in age from 19 to 88. Although significant age \times experience interactions were not obtained for either perceptual or memory tasks, age effects were larger when experience was controlled in multiple regression analyses. Such effects provide some support for the proposal that positive age-experience relations can offset the negative age-speed and memory relations. However, these results do not support the proposal that age differences will be eliminated or reduced substantially among experienced musicians.

C. SOME SPECULATIONS ON REASONS FOR DISCREPANCIES BETWEEN STUDIES THAT FIND AGE-RELATED EXPERTISE BENEFITS AND STUDIES THAT DO NOT FIND SUCH BENEFITS

An interesting issue concerns the source of the discrepancy in the strength of the age \times expertise effects in the Krampe and Ericsson (1996) as compared to the Meinz (2000) and Halpern et al. (1995) studies. One possibility concerns the nature of the component tasks. In Krampe and

Ericsson (1996) study musicians were assessed on a series of psychomotor tasks, whereas memory-based component tasks were employed in the Mainz (2000) and Halpern et al. (1995) studies. Thus, age-related deficits in memory processes might be more difficult to overcome with expertise-accrued knowledge than psychomotor deficits. However, this explanation seems unlikely when viewed in terms of the expertise \times age interactions that have been observed in gaming (i.e., chess and Go) as well as piloting. Of course, it is conceivable that the component memory tasks employed in the research with musicians were less domain relevant than those used in the other domains and were therefore less amenable to knowledge-based compensatory strategies (Morrow et al., 2001). Another possible explanation for the discrepancy in the strength of the age \times expertise effects in the Krampe and Ericsson (1996) study as compared to the Mainz (2000) and Halpern et al. (1995) studies concerns the strength of the age and performance and expertise and performance effects in the different studies. These relationships were weaker in the Mainz (2000) and Halpern et al. (1995) studies than in the Krampe and Ericsson (1996) study. Given that it is more difficult to discern age \times expertise interactions with weak age-performance or expertise-performance relations, it is perhaps not surprising that the influence of expertise on age-related cognitive processes was not observed in the Mainz (2000) and Halpern et al. (1995) studies. Additional studies that employ a variety of component tasks and ensure both strong age-performance and age-experience relations will be needed to examine these hypotheses further.

The studies discussed earlier establish that age-related deficits in cognition can indeed be reduced and, in some cases, even eliminated through various forms of experience and expertise. However, despite the impressive expertise effects discussed earlier, a number of cautions need to be noted. First, cognitive sparing appears to be domain specific rather than general. That is, expertise effects on the cognitive processes of older adults tend to be both more consistent and more substantial with component tasks that are similar to the complex skills on which expertise is expressed than for more general cognitive tasks. Second, in many cases the expertise \times age interactions appear to be compensatory in nature rather than influencing the component processes directly. For example, well-developed and elaborate conceptual models of relevant domain knowledge appear to enable the older expert to bypass perceptual, cognitive, and motor processes that decline with age (Clancy & Hoyer, 1994; Charness, 1981; Linderberger, Kliegl, & Baltes, 1992; Morrow et al., 1994). Third, expertise benefits in the form of age \times expertise interactions appear to depend on the maintenance of deliberate practice rather than just the performance of the complex skills and tasks (Ericsson et al., 1993; Krampe & Ericsson, 1996).

It is important to note that while an increasing number of studies have obtained data that suggest that age-related cognitive declines can be reduced or compensated for through experience and expertise, there have also been a substantial number of failures to observe such effects, some of which have been discussed earlier (see also Salthouse, 1991; Salthouse, Babcock, Skovronek, Mitchell, & Palmon, 1990; Salthouse & Mitchell, 1990). As briefly indicated earlier, there are a number of reasons for discrepancies between studies, including (a) the manner in which expertise is characterized, including the extent of recent deliberate practice on the molar skills, (b) the strength of the relationship between age and performance and expertise and performance on component tasks, (c) the domain relevance of the component tasks, and (d) the health, age, and lifestyle choices of the subject populations. Clearly, all of these factors need to be examined in greater and more systematic detail in future studies of expertise effects on age-related changes in cognitive processes.

D. MODELS OF AGING, EXPERTISE, AND COGNITION

Before leaving the topic of expertise as a means to reduce age-related cognitive decline, it may be useful to briefly describe some attempts to model these processes. Modelers have taken two different perspectives in examining the relationship among age, expertise, and cognition. The work of Paul Baltes and colleagues (Baltes et al., 1999; Wiese, Freund, & Baltes, 2000, 2002) represents an attempt to describe the trade-offs between maximization of gains and minimization of losses in skilled performance during the adult life span. Their approach is characterized by the selection, optimization, and compensation (SOC) model. The model describes a number of processes, which, in combination, serve to maintain performance during the course of aging. Selection entails reduction in the repertoire of skills that are involved in the molar skill set that comprises a profession, sport, artistic, or leisure pursuit. For example, an older tennis player might focus on doubles rather than singles play. Optimization involves an attempt to structure the environment so as to focus attention, to a greater extent than the individual had done before, on the skill set that has been retained. For the tennis player that would entail increasing deliberate practice on strategies and skills related to doubles play. Finally, compensation involves the use of cognitive processes and skills that have been maintained or enhanced over the adult life span, such as elaborated knowledge representations, to offset costs associated with processes, such as working memory and some aspects of sensory and motor processes, which have become less efficient. The tennis player might compensate by more effectively hitting the ball to her opponent's weak side. While the SOC

model has mostly been used to describe changes in cognition and skill across the adult life span, it has also been employed to prescribe environmental changes, in a number of domains to enhance older adults' performance (Wiese et al., 2002).

A second class of models is exemplified by the work of Mireles and Charness (2002; see also Hanon & Hoyer, 1994; Li, Linderberger, & Frensch, 2000). In the context of a recurrent neural network model, these researchers have examined the implications of various neuronal changes on the relationship among expertise, age, and performance. They accomplished this by training neural networks so as to develop either large or small knowledge bases of chess moves and then examining the ability of the networks, given different types and magnitudes of neural changes, to learn new moves. Several interesting results were obtained in their simulations. First, changes in the signal/noise ratio in the form of unit weight changes or the addition of random noise to the networks resulted in performance changes that favored the networks with more extensive knowledge bases. That is, the more expert networks showed less extensive performance decrements much like the age \times expertise effects discussed earlier (Charness, 1981; Masunaga & Horn, 2001; Morrow et al., 1994). However, changes in neural plasticity in the form of reduced learning rates and pathological damage in the form of lesioned units produced equivalent performance decrements for the large and small knowledge bases, similar to research that has failed to observe the expertise benefits on age-related decline (Morrow et al., 2001; Salthouse, 1990; Salthouse et al., 1990). The Mireles and Charness (2002) modeling effort and others like it are interesting in that they attempt to map expertise and age effects to underlying mechanisms, many of which have been identified in cognitive and neuroscience research. Interestingly, however, the Mireles and Charness (2002) modeling did not address age differences in the learning of new skills and tasks, a topic to which we now turn.

V. Can Laboratory-Based Training Be Used to Reduce Age-Related Decline in Cognition, and If So, What are the Nature of These Training Benefits?

The previous section discussed the influence of expertise in real-world tasks, professions, and endeavors on the maintenance of cognitive skills and processing. This section discusses the results of laboratory-based practice and training studies on the development or improvement in cognitive skills, as well as the retention of these skills. We also address, as was done in the previous section, the specificity of these skills. We begin with a discussion of cross-sectional comparisons in training and practice effects and conclude

this section with an examination of longitudinal studies in which specific individuals serve as their own controls for age-related practice and training benefits.

It is important to note that there are both advantages and disadvantages to the laboratory training approach as compared to the examination of expertise effects on age-related cognitive decline. A clear advantage of the laboratory-based training approach is the ability to precisely control and manipulate the nature of the training process. This might include the amount and frequency of training and practice, the type of the feedback provided to the trainee, and the environment and conditions (e.g., whether under time stress, in the presence of other tasks or demands) under which training and performance take place. None of these factors are controlled easily in professional or leisure activities in which expertise develops over the course of many years. Of course, laboratory-based studies also have the advantage of random allocation of individuals, who may differ on a multitude of factors, which may influence training benefits, to different control or training groups. Clearly, this is not possible in real-world studies of expertise effects. However, laboratory-based training is quite limited in terms of the extent to which high levels of expertise are achieved and the complexity of the tasks and skills that are examined. Such are important strengths of expertise-based research. Thus, both the expertise-based studies and the laboratory-based training approach are necessary to provide a detailed understanding of the impact of training and experience on the maintenance and enhancement of cognitive processes and skills over the course of the adult life span.

A. CROSS-SECTIONAL PRACTICE AND TRAINING STUDIES WITH YOUNG AND OLD ADULTS

In general, old and young adults have been found to learn new tasks and skills at approximately the same rate or to show the same magnitude of training gain (Hertzog, Williams, & Walsh, 1976; Peretti, Danion, Gierski, & Grange, 2002; Salthouse, 1990). This finding has been observed across a wide variety of tasks, including perceptual discrimination, visual search, recognition, recall, and spatial perception. Such data clearly suggest that older adults can learn new skills. However, given that older adults' baseline performance on most tasks is lower than that observed for younger adults, these data also suggest that age-related differences in the level of performance will be maintained at posttest.

Visual search is one domain in which age-related differences have been well documented and for which there have been a variety of practice studies that have examined the nature of improvements in underlying processes and

performance across the adult life span. In general, this literature suggests that age effects are small or nonexistent in feature and conjunction search when target–distractor similarity is low (Humphrey & Kramer, 1997; Plude & Doussard-Rossevelt, 1989; Scialfa, Esau, & Joffe, 1998; Scialfa & Joffe, 1997). However, age differences can be quite large when target–distractor similarity is increased in either a feature or a conjunction search (Humphrey & Kramer, 1997; Plude & Doussard-Rossevelt, 1989; Scialfa et al., 1998).

Scialfa and colleagues (Anandam & Scialfa, 1999; Ho & Scialfa, 2002; Scialfa, Jenkins, Hamaluk, & Skaloud, 2000) conducted a number of studies in which they examined improvements in the performance of young and old adults on a variety of consistently mapped feature and conjunction visual search tasks. In general, they found that young and older adults improved at similar rates. Interestingly, when the role of the targets and distractors was reversed, they also found large and age-equivalent disruptions of performance, particularly for targets that appeared close to fixation. This is an important observation, as disruption effects, when the role of consistently mapped targets and distractors is reversed, suggest that subjects have automatized their search processes (Shiffrin & Dumais, 1981).

Fisk, Rogers, and colleagues (Fisk, Rogers, & Giambra, 1990; Fisk, Rogers, Cooper, & Gilbert, 1997; Rogers & Fisk, 1991; Rogers, 1992; Rogers, Fisk, & Hertzog, 1994) also examined age differences in the development of automaticity in a variety of search (visual, memory, and semantic search) tasks. Given the results of the research discussed earlier, one might expect similar patterns of learning and disruption effects upon reversal of the role of targets and distractors, for young and old adults. However, instead it was observed that, in consistently mapped tasks, younger adults showed faster rates of learning and larger disruption effects with the reversal of targets and distractors than older adults. Such a pattern of results was interpreted as evidence of a failure for the older adults to automatize search performance.

An important question concerns the reason for the discrepancy in aging effects in the search tasks employed by the two different research groups. Although an unequivocal answer must await further research, one reasonable hypothesis concerns the nature of the tasks that subjects performed. Scialfa and colleagues had the subjects perform what are traditional visual search tasks (i.e., search for a single target among distractors). However, Fisk, Rogers, and colleagues often had subjects search for multiple targets (in essence a memory search task) among multiple distractors (a visual search task). Given the observation that older adults often have difficulty with large working memory loads as well as in switching between heterogeneous tasks (Bailey & Lauber, 1998; Kray & Lindenberger, 2000), it is perhaps not surprising that evidence for

age-related equivalence in learning to perform the search tasks was not obtained when the tasks included both memory and attentional components. Thus, contextual constraints and additional processing requirements may limit the training benefits on visual search found for older adults.

Despite the potential age-related limits in training effects discussed earlier, Ball, Owsley, and colleagues (Ball & Owsley, 2000; Ball, Beard, Roenker, Miller, & Griggs, 1988; Ball, Owsley, Stalvey, Roenker, Sloane, & Graves, 1998; Owsley, Ball, Sloane, Roenker, & Bruni, 1991; Owsley, Ball, & Keaton, 1995) have reported that older adults can benefit, to the same extent as younger adults, from practice on a useful field of view (UFOV) test that entails extracting information from the visual field rapidly and accurately. Indeed, these training benefits can also be retained for up to 6 months following training. Given that a restricted attentional field has been associated with increased automobile accidents, it is important to determine whether laboratory-based training on this skill can be generalized to driving. This question has been addressed in a study that entailed on-road driving assessments prior to and following practice on a UFOV test. Older drivers who received UFOV training showed substantially larger driving performance gains than older adults who did not receive training (Ball & Owsley, 2002). Thus, it would appear that visual search and attentional skills of older adults can indeed be trained in the laboratory and transferred to complex tasks in real-world environments.

Over the past several decades, extensive research has been conducted to examine whether age-related memory loss can be reduced with mnemonic training. This body of research has been summarized in the form of a meta-analysis of 33 separate studies with 1539 participants (Verhaeghen, Marcoen, & Goossens, 1992). Several interesting results were obtained in the meta-analysis. First, training gains were found to be substantially larger for older individuals (all participants were >60 years of age) who were trained with mnemonic techniques (.73 SD) than control subjects (.38 SD). Second, no differences in training gains were found for different mnemonic training techniques (e.g., method of loci, name-face, pegword). Third, several variables were found to moderate the training effect. Training gains were larger for younger participants when pretraining was provided, when training was carried out in groups rather than individually, and when training sessions were brief. Thus, these data clearly suggest that older adults can benefit from memory training.

However, do older adults benefit to the same degree as younger adults from mnemonic training? The answer appears to be no. Kliegl and colleagues (Baltes & Kliegl, 1992; Kliegl, Smith, & Baltes, 1989, 1990; see also Verhaeghen & Marcoen, 1996) carried out a series of studies to address this issue with a methodology that they refer to as testing the limits. The

testing-the-limits method entails the design of interventions that enable an estimation of the current and future reserve capacity of individuals. Three levels of information about performance and latent potential are distinguished in the testing-the-limits paradigm. Baseline performance refers to an individual's initial performance under standardized conditions. Baseline reserve capacity is defined as an individual's maximal performance if conditions of assessment are optimized in the absence of any attempt to modify the individuals cognitive skills or motivation. Finally, developmental reserve capacity is defined as maximal performance following interventions that are aimed at maximizing motivation and cognitive processes needed for performance.

In experiments that have employed the testing-the-limits method, the general finding has been that age differences in mnemonic performance, with the method of loci, increase from pretraining assessments to assessments that follow several weeks of practice. Older adults clearly do show dramatic performance improvements in word recall with extensive training. However, younger adults show larger improvements than older adults, particularly under difficult conditions (e.g., when little time is available to encode each of the words in a list).

Results obtained using the testing-the-limits method with mnemonic practice may indeed set some boundaries on the cognitive plasticity of older adults. However, thus far there are a number of unanswered questions with respect to these findings. For example, would an amplification of age-related performance differences still be observed with additional practice (comparable to the amounts of practice/training received in most professions or leisure activities)? Will age-related amplification effects hold up with within subject designs or when other tasks and processes are trained? To what extent do lifestyle factors (e.g., fitness, nutrition, education) influence the course of training effects? Clearly, additional research will be required to answer these questions.

There have, in recent years, been some interesting exceptions to the general observations of age-equivalent and age-deficient training outcomes. For example, Baron and Mittila (1989) examined the influence of training on the speed and accuracy with which young and older adults performed a memory search task (i.e., a task in which they compared probe items to items stored in memory). Subjects were trained for 44 hours with a deadline procedure in which they were required to constantly increase the speed with which they performed the task. Prior to training, young and older adults performed the memory search task with comparable accuracy but the older adults were substantially slower than the younger adults. During training with the deadline procedure, both young and older adults performed more quickly but with a substantially elevated error rate. Most interestingly, when

the deadline procedure was relaxed, both young and old adults performed with equivalent accuracies and the response time differences between the groups were reduced substantially. Thus, these data suggest a more substantial improvement in performance related to speed of responding for the old than for the younger adults (for an age-related decrease in the effects of complexity on performance with practice, see Falduto & Baron, 1986).

A similar pattern of results was obtained in the study of training effects on the dual-task performance of young and old adults (Kramer, Larish, Weber, & Bardell, 1999; see also Kramer, Larish, & Strayer, 1995). Young and old adults were trained to concurrently perform two tasks, a pattern-learning task and a tracking task, with either of two training strategies. In the fixed priority training strategy, subjects were asked to treat each of the tasks as equal in importance. In the variable priority training procedure, subjects were required to constantly vary their priorities between the two tasks. On-line performance feedback was presented in both training conditions.

Several interesting results were obtained. First, consistent with previous studies, young and old adults improved their dual-task performance at the same rate with the fixed priority training strategy. Second, variable priority training led to faster acquisition and a higher level of mastery in performing the tasks together than fixed priority training. Furthermore, individuals trained in the variable priority condition also displayed a superior transfer to untrained tasks and better retention of time-sharing skills over a 2-month period than those individuals trained in the fixed priority condition. Finally, and most importantly, age-related differences in the efficiency of dual-task performance were reduced substantially for individuals trained in the variable priority condition (for another example of diminished age effects with practice in task switching, see Kramer, Hahn, & Gopher, 1999).

Finally, Jennings, Webster, Kleykamp, and Dagenbach (2002) presented some intriguing data with respect to memory training of older adults. Their study involved recollection training with unrelated word lists of a small (12) group of older adults. A key component of this strategy was the use of Jacoby's (Jacoby, 1998; Kelly & Jacoby, 2000) process dissociation paradigm, which enables the dissociation of two different types of memory processes: recollection and familiarity. Recollection processes entail conscious and effortful memory processes, just those processes with which older adults have great difficulty. Familiarity processes involve more automatic and some would say unconscious memory processes. Older adults show small to negligible deficits in familiarity-based processes (Hay & Jacoby, 1999).

Jennings et al. (2002) emphasized recollection processes by requiring subjects to respond differently to words that they had remembered from

previous lists from words that were repeated from a recently presented study list. They used an adaptive algorithm, based on subjects recollection performance, to gradually increase the number of intervening items between previously presented words. The older adults recollection performance improved from 1 to over 25 intervening items in less than 30 sessions of practice. Furthermore, the training improvements transferred to several other memory tasks, including working memory (n-back), self-ordered pointing, and digit-symbol substitution. A second study replicated these effects and included a control group who did not show memory improvements. These results are quite remarkable given previous studies that report (a) large and persistent age deficits in recollection and (b) little transfer of training between different memory tasks. Clearly, additional research is needed to examine potential age differences in the efficacy of this training procedure and to explicate the boundary conditions for transfer. However, these results do suggest a substantial amount of plasticity in recollection for healthy older adults.

An obvious question concerning the Baron and Mittila (1989) and Kramer et al. (1999) studies (and the Jennings study in terms of the magnitude of the training benefits) is why these projects and several others have observed decreased age-related performance differences with training while many other studies have observed age-equivalent training effects. Although there is quite likely not a single answer to this question, one possibility centers on the nature of the training procedures. Both the Baron and Mattila (1989) and the Kramer et al. (1999) training strategies (i.e., the variable priority strategy) focused explicitly on aspects of performance on which young and older adults showed large differences. For example, one may conceptualize the Baron and Mattila (1989) deadline strategy as encouraging individuals to shift their response criterion from emphasizing accurate to emphasizing speeded performance. Given that older adults typically emphasize accuracy rather than speed, the deadline strategy may be well suited to older adults. Similarly, older adults have been observed to have difficulty in flexibly setting and modifying processing priorities. The variable priority training strategy targets this skill explicitly. Indeed, while Sit and Fisk (1999) found a decrease of age-related dual-task performance decrements with training, they also observed an increase in age-related performance differences when task emphasis instructions were changed. Interestingly, they did not formally train their subjects to shift priorities among multiple tasks. Thus, although additional research is clearly needed to further examine the techniques and situations in which the age gap in performance can be reduced, one potentially fruitful area of inquiry concerns targeting training strategies to specific difficulties encountered by older adults.

B. LONGITUDINAL STUDIES OF PRACTICE AND TRAINING

While a main focus in cross-sectional training studies has been on comparing the training improvement of young and older age cohorts and on examining the efficacy of strategies targeted at deficits in elders, a central focus in training research conducted within longitudinal studies has been to examine the extent to which training remediates or improves cognition in elders in tasks for which there is long-term data. Given the wide individual differences in timing of age-related ability decline, some adults in their sixties and seventies have experienced reliable decline on a given cognitive ability and others have not. Two questions arise: Would training be effective in remediating decline for elders who had shown loss in a specific ability? Second, for elders showing no decline in a specific ability, would training enhance their performance to a level beyond that shown previously? Elders in the Seattle longitudinal study were classified as to whether they had shown reliable decline over the prior 14-year interval on two fluid abilities known to show early age-related decline: inductive reasoning and spatial orientation (Schaie & Willis, 1986; Willis & Schaie, 1994). Elders who exhibited decline on only one of the two abilities were trained on that ability. Elders who had declined on both abilities or showed no decline on either ability were assigned randomly to training on one of the abilities. Over two thirds of trained elders showed reliable improvement on the ability trained immediately after training. Of elders who had declined on the ability trained, 40% showed remediation of performance, such that after training their performance was at the same level or above their performance 14 years prior to training. Elders who had not declined also showed reliable improvement. There was maintenance of training effects for those trained on inductive reasoning up to 7 years after training (Saczynski & Willis, submitted for publication). That is, elders trained on reasoning were performing at a higher level 7 years after training compared to those trained on another ability.

To summarize, cross-sectional training research suggests that both young and old adults profit from training, but that strategies targeted at skills known to decline with age are particularly effective in training of elders, such that performances of young and old are more comparable at posttest. Training research conducted within longitudinal studies allows the investigator to identify the abilities that have declined for a given individual and to examine whether training targeted at individual-level deficits is effective. The longitudinal approach permits examination of the range of plasticity over time within the same individual rather than comparing the magnitude of training effects for different age cohorts. Both types of training research support the position that considerable plasticity in cognitive functioning is

present even at advanced ages. The training findings also support the descriptive experiential studies of sparing in that effects are specific to the particular domain that was practiced or trained.

VI. Can Other Interventions Reduce Age-Related Decline in Cognition: Healthy Body, Healthy Mind?

The study of the relationship between fitness and mental function has been a topic of interest to psychologists, exercise physiologists, physicians, and other scientists and practitioners for the past several decades (Dustman, Ruhling, Emmerson, Shearer, 1994; Spirduso, 1975). The logic behind these studies has been predicated on the assumption that improvements in aerobic fitness would translate into increased brain blood flow, which in turn would support more efficient brain function, particularly in older adults for whom such function is often compromised. Indeed, these assumptions are supported, in part, by findings of compromised mental functions with pulmonary disease and exposure to low oxygen environments such as that experienced during high-altitude mountaineering. Furthermore, animal research has found that aerobic fitness, like psychomotor skills training, promotes the development of new capillary networks in the brains of old rats, the enhancement of cortical high-affinity choline uptake and increased dopamine receptor density in the brains of old rats, and increases in brain-derived neurotrophin factor (BDNF) gene expression in rats (Black et al., 1990; Churchill, Galvez, Colcombe, Swain, Kramer, & Greenough, 2003; Cotman & Berchtold, 2002; van Praag et al., 1999). Thus, the logic that underlies examination of the relationship between fitness and mental function in humans appears well supported by the relevant scientific literatures.

Unfortunately, however, results from intervention studies that have examined the influence of aerobic fitness training on cognition have been mixed. Some studies have reported fitness-related improvements for older adults (Dustman et al., 1984; Hawkins, Kramer, & Capaldi, 1992; Kramer et al., 1999; Rikli & Edwards, 1991), whereas others have failed to observe such improvements (Blumenthal, Emery, Madden, Schniebolk, Walsh-Riddle, George, McKee, Higginbotham, Cobb, & Coleman, 1991; Hill, Storandt, & Malley, 1993; Madden, Blumenthal, Allen, & Emery, 1989). Clearly, there are a number of potential theoretical and methodological reasons for this ambiguity. For example, studies have differed in terms of the length and the nature of the fitness interventions, the manner in which fitness changes have been assessed, the health and age of the study populations, and the aspects of cognition that have been examined.

Colcombe and Kramer (2003) conducted a meta-analysis to ask whether (a) fitness effects on cognition could be discerned when aggregating data across longitudinal studies and (b) whether this effect, if observed, is moderated by other variables such as age, length, and intensity of fitness training and the nature of the tasks used to assess cognition. Fitness intervention studies conducted from 1966 through 2001 were included in the analysis. Several interesting and potentially important results were obtained in the meta-analysis. First, a clear and significant effect of aerobic fitness training was found. Thus, when aggregating across studies, fitness training does indeed have positive effects on the cognitive function of older humans. Second, fitness training had selective effects on cognitive function. Although fitness effects were observed across a wide variety of tasks and cognitive processes, the effects were largest for those tasks that entailed executive control (i.e., planning, scheduling, working memory, interference control, task coordination) processes. As discussed previously, executive control processes have been found to decline substantially as a function of aging (Kramer et al., 1994; West, 1996), as have the brain regions that support them (Raz, 2000). Therefore, results of the meta-analysis suggest that even processes that are quite susceptible to age-related changes appear to be amenable to intervention, as consistent with the research on expertise and cognitive training discussed earlier.

The meta-analysis also revealed that a number of other moderator variables influenced the relationship between fitness training and cognition. For example, fitness training programs that were combined with strength and flexibility training regimens had a greater positive effect on cognition than fitness training programs that included only aerobic components. This effect may be the result of increases in the production of insulin-like growth factor 1 (IGF-1), which has been shown to accompany improvements in strength. IGF-1 is a neuroprotective factor involved in neuronal growth and differentiation (Carro, Nunez, Busiguina, & Torres-Aleman, 2001; Cottman & Berchtold, 2002). Fitness training programs also had a larger impact on cognition if the study samples included more than 50% female participants. Although highly speculative, this effect may be due, in part, to the positive influence of estrogen (in the present case, estrogen replacement therapy) on both brain-derived neurotrophin factor (BDNF) and increased exercise participation (Cotman & Berchtold, 2002). Estrogen has been found to upregulate BDNF, a neuroprotective molecule that is also increased by exercise. Finally, exercise effects on cognition were found to be largest for exercise training interventions that exceeded 30 minutes per session.

The link between brain and cognition has also been examined with regard to fitness differences and fitness training of older adults. Colcombe,

Erickson, Raz, Webb, Cohen, McAuley, & Kramer (2003) explored the implied relationship between cardiovascular fitness and brain health in aging humans using a voxel-based morphometric (VBM) approach. In VBM analyses, high-resolution brain scans are segmented into gray and white matter maps, spatially warped into a common coordinate system, and examined for systematic changes in tissue density as a function of some other variable (e.g., age, cardiovascular fitness). This technique allows examination of the entire brain in a point-by-point fashion, revealing spatially precise estimates of systematic variation in brain tissues. This technique provides a substantial advantage over other techniques, such as global estimates of gray and white matter volume in that it allows researchers to localize the effects of a given variable to a specific region of the brain.

In a cross-sectional examination of 55 older adults, Colcombe and Kramer (2003) found that, consistent with previous findings, age-related losses in gray and white matter tended to be greatest in the frontal, prefrontal, and temporal regions (e.g., Raz, 2000; O'Sullivan, Jones, Summers, Morris, Williams, & Markus, 2001). Moreover, consistent with predictions derived from the human and animal literatures, there was a significant reduction of declines in these areas as a function of cardiovascular fitness. That is, older adults who had better cardiovascular fitness also tended to lose much less tissue in the frontal, parietal, and temporal cortices as a function of age. Subsequent analyses, factoring out other potential moderating factors such as hypertension, caffeine, tobacco, and alcohol consumption, confirmed that none of these other variables significantly moderated the effect of cardiovascular fitness.

A preliminary cross-sectional analysis of the relationship between cardiovascular fitness and brain function in older adults has shown promising results and is consistent with the notion that cardiovascular fitness tends to spare the brain from the aging process (Kramer, Colcombe, McAuley, Eriksen, Scalf, Jerome, Marquez, Elavsky, & Webb, 2003). Participants in this study performed a modified version of the Eriksen flanker task in which they were asked to identify the orientation of a central arrow presented among an array of distracting stimuli while brain function was recorded using fMRI. On 50% of the trials, the orientation of the distracting stimuli was consistent with the central cue (e.g., '<<<<<'), whereas on the other 50% the distracting stimuli were oriented inconsistently with the central cue (e.g., '>><>>'). On inconsistent trials, participants were required to suppress the information provided by the flanking stimuli in order to make a correct response. On these trials, highly fit older adults, much like young adults, tended to show less activity in the left prefrontal regions of the cortex than their low-fit older counterparts.

These results, although preliminary, suggest that cardiovascular fitness may provide a prophylactic effect to the functional integrity of the older adult brain.

VII. Conclusions and Future Directions

The research reviewed in this chapter clearly suggests that the cognitive vitality of older adults can be enhanced through cognitive training, whether in the form of domain-relevant expertise or laboratory training, and improved fitness. However, it is important to note that these benefits are often quite specific and not universally observed. Therefore, one important goal of future research is to explicate the boundary conditions for the beneficial effects of cognitive and fitness training on the cognitive efficiency of older adults. Clearly, there are some obvious candidate factors that should be examined in more detail. These include age, health conditions, medication use, gender, education, lifestyle choices, genetic profile, and family and social support.

The nature and length of training, whether in terms of cognitive or fitness training, bear further study. It is important to note that many of the previous studies of “training” have entailed unsupervised practice rather than an examination of specific training procedures that might be well suited to the capabilities of older adults. The development of new methods, such as the testing-the-limits approach (Kliegl et al., 1989), will clearly also be important in future studies of training and other interventions.

At present, we have little understanding of the mechanisms and processes that subserve age-related enhancements in cognitive efficiency. Possibilities include improvements in basic cognitive abilities, the development of compensatory strategies, and automatization of selective aspects of a skill or task (Baltes, Staudinger, & Lindenberger, 1999). Thus, the nature of cognitive and brain (Churchill et al., 2003; Cotman & Berchtold, 2002) processes that support improvements in cognitive efficiency is an important topic for future research.

A related question concerns the extent to which cognitive improvements, engendered by intellectual training, fitness training, social networks and interactions (Fillit, Albert, Birren, Butter, Carey, Cotman, Grecnough, Gold, Kramer, Kuller, O'Connell, Perls, Reynolds-Foley, Sahagan, & Tully, 2002; Ybarra et al., 2001), and nutritional interventions (Bickford, Gould, Briederick, Chadman, Pollock, Young, Shukitt-Hale, & Joseph, 2000; Galli, Shukitt-Hale, Youdim, & Joseph, 2002), have similar effects on neural structure and processes or whether these interventions improve aspects of cognition through different neuronal routes. Previous animal

studies that have examined a myriad of interventions, including psychomotor skills training, fitness training, and social manipulations, suggest at least some overlap in the effects of these influences on brain and performance (Rosenzweig & Bennett, 1996). However, clearly more research will be needed to explore these potential interactions in animals and humans.

Finally, the development of models, preferably quantitative in nature (e.g., Braver et al., 2001; Hanon & Hoyer, 1994; Li et al., 2000; Mireles & Charness, 2002) that describe the mechanisms that relate changes in cognition and brain function across the adult life span, will be necessary to further enhance our understanding of cognitive plasticity and aging.

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INDEX

A

Action–sentence compatibility
 effectdescription of, 93
 experiments of, 97–98
 interactions, 98–99
 verb coercion, 105

Adults

concepts studies in, 4–6
 slowmapping of, 19–21
 syntactic patterns learned by, 121

Aerobic fitness, age-related cognitive and
 memory declines affected by, 290–292

Affective responses, embodied states effect on
 bodily elicitations, 52–54
 causes of, 80
 facial elicitations, 54–55

Affordances

constructional knowledge effects, 102–103
 definition of, 100
 meshing of, 102
 perceptual symbols as source of, 101

Aging

brain function and structure changesaerobic
 fitness effects, 290–293
 executive control declines, 272
 functional magnetic resonance imaging
 assessments, 273
 gray matter, 271
 neural resources, 273
 neuroimaging studies of, 272–275
 nonhomologous regions, 274
 nonuniformity of, 272
 positron emission tomography
 findings, 272–273

regional differences in, 272

slowing of, 274–275

studies of, 271

variability in, 274

cognition declinescommon cause

explanations, 269–271

exceptions to, 268–269

exercise benefits for, 290–291

experience effects, 275–283

expertise as means to reducedescription of,
 275–279

discrepancies in studies of, 279–282

models of, 282–283

fitness training for, 290–292

laboratorybased training to reduce

advantages and disadvantages

of, 283–284

crosssectional practice and training

studies, 284–289

longitudinal studies, 289–290

perceptual speed, 268

rates of, 268

studies of, 267–268

text recall, 268

word recall, 268

cognitive flexibility effects, 268

description of, 267

inhibitory processes affected by, 199

interference in memory processes, 199

memory declines associated with

description of, 198–200, 270

mnemonic training to

lessen, 286–287

visual search variations, 284–285

Amodal symbols, 95

- Amodal theories
 - embodiment effects, 82–83
 - symbols in, 95
- Associative learning, 24
- Attention, inhibition effects on
 - inhibition of return, 176–181
 - negative priming, 170–176
 - overview of, 169–170
 - processes involved in, 202
 - Stroop effect, 181–183
 - task switching, 183–184
 - visual marking, 184–185
- Attention and vector sum
 - model, 152–156
- Automatic inhibition of attention, 202
- Automatic memory retrieval, 203–204
- Automaticity
 - causes of, 204
 - description of, 82
 - instance theory of, 172
- B**
- Behavior, language effects on, 97
- Biologically based mechanisms,
 - pattern completion through, 75–76
- Blocking, 164
- Bodily elicitation, 52–54
- Bodily mimicry, to embodied mimicry
 - to others, 50–51
- Bodily responses, to perceived social stimuli, 45–47
- Brain function and structure, age-related changes in
 - aerobic fitness effects, 290–293
 - executive control declines, 272
 - functional magnetic resonance imaging assessments, 273
 - gray matter, 271
 - neural resources, 273
 - neuroimaging studies of, 272–275
 - nonhomologous regions, 274
 - nonuniformity of, 272
 - positron emission tomography findings, 272–273
 - regional differences in, 272
 - slowing of, 274–275
 - studies of, 271
 - variability in, 274

C

- Capacities
 - cognitive, 15
 - depression, 14
 - language, 14–15
- Categories
 - classical view of, 7
 - family resemblance, 7–8, 11
 - feature listings, 27–29
 - of foods, 33–34
 - hypothesis testing in research of, 8–12
 - knowledge of, 21–24
 - linearly separable, 4, 9, 23
 - naming and, 31–33
 - nonlinearly separable, 4, 7, 9, 23
 - objects, 32
 - scriptbased, 33
 - simulators, 67–70
 - structure of, 26–30
 - unique elements of, 7
- Category learning
 - by children, 23
 - definition of, 18
 - experiments of, 9–10, 24–27
 - knowledge in, 3–4, 22
 - stimulus–response theory of, 10–11
 - structural effects of, 23
 - unsupervised, 22
- Central executive, in human cognitive architecture
 - indirect instruction as substitute for, 246
 - map as, 244–245
 - problem solving as substitute for, 245
 - schemas as, 227–229
- Children
 - category learning by, 23
 - concepts studies in, 4–6
 - fastmapping, 5, 19–21
 - language comprehension by, 110, 118
 - reading comprehension in, 110
 - vocabulary learning, 19
 - word learning in, 5, 20
- Cognition
 - age-related declines uncommon cause explanations, 269–271
 - exceptions to, 268–269
 - exercise benefits for, 290–291
 - experience effects, 275–283
 - expertise as means to reduce

- description of, 275–279
 - discrepancies in studies of, 279–282
 - models of, 282–283
 - fitness training for, 290–292
 - laboratorybased training to
 - reduce advantages and disadvantages of, 283–284
 - crosssectional practice and training studies, 284–289
 - longitudinal studies, 289–290
 - perceptual speed, 268
 - rates of, 268
 - studies of, 267–268
 - text recall, 268
 - word recall, 268
 - embodied theories of, 44
 - social embodiment and
 - description of, 44
 - facial categorization performance effects, 59–60
 - factors associated with, 80–81
 - memory performance effects, 57–59
 - motor performance effects, 56–57
 - nonsocial effects, 61–62
 - overview of, 55–56
 - reasoning performance effects, 60
 - secondary task performance effects, 60–61
 - Cognitive architecture, human. *See* Human cognitive architecture
 - Cognitive architecture
 - capacities, 15
 - Cognitive load theory, 248
 - Cognitive training
 - fitness training benefits, 290–293
 - laboratorybased advantages and disadvantages of, 283–284
 - crosssectional practice and training studies, 284–289
 - longitudinal studies, 289–290
 - Communicative mimicry, to embodied mimicry to others, 51–52
 - Communicative responses, to perceived social stimuli, 48–49
 - Computational framework, of spatial term apprehension
 - description of, 131–132
 - directions assigned to space
 - description of, 133–137
 - direction parameter, 144–149
 - orientation parameter, 144–149
 - origin parameter, 139–144
 - reference frame, 145–149
 - scale parameter, 149–152
 - spatial templates. *See* Spatial templates
 - finding the relevant objects, 133
 - spatial relation computations and comparisons, 137–138
 - study of, 132–138
 - supporting evidence for, 132–138
 - Computational theory, 165
 - Concepts
 - description of, 1
 - detached database view of, 70
 - exemplar theory, 2–3
 - experimental design for, 4–5
 - family resemblance, 7–8, 11
 - hierarchically organized, 17
 - knowledge in category learning, 3–4, 22
 - object, 13
 - perceptual classification and, 12–13
 - phenomena, 16–17
 - prototype theory, 2–3
 - psychoanthropological studies of, 30–31
 - psychology of, 6–14, 16–19
 - studies of
 - in adults, 4–6
 - in children, 4–6
 - unconstrained construction of, 8, 13, 15
 - Conflict resolution, 205–206
 - Connected discourse, 108–111
 - Connectionist models, 94
 - Conscious access of features, 28–29
 - Consonant–vowel–consonants, 18–19
 - Construction(s)
 - definition of, 93
 - grammatical, 112–118
 - incredulous response, 115–116, 119–120
 - language based on, 117, 119
 - learning of, 119
 - Construction grammar, 102
 - Constructional knowledge, 116
 - Convergence zones, 66
- D**
- Delay–no warning condition, 188–190
 - Delay–warning condition, 188–190
 - Diagram/text redundancy, 253
 - Direct instruction, 244–245
 - Directed forgetting, 185–193

Direction parameter, 144–149
 Doubleobject construction, 102, 104

E

Elderly. *See* Aging; Older adults
 Element
 interactivity
 cognitive load effects, 253–254
 conceptualization of, 218–219
 description of, 216
 highdescription of, 216–218
 working memory processing of, 223
 low, 217
 relational complexity and, 219
 Embodiment. *See* Social
 embodiment
 Entrenched situated
 conceptualizations
 description of, 72–73, 84
 pattern completion with, 74–75
 social processing effects, 73
 Eventrelated potentials, 133
 Executive control, age-related declines in, 272
 Executive inhibition, 202
 Exemplar theory, 2–3
 Exemplars, 2–3
 Exercise, age-related cognitive and memory
 declines affected by, 290–292
 Expertise reversal effect, 256–258
 Exploratory learning, 244

F

Facial categorization, social embodiment
 effects on, 59–60
 Facial elicitation, 54–55
 Facial feedback, 54
 Facial mimicry, to embodied mimicry to others,
 51
 Facial responses, to perceived social stimuli, 47–
 48
 Family resemblance concepts, 7–8
 Fast mapping, 5, 19–21
 Feature(s)category, 29
 conscious access, 28–29
 list of, 27–28
 object, 29
 verbal, 28
 Feature maps, 64–66
 Feature mismatch, 172
 Feedback, 18, 54

Forgetting
 directed, 185–193
 retrievalinduced, 193–198
 Functional bias, 140

G

Gestures, 111
 Goalfree effect, 248–249
 Grammatical constructions, 112–118
 Grounding
 sentence, 101
 symbol
 description of, 93
 meaning and, 94–97
 principles of, 95–96
 word, 101
 Guidance fading effect, 258–259

H

Hardware implementation, 165
 Hemispheric asymmetry reduction in older
 adults model, 273
 High element interactivity
 description of, 216–218
 working memory processing of, 223
 Human cognitive architecture
 automation, 221–222
 central executive
 indirect instruction as substitute
 for, 246
 map as, 244–245
 problem solving as substitute for, 245
 schemas as, 227–229
 coalescing of isolated cognitive
 structures, 222–223
 continuachanges in, 243
 description of, 225
 element combinations, 226, 229–230
 elements of, 227–233
 evolution by natural selection, 242
 generalized matrix of, 240–244
 learning, 227–228, 240–241
 meansends analysis, 230
 problemsolving search
 continuum, 229–231
 processing novel, yettobelearned
 material, 234–235
 processing welllearned material, 233

schematic diagram of, 226
 summary overview of, 232–233
 working memory limitations, 226, 231–233
 description of, 215–216
 information processing systems
 environmental coordination rule, 237
 features of, 235
 information stores
 description of, 235
 human genome example, 236
 natural
 description of, 237
 random variations to, 238–240
 size of, 236–237
 variations in
 effectiveness of, 237–238
 random, 238–240
 information structures
 description of, 216–217
 element interactivity. *See* Element
 interactivity
 instructional consequences
 creativity, 246–248
 direct instruction, 244–245
 explanation, 244–245
 general, 244–246
 indirect instruction, 246
 map, 244–245
 instructional designs
 element interactivity effect, 253–254
 expertise reversal effect, 256–258
 goalfree effect, 248–249
 guidance fading effect, 258–259
 imagination effect, 255–256
 isolated interacting elements
 effect, 254–255
 modality effect, 252
 problem completion effect, 250–251
 redundancy effect, 252–253
 split attention effect, 251
 worked example effect, 249–250
 longterm memory, 220
 schemas
 central executive function of, 227–229
 description of, 220–222
 information coordination by, 227, 240
 longterm memory use of, 221, 223–224
 summary overview of, 259–261
 working memory
 attributes of, 220

capacity limitations of, 223–227
 description of, 215
 functions of, 219–220
 high element interactivity material
 processed in, 223
 increasing of, 252
 limitations of, 220, 223, 231–233
 longterm, 225
 unlimited, 224–227
 Hypothesis testing, in categorization
 research, 8–12

I

Imagination effect, 255–256
 Incredulous response
 construction, 115–116, 119–120
 Indexical hypothesis
 description of, 93
 learning and, 118–121
 misconceptions regarding, 103–105
 principles of, 98, 100
 supporting evidence for, 118
 Information stores
 description of, 235
 human genome example, 236
 natural
 description of, 237
 random variations to, 238–240
 size of, 236–237
 variations in
 effectiveness of, 237–238
 random, 238–240
 Inhibition
 aging-related declines in cognition
 caused by, 269
 attention case studies
 inhibition of return, 176–181
 negative priming, 170–176
 overview of, 169–170
 processes involved in, 202
 Stroop effect, 181–183
 task switching, 183–184
 visual marking, 184–185
 automatic inhibition of attention, 202
 cognitive
 description of, 164–165
 history of, 168–169
 concept of, 201–202
 dictionary definition of, 163

Inhibition (*Continued*)

- executive, 202
 - history of, 165–166
 - interference vs., 202–203
 - list method, 187
 - memory case studies
 - aging effects on memory, 198–200
 - directed forgetting, 185–193
 - lexical decision, 200–201
 - overview of, 169–170
 - processes involved in, 202
 - retrieval-induced forgetting, 193–198
 - motivational, 202
 - neural, 166–168
 - noninhibitory mechanisms
 - automaticity, 203–206
 - conflict resolution, 205–206
 - description of, 203–204
 - nonword prime, 200
 - during reference frame selection, 145–149
 - retrieval, 192
 - terminology difficulties associated
 - with, 202–203
 - word origin of, 163
- Inhibition of return, 176–181**
- Innovative denominal verb, 113–114**
- Instance theory of automaticity, 172**
- Isolated interacting elements effect, 254–255**

K**Knowledge**

- categories, 21–24
- in category learning, 3–4
- composition of, 44, 63
- constructional, 116
- entrenched, 72
- grounding of, 96
- repeated social situations effect on, 72–73

L**Language**

- abstract approach to, 93
- acquisition of, 114
- behavior affected by, 97
- capacities, 14–15
- constructions involved in, 117, 119
- diaries of, 34–35
- gestures and, 111

- performance model of, 14–15
 - propositional representations of, 94
 - spatial, 127–128
 - symbol grounding, 94–97
 - uniqueness of, 16
- Language comprehension**
- by children, 110
 - constructions' role in, 116–117
 - grammatical constructions in, 112–118

Learning

- category
 - by children, 23
 - definition of, 18
 - experiments of, 9–10
 - knowledge in, 3–4, 22
 - stimulus–response theory of, 10–11
 - structural effects of, 23
 - unsupervised, 22
- exploratory, 244
- indexical hypothesis and, 118–121
- knowledge effects on, 22–23
- paired associate, 217
- perceptual symbols' role in, 105–111
- setting for, 24–26
- syntax, 217–218
- time course for, 24–26
- with understanding, 217

Lexical decision, inhibition effects on, 200–201**Linearly separable categories, 4, 9, 23****Longterm memory**

- description of, 220
- schemas stored in, 221, 223–224

Low element interactivity, 217**Lowfrequency syntactic patterns, 121****M****Meaning**

- actionbased, 109–110
- affordancebased
 - constructional knowledge
 - effects, 102–103
 - definition of, 100
 - innovative denominal verb, 113–114
 - meshing of, 102
 - perceptual symbols as source of, 101
- definition of, 100
- individual construal of, 100
- sentence, 114–115

simulations as, 73
 symbol grounding and, 94–97
 Meansends analysis, 230
Memory
 agingrelated declines
 description of, 198–200, 270
 mnemonic training to lessen, 286–287
 automatic retrieval, 203–204
 inhibition effects
 aging effects on memory, 198–200
 directed forgetting, 185–193
 lexical decision, 200–201
 overview of, 169–170
 processes involved in, 202
 retrievalinduced forgetting, 193–198
 longterm
 description of, 220
 schemas stored in, 221, 223–224
 of older adults, 288
 simulators in, 69
 social embodiment effects on, 57–59
 working
 attributes of, 220
 capacity limitations of, 223–227
 description of, 215
 functions of, 219–220
 increasing of, 252
 limitations of, 215, 220, 223, 231–233
 longterm, 225, 254
 unlimited, 224–227
Mental activity/physical activity
 redundancy, 253
Mental imagery, 66
Mimicry
 bodily, 50–51
 communicative, 51–52
 facial, 51
 mirror neuron circuit's role in causing, 78–79
 social contagion secondary to, 79
 wincing, 79
Mirror neuron circuit, 78–79
Mnemonic training, for agerelated memory
 declines, 286–287
Modality effect, 252
Modalityspecific states
 features maps arising from, 64–66
 reenactments of, 66–67
Motivational inhibition, 202
Motor performance, social embodiment
 effects on, 56–57

N

Negative priming, 147–148, 170–176
 Neural inhibition, 166–168
 No delay condition, 188–190
 Nonlinearly separable categories, 4, 7, 9, 23
 Nonsense verbs, 114
 Nonword prime inhibition, 200

O

Object(s)
 category of, 32
 features of, 29
 spatial relations of, 130
Object concepts, 13
Older adults. *See also* Aging
 memory training in, 288
 recollection processes, 288
Orientation parameter, 144–149
Origin parameter functional part
 context's role in defining, 140–144
 origin defined relative to, 139–140

P

Paired associate learning, 217
Partlist cuing effect, 197
Pattern completion
 with biologically based mechanisms, 75–76
 with entrenched situated
 conceptualizations, 74–75
 social inferences from, 74–76
 social stimuli effects on bodily responses
 caused by, 78
Perception
 agingrelated declines in speed of, 268
 emotional reactions and, 75
 inhibition of return, 177
 modal reenactments of, 63–67
Perceptual classification, 12–13
Perceptual symbols
 affordances derived from, 101
 conceptual tasks use of, 106
 connected discourse and, 108–111
 description of, 96
 gestures and, 111
 learning comprehension role of, 105–111
 modal nature of, 106
 sentence understanding and, 106–108

Perceptual symbols (*Continued*)

- simulation using, 96, 106
- visual images vs., 103

Performance

- agerelated declines in, expertise as means to reduce, 275–283
- models of, 14

Preview effect, 184

Problem completion effect, 250–251

Problem solving

- central executive function of, 245
- creativity and, 247–248
- in human cognitive architecture
 - continuum, 229–230
- worked examples as guidance for, 250

Prototype theory, 2–3

Psychoanthropological studies of concepts, 30–31

R

Reasoning, social embodiment effects on, 60

Redundancy effect, 252–253

Reenactments

- modalityspecific states, 66–67
- perception, 63–67

Reference frames

- inhibition during selection of, 145–149
- scale parameter for, 149–152

Reference system, for spatial term

- apprehension, 130–131

Relational complexity, 218–219

Representation and algorithm, 165

Restraint, 164

Retrieval inhibition, 192

Retrievalinduced forgetting, 193–198

Rote learning, 216

S

Scale parameter, for reference frames, 149–152

Schemas

- central executive function of, 227–229
- description of, 220–222
- information coordination by, 227, 240
- longterm memory use of, 221, 223–224

Scriptbased categories, 33

Secondary tasks, social embodiment effects on, 60–61

Selection, optimization, and compensation model, 282

Semantic network, 94

Sentence

- grammatical constructions, 112–118
- grounding of, 101
- innovative denominal verbs, 113–114
- meaning of, 114–115
- understanding of, perceptual symbols used in, 106–108

Simulations

- as meaning, 73
- description of, 68–69
- perceptual symbols in, 96, 106
- situated conceptualizations implemented by, 71–72

Simulators, 67–70

Situated conceptualizations

- components of, 72
- definition of, 70
- entrencheddescription of, 72–73, 84
 - pattern completion with, 74–75
 - social processing effects, 73
- example of, 70–71
- multimodal simulations, 71–72
- simulations in, 72

Social embodiment

- affective processing elicited by
 - bodily elicitation, 52–54
 - causes of, 80
 - description of, 52
 - facial elicitation, 54–55
- amodal accounts of effects of, 82–83
- cognition and
 - description of, 44
 - facial categorization performance effects, 59–60
 - factors associated with, 80–81
 - mediating structures that link, 82
 - memory performance effects, 57–59
 - motor performance effects, 56–57
 - nonsocial effects, 61–62
 - overview of, 55–56
 - reasoning performance effects, 60
 - redundancy, 81
 - secondary task performance effects, 60–61
- description of, 43
- effects ofdescription of, 43, 84
 - direct, 81–82
 - indirect, 81–82

- embodied mimicry in self from
 - bodily mimicry, 50–51
 - causes of, 78–79
 - communicative mimicry, 51–52
 - description of, 50
 - facial mimicry, 51
 - mirror neuron circuit's role in
 - causing, 78–79
 - social contagion effects, 79
 - multimodal simulations and, 73
 - perceived social stimuli effects on embodied responses
 - bodily responses, 45–47
 - causes of, 77–78
 - communicative responses, 48–49
 - description of, 45
 - facial responses, 47–48
 - nonsocial effects, 49
 - theory of
 - modal reenactments of perception, action, and introspection, 63–67
 - overview of, 62–63
 - simulations, 68–69
 - simulators, 67–70
 - situated conceptualizations. *See* Situated conceptualizations
 - social inference through pattern completion, 73–77
 - Social inferences, through pattern completion
 - biologically based mechanisms, 75–76
 - entrenched situated
 - conceptualizations, 74–75
 - simulation vs. execution of, 76–77
 - statistical character of, 76
 - variations in, 76
 - Social situations, entrenched situated
 - conceptualizations for, 72–73
 - Spatial description
 - components of, 128–131
 - utterance, 129
 - Spatial language
 - description of, 127
 - reasons for studying, 127
 - simplicity of, 128
 - Spatial relations, 130
 - Spatial templates
 - attention and vector sum model, 152–156
 - description of, 152
 - mechanisms underlying, 152–153
 - Spatial term apprehension
 - computational framework of, 131–138
 - description of, 128–129
 - directions assigned to spacedescription of, 133–137
 - direction parameter, 144–149
 - orientation parameter, 144–149
 - origin parameter, 139–144
 - reference frame, 145–149
 - scale parameter, 149–152
 - spatial templates. *See* Spatial templates
 - finding the relevant objects, 133
 - located and referenced objects
 - attention and vector sum model, 153
 - context's role in defining, 140–144
 - description of, 130
 - distance computations, 149–150
 - placement of, 139–140
 - reference system for, 130–131
 - spatial relation computations and comparisons, 137–138
 - study of, 132–138
 - supporting evidence for, 132–138
 - Splitattention effect, 251, 257
 - Stimulus–response learning theories, 10–11
 - Stroop effect/interference, 168, 170, 181–183
 - Suppression, 164
 - Symbol(s)
 - amodal, 95
 - perceptual. *See* Perceptual symbols
 - Symbol grounding
 - description of, 93
 - meaning and, 94–97
 - principles of, 95–96
 - Syntactic nuts, 117
 - Syntactic patterns, 121
 - Syntax learning, 217–218
- T**
- Task switching, 183–184
 - Text recall, aging effects on, 268
- U**
- Unconstrained concept construction, 8, 13, 15
 - Utterance, 129
- V**
- Verb
 - innovative denominal, 113–114

- nonsense, 114
- Verb coercion, 105
- Verbal features, 28
- Verb–argument construction, 102
- Visual marking, 184–185

W

- Word grounding, 101
- Word learning, in children, 5, 20
- Word recall, aging effects on, 268

Index

- Worked example effect, 249–250
- Working memory
 - attributes of, 220
 - capacity limitations of, 223–227
 - description of, 215
 - functions of, 219–220
 - increasing of, 252
 - limitations of, 215, 220, 223, 231–233
 - longterm, 225, 254
 - unlimited, 224–227

CONTENTS OF RECENT VOLUMES

Volume 30

Perceptual Learning

Felice Bedford

A Rational-Constructivist Account of Early

Learning about Numbers and Objects

Rochel Gelman

Remembering, Knowing, and Reconstructing the Past

Henry L. Roediger III, Mark A. Wheeler,
and Suparna Rajaram

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Fletcher, Eileen Kintsch, Suzanne M. Mannes,
and Mitchell J. Nathan

Separating Causal Laws from Causal Facts:

Pressing the Limits of Statistical
Relevance

Patricia W. Cheng

Categories, Hierarchies, and Induction

Elizabeth F. Shipley

Index

Volume 31

Associative Representations of Instrumental

Contingencies

Ruth M. Colwill

A Behavioral Analysis of Concepts: Its

Application to Pigeons and Children

Edward A. Wasserman and Suzette L. Astley

The Child's Representation of Human Groups

Lawrence A. Hirschfeld

Diagnostic Reasoning and Medical Expertise

Vimla L. Patel, Jos F. Arocha, and David
R. Kaufman

Object Shape, Object Name, and Object Kind:

Representation and Development

Barbara Landau

The Ontogeny of Part Representation in

Object Concepts

Philippe G. Schyns and Gregory L. Murphy

Index

Volume 32

Cognitive Approaches to Judgment and Decision

Making

Reid Hastie and Nancy Pennington

And Let Us Not Forget Memory: The Role of

Memory Processes and Techniques in the
Study of Judgment and Choice

Elke U. Weber, William M. Goldstein, and
Sema Barlas

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Implications of Domain Specificity in
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on Choice

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Choice

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D. Ordez, and Alan D. J. Cooke

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Eldar Shafir

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David V. Budescu and Thomas S. Wallsten

Compositional Anomalies in the Semantics of Evidence
John M. Miyamoto, Richard Gonzalez, and Shihfen Tu

Varieties of Confirmation Bias
Joshua Klayman

Index

Volume 33

Landmark-Based Spatial Memory in the Pigeon
Ken Cheng

The Acquisition and Structure of Emotional Response Categories
Paula M. Niedenthal and Jamin B. Halberstadt

Early Symbol Understanding and Use
Judy S. DeLoache

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The Universal Word Identification Reflex
Charles A. Perfetti and Sulan Zhang

Prospective Memory: Progress and Processes
Mark A. McDaniel

Looking for Transfer and Interference
Nancy Pennington and Bob Rehder

Index

Volume 34

Associative and Normative Models of Causal Induction: Reacting to versus Understanding Cause
A. G. Baker, Robin A. Murphy, and Frdric Valle-Tourangeau

Knowledge-Based Causal Induction
Michael R. Waldmann

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The Use of Intervening Variables in Causal Learning
Jerome R. Busemeyer, Mark A. McDaniel, and Eunhee Byun

Structural and Probabilistic Causality
Judea Pearl

Index

Volume 35

Distance and Location Processes in Memory for the Times of Past Events
William J. Friedman

Verbal and Spatial Working Memory in Humans
John Jonides, Patricia A. Reuter-Lorenz, Edward E. Smith, Edward Awh, Lisa L. Barnes, Maxwell Drain, Jennifer Glass, Erick J. Lauber, Andrea L. Patalano, and Eric H. Schumacher

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Brian H. Ross

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Spatial Effects in the Partial Report Paradigm: A Challenge for Theories of Visual Spatial Attention
Gordon D. Logan and Claus Bundesen

Structural Biases in Concept Learning: Influences from Multiple Functions
Dorrit Billman

Index

Volume 36

Learning to Bridge Between Perception and Cognition
Robert L. Goldstone, Philippe G. Schyns, and Douglas L. Medin

The Affordances of Perceptual Inquiry: Pictures Are Learned From the World, and What That Fact Might Mean About Perception Quite Generally
Julian Hochberg

Perceptual Learning of Alphanumeric-Like Characters

Richard M. Shiffrin and Nancy Lightfoot

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James Tanaka and Isabel Gauthier

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A Computational Investigation

Terry Regier

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A Network Model of the Development of Dimensions

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Catherine M. Sandhofer

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Visual Phenomena in a Laterally Connected

Map Model of the Primary Visual Cortex

Risto Mikkulainen, James A. Bednar,

Yoonsuck Choe, and Joseph Sirosh

Perceptual Learning From Cross-Modal Feedback

Virginia R. de Sa and Dana H. Ballard

Learning As Extraction of Low-Dimensional Representations

Shimon Edelman and Nathan Intrator

Index

Volume 37

Object-Based Reasoning

Miriam Bassok

Encoding Spatial Representation Through

Nonvisually Guided Locomotion: Tests of Human Path Integration

Roberta L. Klatzky, Jack M. Loomis, and

Reginald G. Golledge

Production, Evaluation, and Preservation of

Experiences: Constructive Processing in

Remembering and Performance Tasks

Bruce W. A. Whittlesea

Goals, Representations, and Strategies in a

Concept Attainment Task: The EPAM Model

Fernand Gobet, Howard Richman,

Jim Staszewski, and Herbert A. Simon

Attenuating Interference During Comprehension:

The Role of Suppression

Morton Ann Gernsbacher

Cognitive Processes in Counterfactual Thinking

About What Might Have Been

Ruth M. J. Byrne

Episodic Enhancement of Processing Fluency

Michael E. J. Masson and Colin M. MacLeod

At a Loss From Words: Verbal Overshadowing of

Perceptual Memories

Jonathan W. Schooler, Stephen M. Fiore, and

Maria A. Brandimonte

Index

Volume 38

Transfer-Inappropriate Processing: Negative Priming and Related Phenomena

W. Trammell Neil and Katherine M. Mathis

Cue Competition in the Absence of Compound

Training: Its Relation to Paradigms of

Interference Between Outcomes

Helena Matute and Oskar Pineo

Sooner or Later: The Psychology of Intertemporal Choice

Gretchen B. Chapman

Strategy Adaptivity and Individual Differences

Christian D. Schunn and Lynne M. Reder

Going Wild in the Laboratory: Learning About

Species Typical Cues

Michael Domjan

Emotional Memory: The Effects of Stress on

“Cool” and “Hot” Memory Systems

Janet Metcalfe and W. Jake Jacobs

Metacomprehension of Text: Influence of Absolute

Confidence Level on Bias and Accuracy

Ruth H. Maki

Linking Object Categorization and Naming: Early

Expectations and the Shaping Role of Language

Sandra R. Waxman

Index

Volume 39

Infant Memory: Cues, Contexts, Categories, and Lists

Carolyn Rovee-Collier and Michelle Gulya

The Cognitive-Initiative Account of Depression-

Related Impairments in Memory

Paula T. Hertel

Relational Timing: A Thermomorphic Perspective

J. Gregor Fetterman

The Influence of Goals on Value and Choice

Arthur B. Markham and C. Miguel Brendl

The Copying Machine Metaphor

Edward J. Wisniewski

Knowledge Selection in Category Learning

Evan Heit and Lewis Bott

Index

Volume 40

Different Organization of Concepts and

Meaning Systems in the Two Cerebral

Hemispheres

Dahlia W. Zaidel

The Causal Status Effect in Categorization: An Overview

Woo-kyoung Ahn and Nancy S. Kim

Remembering as a Social Process

Mary Susan Weldon

Neurocognitive Foundations of Human Memory

Ken A. Paller

Structural Influences on Implicit and Explicit

Sequence Learning

Tim Curran, Michael D. Smith, Joseph

M. DiFranco, and Aaron T. Daggy

Recall Processes in Recognition Memory

Caren M. Rotello

Reward Learning: Reinforcement, Incentives, and Expectations

Kent C. Berridge

Spatial Diagrams: Key Instruments in the Toolbox for Thought

Laura R. Novick

Reinforcement and Punishment in the Prisoner's Dilemma Game

Howard Rachlin, Jay Brown, and Forest Baker

Index

Volume 41

Categorization and Reasoning in Relation to Culture and Expertise

Douglas L. Medin, Norbert Ross, Scott Atran, Russell C. Burnett, and Sergey V. Blok

On the Computational basis of Learning and

Cognition: Arguments from LSA

Thomas K. Landauer

Multimedia Learning

Richard E. Mayer

Memory Systems and Perceptual Categorization

Thomas J. Palmeri and Marci A. Flanery

Conscious Intentions in the Control of Skilled Mental Activity

Richard A. Carlson

Brain Imaging Autobiographical Memory

Martin A. Conway, Christopher W. Pleydell-Pearce, Sharon Whitecross, and Helen Sharpe

The continued Influence of Misinformation in Memory: What makes a Corrections Effective?

Colleen M. Seifert

Making Sense and Nonsense of Experience: Attributions in Memory and Judgment

Colleen M. Kelley and Matthew G. Rhodes

Real-World estimation: Estimation Modes and Seeding Effects

Norman R. Brown

Index

Volume 42

Memory and Learning in Figure-Ground Perception

Mary A. Peterson and Emily Skow-Grant

Spatial and Visual Working Memory: A

Mental Workspace

Robert H. Logie

Scene Perception and Memory

Marvin M. Chun

Spatial Representations and Spatial Updating

Ranxiano Frances Wang

Selective Visual Attention and Visual Search: Behavioral and Neural Mechanisms

Joy J. Geng and Marlene Behrmann

Categorizing and Perceiving Objects: Exploring a Continuum of Information Use

Philippe G. Schyns

From Vision to Action and Action to Vision: A Convergent Route Approach to Vision, Action, and Attention

Glyn W. Humphreys and M. Jane Riddoch

Eye Movements and Visual Cognitive Suppression

David E. Irwin

What Makes Change Blindness Interesting?

Daniel J. Simons and Daniel T. Levin

Index