

Working Memory

Learning Objectives

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Revisit and Reflect

You're in the middle of a lively conversation about movies, one in particular. You and your friends have all seen it and have come away with different views. One friend says he felt that one of the leads was not convincing in the role; you disagree—you think the failing was in the screenplay, and want to make your case. But before you have a chance to get going, another friend jumps in and says she doesn't think this actor was miscast, just that he's not very good, and is prepared to argue chapter and verse. You think your point is a good one, and you want to make it; but you'll only offend this friend, who's now arguing her point with enthusiasm. Moreover, you find yourself agreeing with some of what she's saying. Your challenge is

to manage two tasks at once: pay attention to what your friend is saying, both out of courtesy and to follow her argument so you don't repeat or overlook her points when you speak; and hold on to your own argument, which is forming in your head as you listen. Your working memory is getting a workout!

Working memory is widely thought to be one of the most important mental faculties, critical for cognitive abilities such as planning, problem solving, and reasoning. This chapter describes current conceptions regarding the nature of working memory, its internal components, and the way it works. We specifically address five questions:

1. How is working memory used in cognition?
2. How did the modern view of working memory arise?
3. What are the elements of working memory?
4. How does working memory “work” in the brain?
5. How might views of working memory change in the future?

1. USING WORKING MEMORY

Every day we have occasion to keep particular pieces of critical information briefly in mind, storing them until the opportunity to use them arrives. Here are some examples: remembering a phone number between the time of hearing it and dialing it (“1 646 766-6358”); figuring a tip (the bill is \$28.37, call it \$30; 10 percent of that is \$3.00, half of that is \$1.50, \$3.00 plus \$1.50 is \$4.50, the 15 percent you're aiming for); holding driving directions in mind until you get to the landmarks you've been told to watch for (“take the first left, continue for one mile, past the school, bear right, left at the four-way intersection, then it's the third building on the left—you can pull into the driveway”). Sometimes a problem offers multiple possible solutions, such as when you must look ahead along various possible sequences of moves in a chess game, and sometimes, as when you must untangle the structure of a complex sentence like this one, it is straightforward but nonetheless requires holding bits of information in mind until you can put it all together.

In situations like these, not only do we need to keep certain bits of information accessible in mind, but also we need to perform cognitive operations on them, mulling them over, manipulating or transforming them. These short-term mental storage and manipulation operations are collectively called **working memory**. Think of working memory as involving a mental blackboard—that is, as a workspace that provides a temporary holding store so that relevant information is highly accessible and available for inspection and computation. When cognitive tasks are accomplished, the information can be easily erased, and the process can begin again with other information.

1.1. A Computer Metaphor

The computer, so useful a metaphor in cognitive psychology, offers an intuitively appealing model for thinking about the nature and structure of working memory.

Simplifying the workings of a computer, there are two means by which information is stored, the hard disk and random-access memory (RAM). The hard disk is the means by which information is stored permanently in a stable and reliable form; all software programs, data files, and the operating system of the computer are stored on the hard disk. To use this stored information you must retrieve it from the hard disk and load it into RAM. Now for the analogy: the information stored in the hard disk is like long-term memory, RAM corresponds to working memory.

The notion of working memory as a temporary workspace fits nicely: in a computer, RAM is cleared and reset when the task executed by the program is finished, or when the program is closed. The computer metaphor also suggests two further characteristics of working memory. First, RAM is completely flexible with regard to content. That is, there is no fixed mapping between the location of a part of RAM and the program that uses it; any program can access any part of RAM. Second, the more RAM a computer has, the more complex and sophisticated the programs that can be run on it, and the more programs that can be running simultaneously. Thus, if the computer-based metaphor of working memory holds, storage in working memory involves a content-free flexible buffer (the term in computer science for a limited-capacity memory store), and cognitive abilities are dependent on the size of the buffer.

How well does this metaphor fit with actual human working memory structure and function? The evidence is not all in, but cognitive and neuroscience approaches to the study of working memory have in many ways revolutionized the types of questions that can be asked and provided new insights into how working memory works.

1.2. Implications of the Nature of Working Memory

A better understanding of the nature of human working memory may have important implications for understanding why people differ in cognitive skills and abilities and why individuals have different degrees of success in their efforts to accomplish real-world goals. Research suggests that people vary widely in **working memory capacity** (also known as **working memory span**), the amount of information that can be held accessible (Daneman & Carpenter, 1980), and that these differences predict general intelligence (as measured by standard IQ tests), verbal SAT scores, and even the speed with which a skill such as computer programming is acquired (Kane & Engle, 2002; Kyllonen & Christal, 1990).

A test to determine working memory capacity is shown in Figure 6–1. (Why not take it yourself? Do the results accord with your view of your own working memory?) A relationship between working memory and cognitive ability is not surprising, given how pervasively working memory affects a wide range of complex cognitive tasks, not all of them as mundane as figuring out a tip. The more interesting questions remain: why do people differ so widely in working memory capacity, and where exactly do the differences lie? If we understood more precisely the components of working memory, and which aspects are the most critical for real-world cognitive

IS $(5 \times 3) + 4 = 17$? BOOK
IS $(6 \times 2) - 3 = 8$? HOUSE
IS $(4 \times 4) - 4 = 12$? JACKET
IS $(3 \times 7) + 6 = 27$? CAT
IS $(4 \times 8) - 2 = 31$? PEN
IS $(9 \times 2) + 6 = 24$? WATER

FIGURE 6-1 A standard test of working memory capacity

To take this test yourself, cut out a window in a blank sheet of paper so that it exposes only one line at a time. For each line, determine whether the arithmetic is correct or not: say, out loud, “yes” or “no.” Then look at the word that follows the problem and memorize it. Move through each line quickly. After you have finished all the lines, try to recall the words in order. The number you get correct is an estimate of your working memory capacity. Very few people have a working memory as high as 6; the average is around 2 or 3.

success, we might be able to develop methods to train and exercise working memory in a manner that could improve its function, and consequently enhance a person’s cognitive repertoire.

Today’s conceptions of working memory have evolved from earlier ideas in cognitive psychology, and current research stands, as so often in science, on the shoulders of predecessors. What the earliest workers did not have were the tools provided by modern neuroscience. Nonetheless, their work is a good place to begin.

 **Comprehension Check:**

1. Give an example of an everyday situation in which you would need to use working memory.
2. If working memory were a capacity of a computer, what component might it correspond to, and why?

2. FROM PRIMARY MEMORY TO WORKING MEMORY: A BRIEF HISTORY

The notion that there is a distinct form of memory that stores information temporarily in the service of ongoing cognition is not new, but ideas regarding the nature and function of short-term storage have evolved considerably during the

last hundred years. The very terms for this storage system have changed over the years, from *primary memory* to *short-term memory* to *working memory*. How and why did this happen?

2.1. William James: Primary Memory, Secondary Memory, and Consciousness

The first discussion of a distinction between short-term and long-term storage systems was put forth by the pioneering American psychologist William James in the late nineteenth century. James called these two forms of memory *primary memory* and *secondary memory*, using these terms to indicate the degree of the relationship of the stored information to consciousness (James, 1890). In James's view, **primary memory** is the initial repository in which information can be stored and made available to conscious inspection, attention, and introspection. In this way, such information would be continually accessible. In James's words, "an object of primary memory is thus not brought back; it never was lost." He contrasted primary memory with a long-term storage system, or secondary memory, from which information cannot be retrieved without initiating an active cognitive process. The link between working memory and consciousness that James sought to describe remains a central part of most current thinking; the question of whether or not we are conscious of the entire contents of working memory is still open to debate. Some current models suggest that only a subset of working memory is consciously experienced (Cowan, 1995).

2.2. Early Studies: The Characteristics of Short-Term Memory

Despite James's early work regarding the system for short-term information storage, there were no experimental studies of the characteristics of this system until the 1950s. Part of the reason for this neglect was the dominance of behaviorist views in the first half of the twentieth century, which shifted the focus of investigation away from cognitive studies. Then George Miller, an early and influential cognitive theorist, provided detailed evidence that the capacity for short-term information storage is limited. In what has to be one of the most provocative opening paragraphs of a cognitive psychology paper, Miller declared: "My problem is that I have been persecuted by an integer. . . . [T]his number has followed me around, has intruded in my most private data, and has assaulted me from the pages of our most public journals. This number assumes a variety of disguises, being sometimes a little larger and sometimes a little smaller than usual, but never changing so much as to be unrecognizable" (Miller, 1956, p. 81). In this paper, titled "The Magical Number Seven, Plus or Minus Two," Miller suggested that people can keep only about seven items active in short-term storage, and that this limitation influences performance on a wide range of mental tasks.

What data supported Miller's claim? Tests of short-term memorization, such as repeating a series of digits, showed that regardless of how long the series is, correct recall of digits appears to plateau at about seven items (though for some people this

plateau number is a little lower and for some it is a little higher; Guildford & Dallenbach, 1925). Miller made a further, and critical, point: that although there is a limitation on the number of items that can be simultaneously held in short-term storage, the definition of an “item” is highly flexible, and subject to manipulation. Specifically, Miller (1956) suggested that single items can be grouped into higher level units of organization he called **chunks**. Thus, three single digits could be chunked together into one three-digit unit: 3 1 4 becomes 314. What determines how much information can be chunked together? Miller suggested that chunking might be governed by meaningfulness. For example, if the numbers 3 1 4 are your area code, it is a very natural process to store them together as a chunk. These grouping processes seem to be ubiquitous in language, where we effortlessly group letters into word-chunks and words into phrase-chunks. Indeed, this may be why our ability to maintain verbal information in short-term storage is better than for other types of information.

The key notion of Miller’s chunk idea is that short-term storage, though possibly subject to certain constraints, is not rigid but amenable to strategies, such as chunking, that can expand its capacity. This notion is still very much present in current thinking about working memory. However, although the notion of a “magical number” is still part of current ideas regarding short-term storage capacity, recent work has suggested that this number might not actually be 7 ± 2 , as Miller suggested, but instead may be much less— 3 ± 1 . This revised estimate comes from a review of studies suggesting that storage capacity is much lower than seven when participants are prevented from using strategies such as chunking or rehearsal (Cowan, 2001).

Miller’s (1956) work drew attention to the concept of short-term storage and its functional characteristics. However, other influential evidence suggesting the distinct nature of the short-term storage system came from studies of amnesics who, like H.M. (see Chapter 5), showed grossly impaired long-term memory but relatively intact performance on immediate recall tasks (Baddeley & Warrington, 1970; Scoville & Milner, 1957). As a result, a common view emerged that short-term storage was structurally and functionally distinct from long-term storage and could be independently studied. In particular, it seemed that **short-term memory**, as this capacity began to be called, could be uniquely defined in terms of its short duration and high level of accessibility. During the 1950s and 1960s much research was devoted to examining these characteristics.

2.2.1. Brevity of Duration

A central idea regarding short-term memory was that information would be available only for a very brief period if it were not rehearsed. An experimental technique for studying short-term memory called the **Brown-Peterson task** was developed to test that idea (Brown, 1958; Peterson & Peterson, 1959). Participants are typically given a string of three consonants to memorize and then prevented from engaging in active rehearsal (that is, from saying the consonants to themselves), perhaps by being asked to count from 100 backward by 3s. After variously set delays, participants would be asked to recall the string. Measuring recall accuracy in relation to the delay

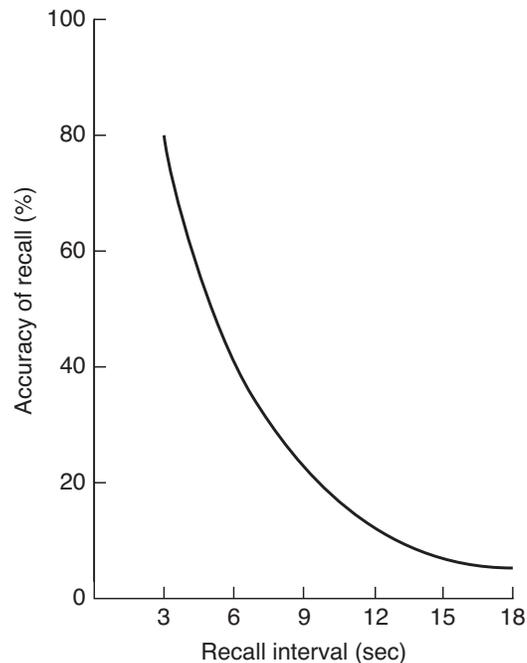


FIGURE 6–2 Short-term recall related to delay interval in the Brown-Peterson task

Typically, accuracy in recalling short consonant strings decays to about 50 percent by 6 seconds and almost to zero by 18 seconds if rehearsal is blocked.

(Peterson, L. R., and Peterson, M. J. (1959). Short-term retention of individual verbal items. *Journal of Experimental Psychology*, 58, 193–198, Fig. 3, p. 195 [adapted].)

interval showed the time course of forgetting. After a delay as short as 6 seconds, recall accuracy declined to about 50 percent, and by about 18 seconds recall was close to zero (Figure 6–2). These findings suggested the shortness of short-term storage. (About this time investigations were also being conducted on an even briefer form of storage—termed *sensory memory*—that serves to keep a perceptual representation of a stimulus persisting for a few hundred milliseconds after the sensory input is gone; Sperling, 1960.)

However, in work that followed, a controversy arose as to whether the forgetting of information was truly due to a passive decay over time, or rather due to interference from other, previously stored information (similar to the controversy regarding long-term memory, discussed in the previous chapter). The argument favoring the role of interference was bolstered by the fact that participants' recall performance tended to be much better in the first few trials of the task (when proactive interference from the earlier trials had not yet built up). Moreover, if a trial was inserted that tested memory for a different type of information than that sought in the previous trials (for example, switching from consonants to vowels), participants' recall performance greatly increased on the inserted trial (Wickens et al., 1976). The debate over whether information is lost from short-term memory because of decay, in addition to interference, has not been resolved, and the question is still studied today (Nairne, 2002).

2.2.2. Ready Accessibility

The high level of accessibility of information stored in short-term memory was demonstrated in a classic set of studies conducted by Saul Sternberg (1966, 1969a), which we briefly considered in Chapter 1. We now consider these findings in greater detail. A variable number of items, such as digits (the memory set), were presented briefly to participants at the beginning of a trial and then removed for a minimal delay. Following the delay, a probe item appeared and participants were to indicate whether or not the probe matched an item in the memory set. The time required to respond should reflect the sum of four quantities: (1) the time required to process the probe item perceptually, (2) the time required to access and compare an item in short-term memory against the probe item, (3) the time required to make a binary response decision (match–nonmatch), and (4) the time required to execute the necessary motor response. Sternberg hypothesized that as the number of items in the memory set increased, the second quantity—the total time required for access and comparison—should increase linearly with each additional item, but the other three quantities should remain constant. Thus, Sternberg hypothesized that when the response time was plotted against the number of memory set items, the result would be a straight line on the graph. Moreover, the slope of that line should reveal the average time needed to access and compare an item held in short-term memory. The results were as predicted—the plotted data formed an almost perfect straight line, and the slope indicated an access plus-comparison time of approximately 40 milliseconds (Figure 6–3). The hypothesis that information held in short-term memory could be accessed at high speed was certainly borne out by these findings.

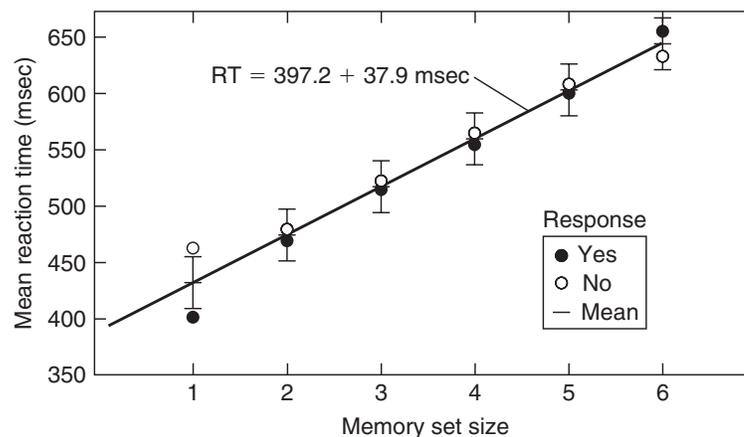


FIGURE 6–3 Recognition time related to memory set size in the Sternberg item recognition task

As the number of items to be memorized—the memory set size—increases from one to six, the time to evaluate a probe increases in a linear manner with about a 40-millisecond increase per additional item. The best-fitting line for the data obtained is plotted here; it is very close to the actual data points.

(Sternberg, S. (1969). The discovery processing stages: Extension of Donders' method. In W. G. Koster (ed.), *Attention and Performance II*. Amsterdam: North-Holland.)

More recent work, however, has called into question the fundamental assumption underlying Sternberg's interpretation of the results of this experiment: that short-term memory scanning proceeds sequentially, one item at a time. In particular, as discussed in Chapter 1, sophisticated mathematical modeling techniques show that similar linear curves could be found from a parallel scanning process that accesses all items simultaneously. In some of these models, the increase in response times is due to the decreasing efficiency of the parallel process as the number of items held in short-term memory increases (McElree & Doshier, 1989; Townsend & Ashby, 1983). But even assuming parallel scanning, the time to access information in short-term memory is very short indeed. Thus, even the more recent accounts retain the basic idea that information held in short-term memory is very quickly accessible.

2.3. The Atkinson-Shiffrin Model: The Relationship of Short-Term and Long-Term Memory

The notion that short-term and long-term memory are distinct modes of storing information was further articulated in the model proposed by Richard Atkinson and Richard Shiffrin (Figure 6–4) (Atkinson & Shiffrin, 1968). In this model, short-term memory serves as the gateway by which information can gain access to long-term memory. The function of short-term memory is to provide a means of controlling and enhancing, via rehearsal and coding strategies (such as chunking), the information that makes it into long-term memory. The [Atkinson-Shiffrin](#)

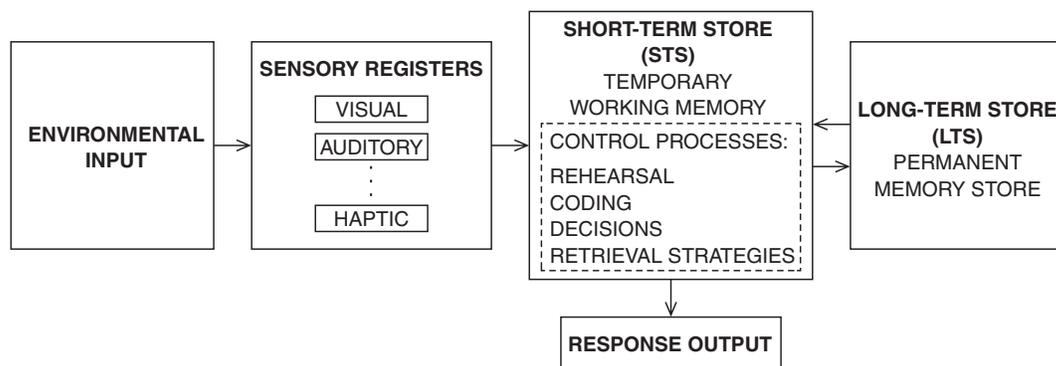


FIGURE 6–4 The Atkinson-Shiffrin model of memory

This model, also termed the modal model, suggests that the flow of information from sensory input to long-term memory must first pass through short-term memory. Information from the environment is registered by sensory receptors—visual, auditory, haptic (relating to touch), and others—and passed to short-term memory. Here it is rehearsed or otherwise manipulated before entering long-term memory; here also are strategies for retrieving information from long-term memory.

(R. C. Atkinson and R. M. Shiffrin, "The control of short-term memory." *Scientific American*, Aug. 1971, Vol. 225, No. 2. Reprinted with permission.)

model was highly influential because it laid out a comprehensive view of information processing in memory. In a nod to the statistical notion of the mode, it is still referred to as the **modal model** of memory, the model most frequently cited.

Yet today the modal model does not have the influence it once had, and most psychologists favor a different conceptualization of short-term storage, one that is not exclusively focused on its relationship to long-term storage and includes a more dynamic role than storage alone. This shift was reflected in the increasing use of the term “**working memory**” which better captures the notion that a temporary storage system might provide a useful workplace in which to engage in complex cognitive activities.

What caused this shift in perspective? For one thing, the Atkinson-Shiffrin model is essentially sequential: information passes through short-term memory before entering long-term memory. But neuropsychological data were showing that this assumption is not correct. Some patients with brain damage (typically to the parietal lobe) who showed drastic impairments in short-term memory nevertheless were able to store new information in long-term memory in a fashion comparable to that of neurologically healthy people (Shallice & Warrington, 1970). This finding demonstrated that information can gain access to the long-term memory system even when the short-term memory system was dramatically impaired. The Atkinson-Shiffrin model could not account for this result: with a poorly functioning short-term memory, according to Atkinson-Shiffrin, long-term storage should also be impaired.

Another strand of evidence, from behavioral experiments with neurologically healthy people, suggested that there is not a single system for short-term storage but multiple ones. Alan Baddeley and Graham Hitch (1974) asked participants to make simple true–false decisions about spatially arrayed letters: for example, shown “B A” they were to decide whether the statement “B does not follow A” was true or false. Before each trial, the participants were *also* given a string of six to eight digits (which according to Miller should fill the capacity of short-term memory) to repeat immediately after each true–false task. If the short-term memory store is critical for performing complex cognitive tasks and there is only one short-term store available, then performance on the reasoning task should drastically decline with the addition of the digit-memorization task. However, this was not the case. The participants took slightly longer to answer questions but made no more errors when also holding digit strings in short-term memory. From these results Baddeley and Hitch argued that there are multiple systems available for short-term storage and that these storage systems are coordinated by the actions of a central control system that flexibly handles memory allocation and the balance between processing and storage.

2.4. The Baddeley-Hitch Model: Working Memory

The dynamic concept of “working memory”—as opposed to the passive nature of a simple information store—is at the heart of the **Baddeley-Hitch model**, a system that

consists of two short-term stores and a control system. Three important characteristics differentiate this model from the Atkinson-Shiffrin model.

First, the function of short-term storage in the Baddeley-Hitch model is not primarily as a way station for information to reside en route to long-term memory. Instead, the primary function of short-term storage is to enable complex cognitive activities that require the integration, coordination, and manipulation of multiple bits of mentally represented information. Thus, in the “A–B” reasoning problem described earlier, working memory is required to (1) hold a mental representation of the two letters and their spatial relationship to each other, (2) provide a workspace for analyzing the statement “B does not follow A” and deciding that it implies that “A follows B,” and (3) enable comparison of the mental representations of the letters and statement.

Second, in the Baddeley-Hitch model there is an integral relationship between a control system—a **central executive**—that governs the deposition and removal of information from short-term storage and the storage buffers themselves. This tight level of interaction is what enables the short-term stores to serve as effective workspaces for mental processes.

Third, the model proposes (as implied earlier) at least two distinct short-term memory buffers, one for verbal information (the **phonological loop**) and the other for visuospatial information (the **visuospatial scratchpad**). Because these short-term stores are independent, there is greater flexibility in memory storage. Thus, even if one buffer is engaged in storing information, the other can still be utilized to full effectiveness. The supervision of these storage systems by a central executive suggests that information can be rapidly shuttled between the two stores and coordinated across them.

The three components of the Baddeley-Hitch model interact to provide a comprehensive workspace for cognitive activity (Figure 6–5). Applying the terms of the Baddeley-Hitch model to the “A–B” task, the phonological loop was occupied storing the digits, and the visuospatial scratchpad did much of the cognitive work in evaluating the spatial relationships in the true–false task. Coordination was supplied by the central executive, which transformed information from reading the statement (essentially in the verbal store) into a mental image on the visuospatial scratchpad. These interactions meant that performance on the reasoning task did not decline greatly when digit memorization was added.



FIGURE 6–5 The Baddeley-Hitch model of working memory

Two distinct storage buffers, one for verbal and the other for visuospatial information, interact with a central executive controller.

(Baddeley, A. D., and Hitch, G. J. (1974). Working memory. In G. Bower (ed.), *The psychology of learning and motivation* (Vol. VIII, pp. 47–89). New York: Academic Press. Reprinted with permission from Elsevier.)

The Baddeley-Hitch model was a major departure from earlier theories about short-term memory in that it emphasized neither its duration nor its relationship to long-term memory, but rather its flexibility and critical importance to ongoing cognition. In the years since his first work on the model, Alan Baddeley has been a major figure in working memory research, continuing to elaborate on the initial conception of the working memory model and providing a great deal of experimental support for its validity and usefulness.



Comprehension Check:

1. What evidence suggested that information in short-term memory is very quickly accessible?
2. What distinguishes the Baddeley-Hitch model of working memory from the Atkinson-Shiffrin model?

3. UNDERSTANDING THE WORKING MEMORY MODEL

Baddeley's conceptualization of working memory is still highly influential and serves as a source of an enormous amount of research. The initial idea of a central controller interacting with dual short-term memory buffers has been retained over the years, and certain aspects of the model have been further elaborated by the work of a number of investigators. In particular, intense research has focused on storage within verbal working memory—the phonological loop—because so much of everyday cognition (especially for students and academics!) seems to rely on this cognitive function.

3.1. The Phonological Loop: When It Works and When It Doesn't

Read the digits below to yourself and then, immediately, close your eyes and try to remember the digits, silently. After a few seconds, repeat them aloud.

7 5 9 4 1 3 2

How did you do in recalling the numbers accurately? It's no coincidence that there were seven digits in the series. The demonstration was meant to mimic the ordinary experience of hearing and remembering a telephone number.

How did you accomplish the task? Many people report that when they read the digits silently they “hear” them in their head, in the sound of their own voice. Then, when their eyes are closed, they “rehearse” the sounds, repeating the words silently to themselves. The subjective experience seems to be of speaking the digits “in your mind.” Does this experience match yours?

The idea that verbal working memory involves both a “mind's ear” (that heard the digits when you read them) and a “mind's voice” (that repeated them in rehearsal) is central to current thinking about the phonological loop. It has been

proposed that the phonological loop system involves two subcomponents: a *phonological store* and an *articulatory rehearsal* process (Baddeley, 1986). When visually presented verbal information is encoded, the information is transformed into a sound-based, or “auditory-phonological,” code. This code is something like an internal echo-box, a repository for sounds that reverberate briefly before fading away. To prevent complete decay, an active process must refresh the information, and this is where the idea of a “loop” comes in. The active refreshment comes via **articulatory rehearsal**, as you voice internally the sounds you heard internally. (The process seems very like our ability to “shadow”; that is, to repeat quickly something that we hear, whether or not we understand it—an indication that the phonological loop may be involved in language learning.) Once the verbal information is spoken internally by the mind’s voice in rehearsal, it can then be again heard by the mind’s ear and maintained in the **phonological store**. In this way a continuous loop plays for as long as the verbal material needs to be maintained in working memory. The first step of the process—translation into a phonological code—is of course necessary only for visually presented material. For auditory information, such as speech, initial access to the phonological store is automatic.

This idea sounds intuitive, because the experience of this kind of internal rehearsal seems universal, and that has been part of its appeal. For example, in your conversation about the movie, it is likely that you would be using the phonological loop to rehearse the key points you want to make and also time-sharing this same system to help process your friend’s speech.

It is significant that this description of the phonological loop component of verbal working memory includes a number of characteristics that should be testable. First, verbal working memory capabilities should depend on the level of difficulty of both “phonological processing” (translating verbal information into a sound-based code) and “articulatory processing” (translating verbal information into a speech-based code). Second, because working memory is flexible, performance on verbal working memory tasks will not be catastrophically disrupted if for some reason the phonological loop component is unusable: in that case, other components, the central executive and the visuospatial scratchpad, kick in. Thus, in your movie conversation, if verbally processing your friends’ ideas temporarily uses up too much capacity of the phonological loop, you might be able to use the visuospatial scratchpad to rehearse your ideas, possibly by using visual mental imagery—forming a mental image of your ideas rather than thinking of them in verbal terms. Third, the phonological loop model suggests that the two primary components of verbal working memory—phonological storage and articulatory rehearsal—are subserved by functionally independent systems, and hence should be dissociable. All these hypotheses have been tested in experiments, and all have held up.

Behavioral studies have suggested that phonological and articulatory factors significantly affect verbal working memory performance. One example is the **phonological similarity effect**: when items simultaneously stored in working memory have to be serially recalled, performance is significantly worse when the items to be

maintained are phonologically similar—that is, when they sound the same (Conrad & Hull, 1964). The effect is thought to be caused by confusions that arise when similar sound-based codes are activated for the different items in the phonological loop. This finding can easily be informally appreciated. Try holding these two strings of letters in working memory, one after the other:

D B C T P G K F Y L R Q

In the first string, the letters all have the “ee” sound; in the second list, all the letter sounds are distinct. Which did you find easier to remember and repeat? In these tasks, the typical error is substituting a phonologically similar item, such as “V” for “G.”

The other part of the phonological loop, articulatory processing, or the “speaking” of presented items by the inner voice, is reflected in the **word-length effect**. Performance on a recall task is worse when the items to be maintained are long words, such as *university*, *individual*, and *operation*, than short words, such as *yield*, *item*, and *brake*. The key factor seems not to be the number of syllables per se, but rather the time it takes to pronounce them: performance is worse for two-syllable words that have long vowel sounds, such as *harpoon* and *voodoo*, than for two-syllable words with short vowel sounds, such as *bishop* and *wiggle* (Baddeley et al., 1975). The phonological loop model accounts for the word-length effect by the assumption that pronunciation time affects the speed of silent rehearsal, which requires speech-based processing. The longer it takes to rehearse a set of items in working memory, the more likely those items will have been dropped from the phonological store.

The relationship between pronunciation time and working memory performance was further tested in a study involving children bilingual in Welsh and English (Ellis & Hennelly, 1980). The names of the digits in Welsh have the same number of vowels as the English names but generally have longer vowel sounds and consequently take longer to say. As predicted, when performing digit-span tests in Welsh, the children scored significantly below average norms. However, when they performed the tests again in English their scores were normal. Follow-up studies have confirmed that the faster an individual’s speech rate, the more items can be recalled correctly from working memory (Cowan et al., 1992).

What happens when the normal operation of the phonological loop is disrupted? The Baddeley-Hitch model suggests that the central executive and the visuospatial scratchpad take over and with the phonological loop out of operation phonological similarity and word length should no longer have an effect on working memory. Can this hypothesis be tested? Yes, by experiments based on dual-task interference. Participants are asked to maintain visually presented words in working memory while simultaneously producing overt and irrelevant speech, a task that interferes with phonological processing and rehearsal of the information. (Imagine that, in your movie conversation, while you are trying to keep in mind the point you want to make you also have to say the word *the* over and over again out loud; you can see how such conditions might make it almost impossible

to rehearse your thoughts). Under these conditions, termed **articulatory suppression**, performance is significantly, although not catastrophically, impaired (demonstrating that although working memory is partially disrupted, it is still working). But critically, neither the phonological similarity nor the word length effect is present—which is as predicted because these effects are thought to be due to the phonological loop, which is rendered useless by the conditions of the experiment (Baddeley, 1986; Baddeley et al., 1984).

Converging evidence for the phonological loop model has come from the results of studies of patients with brain damage. One of them, P.V., was a woman, then 28 years old, who had suffered a stroke that damaged a large extent of her left hemisphere, especially the cortical regions thought to be involved in language processing (Basso et al., 1982; Vallar & Baddeley, 1984; Vallar & Papagno, 1986). Despite this damage, a number of P.V.'s language processing abilities remained intact. For example, she could clearly perceive and comprehend spoken speech. Nevertheless, P.V. suffered a dramatic decline in performance on verbal working memory tasks, especially those involving auditorily presented information. P.V.'s poor auditory verbal working memory—she had a span of only about two items—might be expected if the damage to her brain had selectively targeted the phonological loop; if that were the case, she would have become more reliant on the visuospatial scratchpad in attempting verbal working memory tasks.

And in fact, when performing verbal working memory tasks with visually presented items, P.V. showed no evidence of word-length effect or phonological similarity effect, thus suggesting that the visuospatial scratchpad rather than the phonological loop was engaged for storage. But for auditorily presented information the scratchpad is not much help: the information would first have to be processed phonologically before it could be translated to a visuospatial code. When doing tasks with auditorily presented words, P.V. did show a phonological similarity effect but no word-length effect. This suggested that P.V. was forced to use the phonological buffer—which was why she showed a phonological similarity effect—but because this buffer was defective, the information could not be appropriately transferred to the articulatory rehearsal system—which was why she did not show a word-length effect.

A number of patients have been identified who, like P.V., have selective auditory-verbal short-term memory deficits. Their common pattern of deficits and area of brain damage suggest that the phonological store component of verbal working memory has been damaged in these patients, and that this component relies on the left inferior parietal cortex (Vallar & Papagno, 1995).

Is there evidence that storage and rehearsal are functionally independent processes, as predicted by the phonological loop model? It should be possible to determine functional independence based on patterns of behavioral performance. If word length (which affects rehearsal) and phonological similarity (which affects storage) target independent components of the phonological loop, then manipulations of word length and phonological similarity should not interact with each other. That is exactly what behavioral studies showed: the magnitude of the phonological

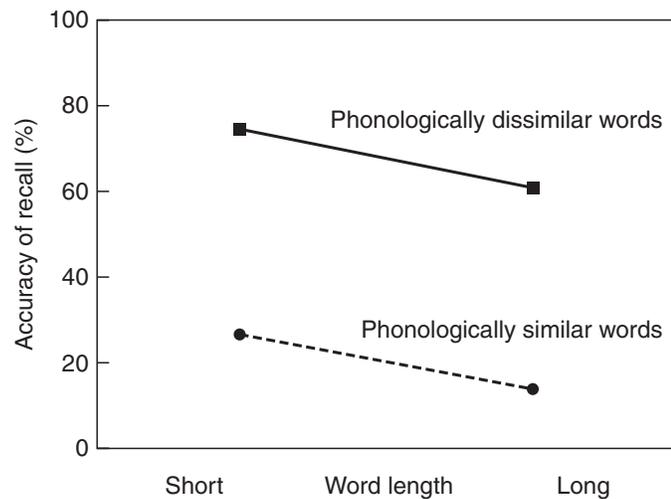


FIGURE 6–6 Independence of the effects of word length and phonological similarity

An immediate recall task presented participants with five words that were either phonologically similar (such as FASTER, PLASTER, MASTER, TASTER, and LASTED) or dissimilar (such as FAMOUS, PLASTIC, MAGIC, TEACHER, and STAYED), and were either short (two syllables) or long (four syllables). Both similarity and greater word length decreased recall performance, but the parallel slopes of the lines indicate that the two effects are independent.

(Adapted from Longoni, A. M., Richardson, J. T. E., and Aiello, A. (1993). Articulatory rehearsal and phonological storage in working memory. *Memory and Cognition*, 21(1), 11–22. Reprinted with permission.)

similarity effect on performance was not influenced by word length, and vice versa (Figure 6–6) (Longoni et al., 1993).

Of course, behavioral data can provide only one kind of evidence for functional independence. Results from brain-based studies provide a different kind of evidence, showing that separate systems support phonological storage and rehearsal.

On the one hand, studies of patients with brain damage have documented a relationship between left inferior parietal damage and phonological storage impairments, and a relationship between left inferior frontal cortex damage and articulatory rehearsal impairments (Vallar & Papagno, 1995). (The left inferior frontal cortex, also referred to as Broca's area, is known to be involved with language.) On the other hand, neuroimaging studies have provided a means to examine these relationships in neurologically healthy participants. Such studies can show whether these brain regions are in fact the ones engaged during normal processing conditions. For example, participants in one study were asked to memorize a series of six visually presented items, either six English letters or six Korean language characters (none of the participants were speakers of Korean) (Paulesu et al., 1993). The researchers assumed that the phonological loop system would be engaged to maintain the English letters but not utilized for the Korean characters (because the sounds represented by the characters were unknown to the participants). This assumption was validated by testing the effects of articulatory suppression—as

expected, articulatory suppression impaired memory performance for the English letters, but had no effect on memory for the Korean letters. PET images revealed increased blood flow in both left inferior parietal cortex (storage) and left inferior frontal cortex (rehearsal) only for the English letters. It is interesting that activation was also observed in brain structures associated with motor-related components of speech, even though the task did not require participants to speak overtly. The speech-related brain activity was thus thought to represent “internal speech” or subvocal rehearsal.

In a second experiment, Paulesu and colleagues (1993) attempted to dissociate regions associated with phonological storage from those involved in rehearsal. They asked the same participants to perform rhyme judgments on the English letters, deciding whether each letter in turn rhymed with “B.” Here the researchers assumed that the rhyme task would engage rehearsal but not storage, and so it proved. In contrast to the results for the English letter group in the first experiment, in which there was increased blood flow in both brain regions, this time only the left frontal cortex was activated; the left parietal cortex was not active above baseline (Figure 6–7b on Color Insert I). Thus, behavioral and neuroimaging results converge to establish the dissociability of the storage and rehearsal components of verbal working memory.

However, additional neuroimaging studies suggest a more complex picture. For example, different subregions of Broca’s area (which is crucially involved in producing speech) appear to be engaged at distinct points in time during the delay period of working memory tasks (Chein & Fiez, 2001). The investigators argue that the more dorsal region of Broca’s area is active only during the first part of the delay period, and is involved in the formation of an articulatory rehearsal program; in contrast, the more ventral region of Broca’s area is active during the remainder of the delay period, and is involved with the act of rehearsal itself. Neuroimaging studies continue to play an important role in refining and reshaping the verbal working memory model.

The larger question is what is the true function of the phonological loop in cognition? Surely it did not arise just to help us retain letter strings or telephone numbers! It seems intuitive that the phonological loop would have to play some role in language processing, because it is so clearly integrated with language comprehension and production systems. One hypothesis is that working memory—specifically, the phonological loop—is not critical for *comprehension* of familiar language, but it is essential for *learning* new language (Baddeley et al., 1998), a challenge experienced both by children learning their first language and by adults learning a second one or acquiring new vocabulary. It may be that evolution has imbued us with a specific expertise in repeating what we hear, even if we don’t initially understand it. This form of imitation is something that even young infants can do, and it may provide a means for helping us learn new words via a linkage of sound and meaning.

Developmental data strongly support this claim: the level of children’s ability to repeat nonwords strongly predicts the size of their vocabulary one year later (Gathercole & Baddeley, 1989). The patient P.V. was found to be completely unable to learn the Russian equivalent of any words in her native Italian despite extensive practice (Baddeley et al., 1988). Yet she could learn a novel association

between two Italian words, indicating that her general learning abilities were intact when dealing with items that were phonologically familiar to her. But her impairment prevented her from being able to accomplish the short-term storage of phonologically unfamiliar items (in her case, Russian words) that apparently is needed to accomplish longer term learning. Thus, the data support the idea that the phonological loop has a primary function as a language-learning device, but that this functionality can be exploited to support a wide range of verbal working memory tasks.

3.2. The Visuospatial Scratchpad

Think of a familiar room (not the one you're in now!). What objects are on the walls? Name them in order, starting from the door and moving clockwise around the room. Now ask yourself, did you do this by “looking around your room with your mind’s eye”? If so, you have just engaged your visuospatial scratchpad.

The ability to develop, inspect, and navigate through a mental image is thought to be a cardinal function of visuospatial working memory. (See Chapter 4 for a more extensive discussion of imagery.) A classic experimental study examined these memory functions by having participants answer questions about an outlined capital letter (Figure 6–8a) (Brooks, 1968). Participants were instructed to form a visual mental image of the letter and then navigate around it. At each corner, they had to answer yes or no to the question, is this corner at the extreme top (or extreme bottom)

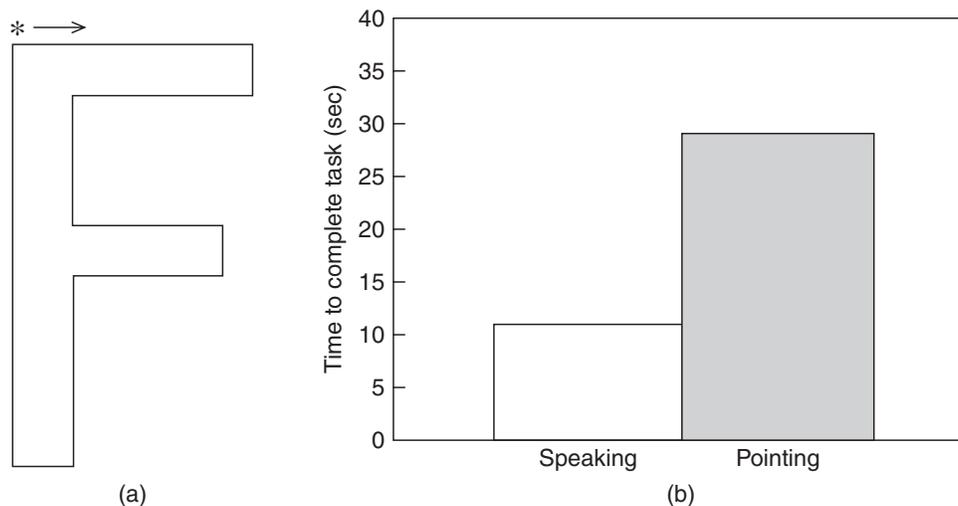


FIGURE 6–8 A visuospatial imagery and interference task

(a) As participants mentally navigated around the figure, starting at the asterisk, they were to answer yes or no questions about each corner as they reached it. (b) The time to respond was considerably longer when participants had to point to a printed YES or NO than when they spoke their responses, suggesting that the spatial movements interfered with the mental navigation.

(Brooks, L. R. (1968). Spatial and verbal components in the act of recall. *Canadian Journal of Psychology*, 22, 349–368.)

of the letter? To test whether the participants were using visuospatial representations to do the task, some participants were instructed to point to the word YES or NO printed irregularly on a page, and others had to speak the words “yes” or “no.” The hypothesis was that if the classification decision depended on visuospatial representations, then requiring the pointing—a visuospatially based response—would interfere with performance. This is exactly what was found; participants took almost three times as long to perform the task when they had to point in response than when they had to speak (Figure 6–8b).

These results, and those of many other studies that followed, suggest that mental navigation is an inherently spatial process (Logie, 1995). The subjective experience of moving the mind’s eye from one spatial location to another also suggests the possibility that visuospatial working memory depends on brain systems that plan movements of the eyes (or possibly other parts of the body), just as verbal working memory depends on brain systems involved with planning speech (Baddeley & Lieberman, 1980). Interestingly, this movement planning system might also be the basis for **spatial rehearsal**, the process of mentally refreshing stored locations to keep them highly accessible. The idea is that when you rehearse spatial locations in working memory (think of mentally visualizing driving directions to turn left at the next block, and then right at the stoplight), you are actually utilizing the same systems that would help you move your eyes or body toward that location. And just as rehearsal of verbal information does not require actual speech, it is thought that rehearsal of spatial information does not require actual eye (or body) movements. Instead, spatial rehearsal may involve *covert* shifts of attention to memorized spatial locations (Awh & Jonides, 2001).

In other words, just as we can keep our attention focused on a place in space without actually physically looking at it, we might also be able to keep remembered locations in memory by covertly focusing our attention on those remembered locations. An example: think of being at a party and talking with one friend, keeping your eyes focused on him, while also paying attention, out of the corner of your eye, to the gestures of another friend to your left.

This analogy leads to concrete predictions. It is thought that paying attention to a spatial location will enhance perceptual processing at that location. If the systems for spatial working memory are the same as those for spatial attention, then keeping a particular location in spatial working memory should also enhance perceptual processing of visual information that is physically presented at the remembered location. This prediction was tested behaviorally (Awh et al., 1998). In a spatial working memory task single letters (the cues) were briefly presented in varying locations on a display; after a short delay, another letter (the probe) was presented. In one condition, participants had to remember the location of the cue, and to decide whether the probe was in the same location. In another condition, it was the identity of the letter cue that had to be maintained, and participants had to decide whether the probe had the same identity. Additionally, during the delay participants had a second task—to classify the shape of an object appearing at different locations. On some trials the object appeared in the same location as the letter cue that was being maintained. It was found that the shape-classification decision was made more quickly when the shape’s location matched that of the cue, but only when the

information being maintained was the location of the cue. This result suggested that maintaining a location in working memory facilitates the orienting of attention to that location (which is what improved the speed of the shape-classification task).

Neuroimaging studies have provided even stronger evidence that rehearsal in spatial working memory and spatial selective attention draw on at least some of the same processes, by demonstrating that they both rely on the same right-hemisphere frontal and parietal cortex brain regions. Maintaining a spatial location in working memory produced enhanced brain activity in visual cortex regions of the opposite hemisphere, as expected because of the contralateral organization of these brain regions (Figure 6–9 on Color Insert J) (Awh & Jonides, 2001; Postle et al., 2004). These results suggest that spatial working memory is accomplished by enhancing processing in brain regions that support visual perceptual processing of those locations.

As the compound nature of its name implies, information processed by the visuospatial scratchpad is of two sorts: spatial, like the arrangement of your room, and visual, like the face of a friend or the image of a favorite painting. It seems that different types of codes may be required to maintain these two types of nonverbal information on the visuospatial scratchpad. For example, we seem to have the ability to “zoom in” on images like faces and paintings, magnifying particular features (Kosslyn, 1980). And we are able to decompose objects into constituent parts and transform them. We can, for example, imagine how a clean-shaven friend would look with a beard. These mental operations seem to be inherently nonspatial, yet nevertheless they require an accurate visual representation to be maintained and manipulated within working memory. Thus, visuospatial working memory may be composed of two distinct systems, one for maintaining visual object representations and the other for spatial ones.

The distinction between object and spatial processing is clearly in line with observations about the visual system: there is a great deal of evidence for distinct neural pathways involved in processing spatial and object visual features (respectively, the dorsal “where” and ventral “what” pathways) (Ungerleider & Mishkin, 1982; see discussion in Chapter 2). In monkeys it has been found that this distinction is also present for working memory: neurons in the dorsal region of the prefrontal cortex respond especially strongly to stimuli during a spatial working memory task, whereas neurons in the ventral prefrontal cortex respond especially strongly during an object working memory task (Wilson et al., 1993). In humans, some patients with brain damage have shown selective impairments on nonspatial mental imagery tasks (for example, making judgments about the shape of a dog’s ears), but not on those involving spatial imagery (for example, rotating imagined objects) (Farah et al., 1988). The reverse pattern has been observed with other patients, demonstrating a double dissociation (Hanley et al., 1991). Neuroimaging studies have also tended to show dissociations between brain systems involved in spatial and in object working memory (Courtney et al., 1996; Smith et al., 1995), although these dissociations have been most reliable in posterior rather than prefrontal cortex (the region identified in monkey studies) (Smith & Jonides, 1999). The specific characteristics of object working memory, such as whether or not it involves a distinct storage buffer or rehearsal system, are not yet well worked out, and the question of a dissociation of object and spatial working memory remains a topic of continued study.

3.3. The Central Executive

The component that most strongly differentiates the idea of working memory from the earlier conceptions of “short-term memory” is the *central executive*. This part of the model (1) determines when information is deposited in the storage buffers; (2) determines which buffer—the phonological loop for verbal information or the visuospatial sketchpad for visual—is selected for storage; (3) integrates and coordinates information between the two buffers; and, most important, (4) provides a mechanism by which information held in the buffers can be inspected, transformed, and otherwise cognitively manipulated. These functions all depend on the central executive’s controlling and allocating attention. The central executive determines both how to expend cognitive resources and how to suppress irrelevant information that would consume those resources (Baddeley, 1986). The central executive is what does the “work” in working memory. (And it does more; in fact, many of the functions associated with the central executive may be only indirectly related to working memory itself. See Chapter 7 for a discussion of the role of the central executive in other contexts.)

The notion of a central executive is supported by studies that show a dissociation between the functions listed above and the operation of the two storage systems. These investigations often involve the problem of **dual-task coordination**, that is, the process of simultaneously performing two distinct tasks, each of which typically involves storage of information in working memory. Participants are given two such tasks, one visuospatial and one auditory-verbal, to perform at the same time. (An example would be doing the “corners-of-the-F” task shown in Figure 6–8 while quickly repeating spoken words.) The assumption is that managing performance of the two tasks requires some sort of time-sharing. If the central executive is specifically required to manage the coordination—the time-sharing—of the two tasks, then it should be possible to find effects of dual-task performance over and above those present when each of the tasks is performed in isolation.

For example, one study examined patient groups with cognitive deficits, matching patients with early-stage Alzheimer’s disease with healthy adults of the same age (Baddeley et al., 1991). The hypothesis was that much of the cognitive impairment exhibited by people in early stages of Alzheimer’s disease is due to a dysfunctional central executive. In the single-task phase, participants performed each of two tasks, one auditory and one visual, separately. In the dual-task phase, participants performed the two tasks simultaneously. An important feature of the study was that the difficulty of each task could be adjusted for each participant individually to enable him or her to reach a fixed level of behavioral performance. Because all participants had the same level of single-task accuracy, any decrements in performance on the dual-task condition could not be attributable to difficulties in single-task performance. The results were clear in showing that the Alzheimer’s patients were markedly worse than the healthy participants in the dual-task condition. The results support the idea that the coordination of storage demands requires the engagement of the central executive.

Neuroimaging studies as well as behavioral ones have explored whether executive functions can be distinguished from short-term storage. One test has been to compare

DEBATE

How Are Working Memory Functions Organized in the Brain?

The Baddeley-Hitch model of working memory suggests distinctions both in terms of the buffers used to store different kinds of information (verbal or visuospatial) and in terms of different working memory processes (storage or executive control). How do these distinctions map onto brain organization? Findings in both neuroimaging studies in humans and neural recording studies in monkeys suggest that the prefrontal cortex is an important component of working memory. Yet these studies appear to suggest differences in the way that prefrontal cortex is organized with respect to working memory.

In the monkey work, neurons in dorsal areas of prefrontal cortex were found to be specialized for spatial working memory, whereas ventral prefrontal cortex neurons were specialized for object working memory (Wilson et al., 1993). Thus, the monkey results suggested a **content-based organization** of working memory in prefrontal cortex; that is, spatial and object information is maintained in different regions. However, the neuroimaging data in humans have not reliably supported such distinctions in the location of prefrontal cortex activity based on the content of working memory. Instead, the neuroimaging data have tended to find that dorsal prefrontal cortex is engaged by working memory tasks that require manipulation in addition to maintenance, whereas ventral prefrontal cortex is active even when the task requires only simple maintenance. Thus, it has been argued that the human neuroimaging data support a **process-based organization** (that is, storage and executive control processes are carried out in different regions). The resolution to the controversy is not yet clear, but some researchers have suggested that the two sets of findings may not be incompatible (Smith & Jonides, 1999).

maintenance versus *manipulation* in working memory, contrasting the brain activity occurring in tasks where the information only has to be briefly stored and then recalled (maintenance) against a similar task in which the stored information also has to be mentally transformed in some way (manipulation). Significantly increased activation was observed when participants in such a study had to recall a sequence of letters in alphabetical order, as opposed to simply recalling them in the order in which they were presented (D'Esposito et al., 1999). A further point: the increased activation was observed in the dorsal regions of the prefrontal cortex. This result, and others, suggest that different portions of the prefrontal cortex implement different processes used in working memory: specifically, simple maintenance recruits ventral regions of prefrontal cortex, and information is manipulated in more dorsal areas (Figure 6–10 on Color Insert K) (Owen, 1997; Postle & D'Esposito, 2000). However, this view remains controversial; see the accompanying *Debate* box.

3.4. Are There Really Two Distinct Storage Systems?

It seems obvious that we use distinct mental representations codes for verbal and visual information while we perform tasks. But what about the storage of such information? Must verbal and visual information be maintained in two distinct buffers, as

the working memory model has it—could they not be maintained in one? Alternatively, might there not be a multitude of buffers, each specialized for a distinct type of information? A number of theorists have proposed many-store accounts (Miyake & Shah, 1999), and this question is unresolved. Nonetheless, there is fairly good experimental evidence in favor of the distinction between verbal and visuospatial working memory.

Many of the behavioral studies demonstrating dissociations between the two working memory systems involve the dual-task methodology, and the results demonstrated the selective nature of interference with working memory. As we have seen, performance on the F-task (with participants instructed to respond verbally or by pointing) was better when participants could respond verbally. When participants then had to make judgments about words in a sentence, pointing produced the better performance (Brooks, 1968). In another study, participants were similarly asked to make judgments about words in a sentence, in this case while either manually tracking a light or repeating the word *the* over and over. The pattern of results was the same as in the F-task: when the interference with this verbal task was verbal, performance was more impaired than when the interference was spatial (Baddeley et al., 1973). The implication? Competition between two verbal (or two spatial) tasks produced more-impaired performance, which is evidence for separate resources or stores for each type of information.

Neuropsychological data support the functional and structural independence of visuospatial and verbal working memory, such as was seen with P.V., whose working memory, poor for spoken words, improved considerably when the test items were presented visually (Basso et al., 1982). P.V., and other patients with similarly impaired verbal working memory, had brain damage involving the left hemisphere. Patients have been studied who show the opposite pattern of deficits—selectively impaired visuospatial working memory (De Renzi & Nichelli, 1975)—and in these instances the brain damage involved the right hemisphere. Thus, the neuropsychological data are consistent with the idea that verbal and visuospatial working memory rely on distinct brain systems.

Moreover, neuroimaging studies have demonstrated dissociations between the two working memory systems in neurologically healthy participants. Many of these studies have also pointed to a pattern in which verbal working memory is associated with the left hemisphere, nonverbal working memory with the right (Smith et al., 1996). This fits the general finding that language-related functions are more associated with the left hemisphere of the brain, whereas spatial processing is more associated with the right. The neuroimaging studies have also indicated that the picture might be a bit more complicated than is indicated by the behavioral and neuropsychological investigations. Many of the working memory tasks that have been studied with neuroimaging involve storage over longer intervals, keeping track of temporal order, and maintenance in the face of distracting information. In these complex tasks, the brain areas activated by verbal and visuospatial working memory tend to be highly overlapping (D'Esposito et al., 1998; Nystrom et al., 2000). So the picture is more complicated, but not necessarily contradictory. Perhaps under more difficult conditions all parts of the working memory system are recruited to perform the task most effectively.

This kind of flexible use of the storage buffers—with their deployment controlled by the central executive—is a key characteristic of the working memory model.

✓ Comprehension Check:

1. What evidence suggests that working memory depends on both phonological processing and articulatory processing?
2. What working memory functions are thought to be handled by the central executive?

4. HOW WORKING MEMORY WORKS

We have looked at the boxes in the working memory model, which are the storage systems and the central executive; much of the research we have discussed provides evidence that these components are distinct and dissociable. The boxes may have sub-boxes: components of the verbal and visuospatial storage systems may be independent, and within each of these systems there may be distinct specialized mechanisms for storage and for the refreshment of stored items via rehearsal. Now the questions concern what is inside the boxes of the model: *What* powers them? *How* do these storage and control mechanisms actually work in the brain?

4.1. Mechanisms of Active Maintenance

A place to begin is to ask “What is the nature of the memory representation that is stored?” This question has been prominent throughout the history of psychology and neuroscience. Today there is fairly widespread agreement that long-term memory representations occur as relatively permanent strengthenings (or weakenings) of connections among neural populations. Using the vocabulary of neural net models, we can call these changes **weight-based memory**, since the memory representation takes its form in the strength or weight of neural connections. Although weight-based memories are stable and long lasting, we are not always aware of them because they reflect a structural change in neural pathways that is revealed only when those pathways are excited by input.

Short-term storage appears to rely on a different mechanism, which we can call **activity-based memory**, in which information is retained as a sustained or persistent pattern of activity in specific neural populations (O’Reilly et al., 1999). Activity-based memories are more highly accessible but less permanent. Activation signals can be continually propagated to all connected neurons, but once the activation level changes, the originally stored information is lost. Think about holding a thought in your mind, such as the point you want to make in the movie conversation. While the information is in this state, in your working memory, it is highly accessible, and so it can directly influence what words you choose to speak and you can make your point fluently. But what if instead your point was lost from working memory? In that case, you’d have to retrieve it from long-term

memory. The information is probably still around, stored in your brain, but less accessible, until it is retrieved into working memory. In that interim, you are likely to be at a loss for words, even if you have a chance to jump into the conversation. These characteristics fit well with the functional distinctions between a rapid, on-line, and flexible working memory and the slower but more permanent long-term memory.

Much of what has been learned about how activity-based storage occurs in the brain has come from neuroscience studies utilizing direct neural recordings in monkeys as they perform simple working memory tasks. A typical experimental procedure is the **delayed response task**: a cue is briefly presented and, after a delay—during which presumably the information in the cue must be held in short-term storage—a response is required. Many of these studies are designed so that the response takes the form of eye movements. The animal is trained by rewards to keep its eyes fixated on a central location in a display screen. A brief visual cue, such as a spot of light, appears in one of up to eight spatial locations on the display, the animal still focusing straight ahead. After a specified delay of between 2 and 30 seconds, the animal is given a “go” signal to move its eyes to the exact location in which the light appeared. Again, this is accomplished by training, with rewards of juice or food for a correct response. Because the location of the cue varies randomly from trial to trial, the animal must rely on its working memory of the cue location in order to make the correct response.

Direct neuronal recordings suggest that the working memory representation used to perform this task relies on the activity patterns of single neurons. In particular, certain neurons in the dorsolateral region of prefrontal cortex have shown transient increases in their activity level (as measured by increased firing rate) during presentation of the cue, whereas others showed firing rate increases throughout the delay interval (Fuster, 1989; Goldman-Rakic, 1987). A critical finding was that activity during the delay was stimulus specific: a given neuron would show activation only in response to a cue in a particular location on the display (Figure 6–11) (Funahashi et al., 1989). These sustained responses could not be due to perceptual stimulation; there was no perceptual stimulation during the delay.

This evidence is correlational. Can it be strengthened to show that the activity in these neurons actually serves as the working memory representation? Well, what happens when the animal *doesn't* remember? (That is, it did not hold the location of the cue in short-term storage.) What about activity in the delay periods preceding *incorrect* responses? Would it be less than in the periods preceding *correct* responses? Yes, indeed; that is exactly what was observed. In trials when an error was made, the activation during the delay showed either no change from the baseline rate or a premature decay of activity in neurons thought to be coding for that location.

Intriguing evidence, but still correlational only. The changes in neuronal firing may have reflected a brain-wide lapse in attention or motivation rather than a specific loss of information. To address this concern, other animal studies have made direct interventions in neural functioning and observed the results. In one study, small areas of cortical tissue were removed from regions of dorsolateral prefrontal

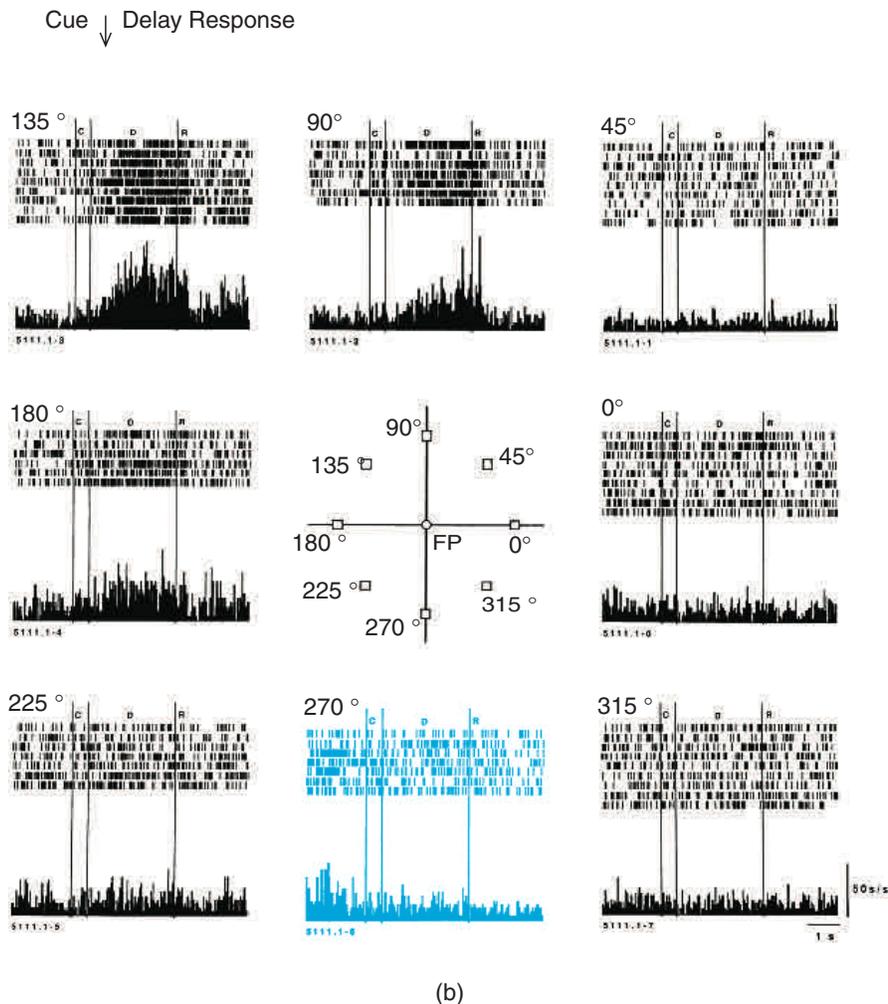
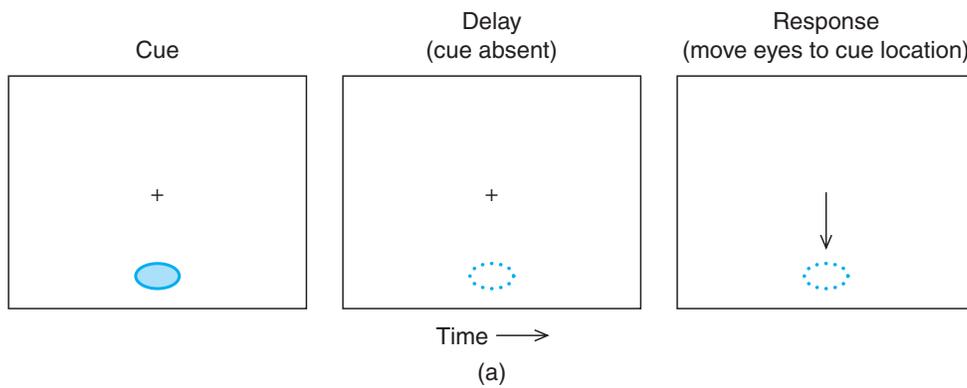


FIGURE 6–11 Neuronal activity in monkey prefrontal cortex during a delayed response task

(a) The task: a cue (the blue ellipse) is briefly presented in one of eight locations surrounding the fixation point (the plus sign). During a delay period the monkey must maintain this location in working memory. Following a go signal (removal of the plus sign), the monkey makes an eye movement toward the remembered location. (b) Averaged activity traces for a representative neuron in the prefrontal cortex. Each trace represents activity during the trial in which the cue was presented in the location corresponding to the layout shown. For this neuron, activity was selective to spatial location: it increased during the delay only when the cue was presented directly below the fixation point, the position shown in part (a).

(Funahashi, S., Bruce, C. J., and Goldman-Rakic, P. S. (1989). Mnemonic coding of visual space in the monkey's dorsolateral prefrontal cortex. *Journal of Neurophysiology*, 61(2), 331–349. Used with permission.)

cortex after the animals had learned the requirements of the experiment. After the lesioning, the animals made the correct responses to most locations, but failed miserably when the cues were presented in locations that normally would have been coded by the neurons in the lesioned area. The lesions had produced *mnemonic scotoma*, or memory blindspots (Funahashi et al., 1993). (The behavioral deficit was neither perceptual nor motor: the animals performed correctly in a control task in which the visual cue at the critical location was present throughout the delay.) Similar results have also been observed in procedures that cooled the neurons to a temperature at which they do not function normally (Bauer & Fuster, 1976). Such cooling procedures are important because they rule out effects due to new learning or functional reorganization following permanent brain damage. In these cooling studies the degree of impairment was related to the length of the delay: the longer the delay, the greater the impairment.

Do humans also show evidence that information storage in working memory occurs through sustained neural activity? Direct experimental single-cell neural recordings are not normally performed on humans (although they are sometimes made before medically necessary neurosurgical procedures). Instead, the research tool is neuroimaging, which can also provide information about how neural activity changes over time and in response to specific events, although at a coarser temporal resolution and only in terms of the activity of larger scale neural populations (rather than single neurons). Nevertheless, these studies have provided remarkably convergent evidence to that observed in single-cell research. Specifically, during the delay period of working memory tasks, dorsolateral prefrontal and parietal cortex show sustained increases in activity levels (Cohen et al., 1997; Courtney et al., 1997; Curtis, 2005).

These results are critical because they inform our notions regarding the nature of short-term storage in the brain. First, they suggest that the distinction between long-term memory and short-term memory—at least in many cases—is not so much in terms of structurally distinct brain systems, but rather in terms of the mechanisms by which the information is maintained. For short-term storage, information is maintained in the form of sustained neural activity, whereas for long-term storage this is unlikely to be the case. Second, for at least some brain regions, short-term memory storage is not like RAM in a computer at all, because RAM is completely flexible with regard to what information gets stored in different locations. Instead, in the brain some neural populations appear to be specialized for the storage of very selective kinds of information, such as a particular location on a screen in front of you. This result indicates a further degree of content-based organization of working memory, as discussed in the *Debate* box on page 260. Yet it is still not known how widespread such content-based organization is in the brain. For example, does it extend to more abstract forms of verbal information, such as meaning? Similarly, it appears as if the neural populations store information by a sustained increase of firing rate. But what happens when more than one item is being stored in working memory? How does the brain store the increased information?

In studies of nonhuman primates, these questions have been hard to answer, because it is very difficult to train an animal to maintain more than one item at a time. Humans, however, can be given more complex assignments. We know that

multiple items can be stored in working memory simultaneously. Thus, it has been possible to examine brain activity when different numbers of items simultaneously must be maintained in working memory. Increasing that number could produce two possible effects on brain activity: (1) The number of active brain regions may remain constant, but the activity levels in at least some of those regions may increase with each additional item stored. (2) The number (or size) of active brain regions may increase, but the activity level of an already active region would not change with additional items. In fact, the studies to date have tended to show a mix of these two patterns: increasing the number of items to be stored appears both to increase the number of active brain regions and also the levels of activity in those regions.

The effect of changing the load on working memory is commonly studied by the ***N*-back task**, in which participants are presented with a continuous stream of items, such as letters, and instructed to decide, as each item is presented, whether it matches one that is *N* items back in the series, where *N* typically equals 1, 2, or 3. (The participant is also instructed to answer “no” if in a given case there are no preceding items or the number of preceding items is less than *N*.) The value of *N* is varied in order to examine how performance and brain activity varies with working-memory load. Thus, given the sequence

D F F B C F B B

participants may be asked to say yes or no to a match when $N = 1$. Here the correct answers are no–no–yes–no–no–no–no–yes. In a three-back condition for the same series, that is, $N = 3$, the correct responses are no–no–no–no–no–yes–yes–no. An elegant aspect of the *N*-back task is that the experimenter can hold constant the identity and order of items presented; the only factor that is changed is the working memory load (1 in a 1-back task vs. 3 in a 3-back task). This means that the possibility of “confounding variables”—other, extraneous, factors that also change with the task condition—is eliminated.

Neuroimaging studies of participants engaged in the *N*-back task have generally found that brain activity in lateral prefrontal cortex (and parietal cortex as well) increases with the value of *N* in a linear relationship (Figure 6–12) (Braver et al., 1997). A common interpretation of this result is that maintaining each additional item in working memory places an additional demand on working memory storage buffers as they approach capacity.

Note, however, that the *N*-back task requires control or executive processes in addition to storage, and that these demands on the central executive also increase with *N*. Both the identity of an item *and its ordinal position* must be stored, and then the test item matched to the one in the appropriate position. More sequence “tags” for the items are needed as the number of items increases. The need for manipulation of information as the item changes means that it is not clear whether to interpret linearly increasing activity in a brain region in these *N*-back trials as reflecting maintenance processes or executive processes.

A number of studies have tried to address this issue by examining brain activity during simpler tasks, such as item recognition (the task studied by Sternberg, discussed earlier in Section 2.2.2). Here the demands on maintenance far outweigh

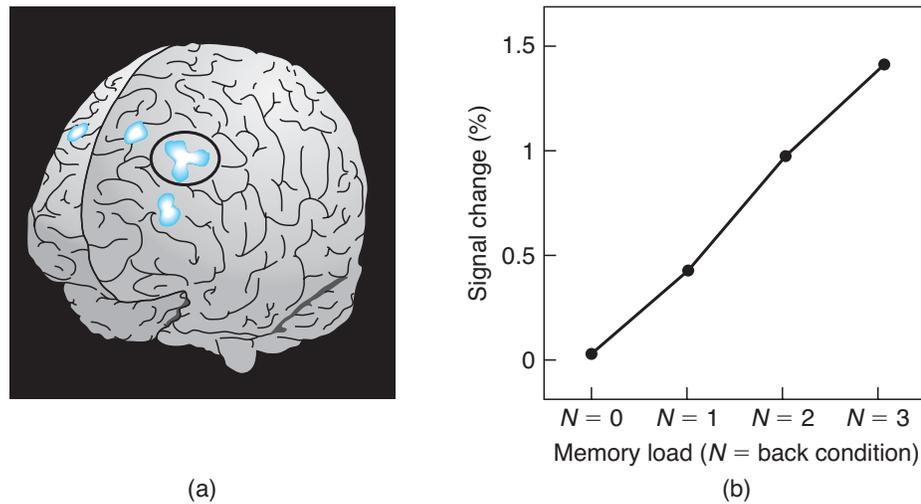


FIGURE 6-12 Working memory load effects in prefrontal cortex during the N -back task

(a) The image shows the surface of a participant's brain. Blue-white areas indicate regions of the prefrontal cortex that demonstrated increased activity with working memory load. (b) Change in activation in the region circled in the image as a function of N -back condition ($N = 0, 1, 2,$ or 3). Activation increased linearly with N .

(Braver, T. S., Cohen, J. D., Nystrom, L. E., Jonides, J., Smith, E. E., and Noll, D. C. (1997). A parametric study of prefrontal cortex involvement in human working memory. *Neuroimage*, 5(1), 49–62. Reprinted with permission from Elsevier.)

those on control processes. Order of items is not an issue; all that is required is a simple match of the test item, and the number of items stored (varied in different trials) is well within the capacity of working memory. These studies have tended to confirm the findings of the N -back task: increases in memory load are associated with increased activity in the prefrontal and parietal cortex. An additional benefit of the item recognition task is that brain activity can be independently computed for each phase of the trial: encoding, maintenance, and retrieval. This fMRI work has demonstrated that the number of items influences the activity of the prefrontal and parietal cortex specifically during maintenance (Jha & McCarthy, 2000). The overall picture is still complex, however; a large number of items may result in greater activation during encoding and retrieval than during maintenance (Rypma & D'Esposito, 1999). This latter finding is consistent with the idea that prefrontal cortex is also important for executive control processes, such as influencing what information is selected for storage and also how the maintained information is used.

The neuroimaging and neuronal recording studies provide strong support for the idea that representations in working memory rely on sustained activity in selected neural populations. These findings are a critical first step in understanding the nature of working memory coding, but in and of themselves they do not tell us exactly how such sustained neural activity arises. What causes the neurons in prefrontal cortex to keep firing after the perceptual information has come and gone? In

other words, what powers the maintenance process? An answer to this question is critical not only for understanding why information in working memory can be kept at a high level of accessibility for a short period of time, but also why there appear to be such strict limitations on both the length of time and number of items that can be stored. One hypothesis is that short-term maintenance occurs as connected neurons recirculate activity among themselves. That is, each neuron in the circuit participates in a **reverberatory loop**, holding onto the information by both “talking” and “listening”—by communicating the information to the other neurons it is connected to, and by later receiving that information from those same (or other) connected neurons (Hebb, 1949). Each time a neuron passes the information on, it provides an input signal to the other neurons it is connected to that allows those neurons also to “pass it on.” Thus, the neurons in the circuit mutually support one another, each neuron contributing to the maintenance of the information.

Sounds good—but are brain neurons really equipped to form such a reverberating circuit? To begin to grapple with this question, psychologists and neuroscientists have built small-scale neural network models to investigate the mechanisms of working memory. In some of these models, the simulated neurons are implemented as computer programs with properties that attempt to capture closely what is known about the physiology and structure of real neurons and their organization within circuits. Now the question is, can the simulated neural circuit achieve short-term information storage with model neurons showing activity patterns that are comparable to those observed in experimental recordings of real neurons? The answer: models have been very successful in showing that short-term information storage can be achieved by means of recirculating activity in neural circuits, and the behavior of model neurons can approximate closely what has been seen in the experimental data (Durstewitz et al., 2000).

Moreover, such models have been used to demonstrate how the limits of storage capacity and storage duration might arise. When more than a few items are maintained simultaneously in overlapping reverberating circuits, they can interfere with each other to a great enough extent that circulating activity is disrupted during the delay period (Lisman & Idiart, 1995; Usher & Cohen, 1999). Similarly, if irrelevant signals leak into such a circuit, potentially from ongoing perceptual input, this can also interfere with the process of reverberation and lead to disruption of the sustained memory signal over time (Brunel & Wang, 2001; Durstewitz et al., 2000). Thus, the models can be used to predict the types of task situations that will be most vulnerable to the loss of information in working memory. A final benefit of these models is that they can be observed over time, to see how the behavior of the system evolves. A number of such models are publicly available as demonstrations on the Internet. If you are interested in looking at an example, try http://www.wanglab.brandeis.edu/movie/spatial_wm.html.

4.2. The Role of the Prefrontal Cortex in Storage and Control

Although the prefrontal cortex is not the only area of the brain that shows sustained activation during the delay in working memory tasks—other areas of increased

activation observed in various studies have included, most notably, the parietal and temporal cortex (Fuster, 1995)—the prefrontal cortex appears to play a special role in the active maintenance of information. This was demonstrated most clearly in a study in which neuronal activity in nonhuman primates was recorded in both temporal and prefrontal cortex during performance of a delayed matching task (Miller et al., 1996). In this variant of an item recognition task, intervening distractor items were shown in the delay between presentation of the item and the subsequent probe. Both temporal and prefrontal cortex showed selective and sustained activation during the delay; however, when a distractor was presented, stimulus-specific activation disappeared in the temporal cortex but was maintained within the prefrontal cortex. This work is examined in greater detail in the accompanying *A Closer Look* box.

In studies that used a spatial variant of the task, the same pattern was observed between parietal and prefrontal activity; the distractors reduced parietal but not prefrontal response (Constantinidis & Steinmetz, 1996). Similar results in humans have been obtained through fMRI studies (Jiang et al., 2000). Taken together, these results suggest that there might be specializations within the brain not just for the type of material being stored in working memory, but also for different ways of storing the information. The prefrontal cortex might be specialized for maintaining information over longer intervals (but still in terms of the sustained activity characteristic of working memory) or in the face of distraction, whereas temporal or parietal brain systems might have different mechanisms for maintaining information over shorter intervals.

In addition to the data suggesting that the prefrontal cortex plays a role in maintaining information in the face of distraction, many human neuroimaging studies have suggested that it is also involved in executive functions such as dual-task coordination or manipulation of information within working memory. Moreover, experimental research conducted on patients with frontal lobe damage seems to indicate an impairment of central executive functions rather than of working memory per se (discussed in Chapter 7) (Stuss & Benson, 1986). What do such findings say about the Baddeley-Hitch model of working memory, in which there is a strict segregation of storage and control functions? In that model, the two buffer systems, the phonological loop and the visuospatial scratchpad, serve as “slave” systems that only maintain information, and the central executive, which controls the operation of the buffers, has no storage capability itself. How might the neuroimaging data be reconciled with cognitive theory? One possible resolution might be that different subregions of prefrontal cortex carry out storage and control functions. And indeed, as we have seen, some studies have shown prefrontal regions selectively involved in the maintenance (the ventral regions) and the manipulation (the dorsal regions) of information. However, these findings appear to be more a matter of degree than a clear-cut distinction and, moreover, they have not been consistently observed (Veltman et al., 2003).

There is another possibility: that the prefrontal cortex is the brain region where goal-related information is represented and actively maintained (Braver et al., 2002; Miller & Cohen, 2001). In this **goal-maintenance model** (Figure 6–13), the

A CLOSER LOOK

Mechanisms of Working Memory Storage in the Monkey Brain

We consider the work of Earl Miller, Cynthia Erickson, and Robert Desimone, who investigated neuronal activity in primates during performance of a delayed matching task. They reported their work in 1996 in a paper titled “Neural Mechanisms of Visual Working Memory in Prefrontal Cortex of the Macaque,” *Journal of Neuroscience*, 16(16), 5154–5167.

Introduction

The investigators were interested in examining the activity of neurons in the prefrontal cortex during a working memory task in which distracting information was presented during the delay interval. The activity of prefrontal neurons was compared to the response observed from neurons in the temporal cortex. The hypothesis was that only the prefrontal neurons would maintain a sustained, stimulus-specific response in the face of distraction.

Method

To test responses of individual neurons, the investigators implanted tiny electrodes into neurons in the cortex of macaque monkeys. In one study, 135 neurons in the inferior temporal cortex were examined; in a second study, involving the same two monkeys, 145 prefrontal neurons were recorded. By measuring the change in voltage on the electrode, the electrical activity of the neuron was monitored to determine how strongly the neuron was responding (in terms of the number of action potentials, or electrical spikes, generated per second). Activity was recorded from each sampled neuron across a large number of trials of a delayed response working memory task. The task involved the presentation of a series of line-drawn objects. The monkey was instructed (through gradual, rewarded training) to release a lever when the presented object matched the sample, the first object presented in the trial. Between the sample and the match, anywhere from 0 to 4 intervening nonmatching drawings might be presented; these were to be ignored.

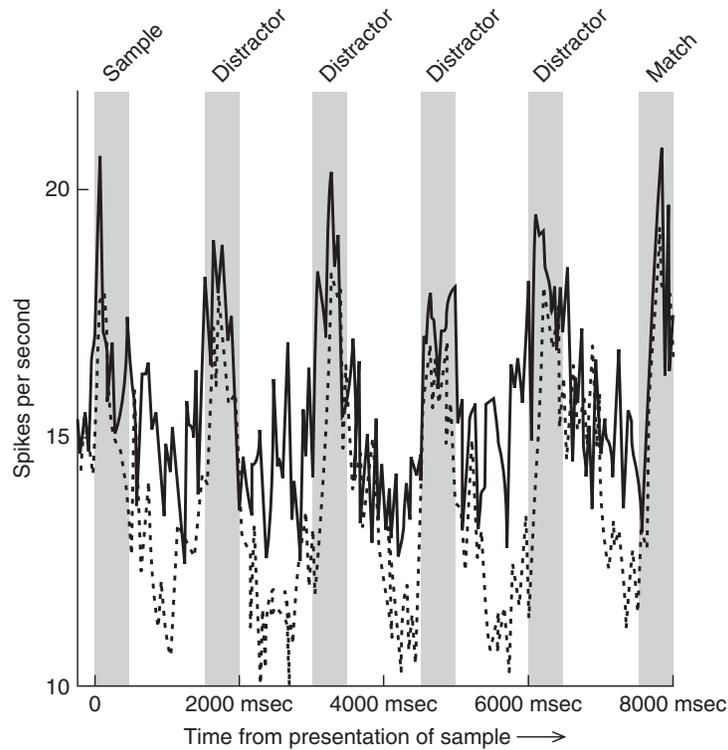


The monkey’s memory task, which required memorizing a sample and responding when a match appeared after a variable number of intervening distractor objects.

(Miller, E. K., Erickson, C. A., and Desimone, R. (1996). Neural mechanisms of visual working memory in prefrontal cortex of the macaque. *Journal of Neuroscience*, 16(16), 5154–5167. Copyright © 1996 by the Society for Neuroscience. Reprinted with permission.)

Results

In both the temporal and prefrontal cortex, many of the neurons were stimulus selective: they showed a greater response when one object was presented as the sample relative to other objects. It is important that this stimulus-selective response was retained when the sample was removed from the display (this is the memory representation of the sample). In the prefrontal cortex neurons the stimulus-selective activity persisted even when intervening distractor items were presented, and continued until the presentation of the match item. However, in the temporal cortex, the stimulus-selective response was abolished following the presentation of the first distractor.



Average neuronal activity in the prefrontal cortex during distractor periods following presentation of sample objects (indicated by bars) that elicit a strong response (solid lines) or a weak response (dashed line). The heightened activity is maintained throughout each distractor and delay period, until the match object is presented.

(Miller, E. K., Erickson, C. A., and Desimone, R. (1996). Neural mechanisms of visual working memory in prefrontal cortex of the macaque. *Journal of Neuroscience*, 16(16), 5154–5167. Copyright © 1996 by the Society for Neuroscience. Reprinted with permission.)

Discussion

The finding that neurons in the prefrontal cortex and inferior temporal cortex retained a stimulus-selective pattern of activity during the delay period immediately following the sample suggests that both brain regions could be involved in activity-based short-term storage. However, the finding that only the prefrontal neurons retained this selective response across intervening distractor items suggests that the two brain regions serve distinct functions in working memory. One interpretation of the results is that the prefrontal cortex is critical for protecting actively maintained information from the disruptive effects of interference.

prefrontal cortex serves *both* a storage and a control function: the maintenance of information about a goal (storage) and a top-down influence that coordinates perception, attention, and action to attain that goal (control). The information stored in the prefrontal cortex may provide a context that aids the interpretation of ambiguous situations and the response to them. Just how might this work? Here's an example.

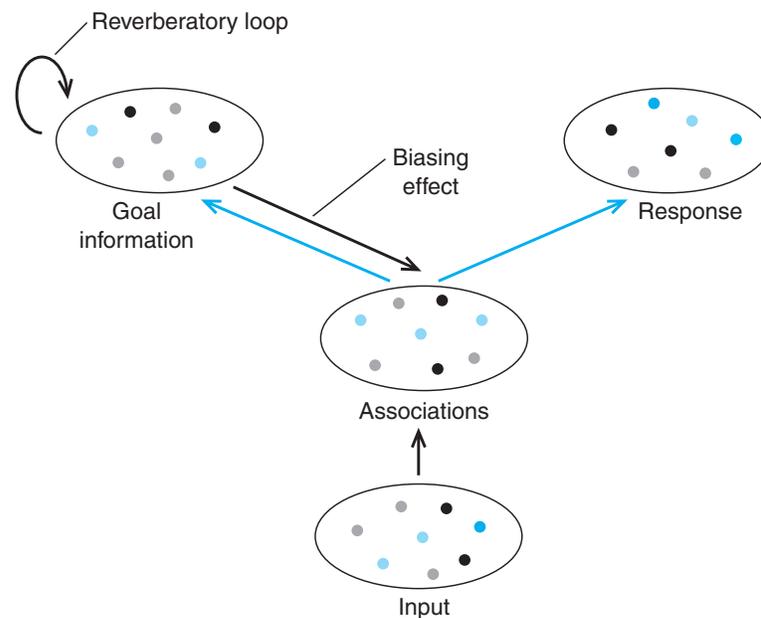


FIGURE 6–13 The goal-maintenance model

In this model, goal information is represented in the prefrontal cortex as a pattern of activity. Reverberatory loops allow this activity to be sustained over delays, and feedback connections enable the maintained activity to bias the internal associations that are activated in response to perceptual input. In this way goal information is able to provide control over thoughts and behavior.

(Adapted from Braver, T. S., Cohen, J. D., and Barch, D. M. (2002). The role of the prefrontal cortex in normal and disordered cognitive control: A cognitive neuroscience perspective. In D. T. Stuss and R. T. Knight (eds.), *Principles of Frontal Lobe Function* (pp. 428–448). © 2002 Oxford University Press. Reprinted with permission of Oxford University Press.)

Suppose you have a regular route you drive, perhaps from a job to where you live. At an intersection, your route directly home is straight through, but you always get yourself in the leftmost lane because it has a left-turn arrow and so the traffic moves through faster, either turning left or going straight ahead, than from the other lanes. So ordinarily—the default pattern—you’re in the leftmost lane but don’t turn left. But, if you need to stop at the grocery store on the way home, as you do now and then, you must turn left at that intersection. Now you’re stopped at the light: do you turn left or go straight ahead? That depends on your goal, which provides a context for determining your action: do you want to go home or to the store? You may very likely find that in the less frequent situation you have to keep the go-to-the-store goal active in working memory while you’re waiting at the light, or you’ll blow it and go straight ahead.

In the goal-maintenance view of the role of the prefrontal cortex in working memory, this is what’s happening: As you wait at the stoplight, the goal of go-to-the-store is actively maintained in the prefrontal cortex, and this activation flows from the prefrontal cortex back to the brain systems serving perception, attention, and action to influence your response when the light turns green. Were the goal not actively

maintained, you'd go straight ahead—your default route—and get home without the milk. The goal provides a context that influences your behavior, overriding your usual response in the situation.

The goal-maintenance theory of prefrontal involvement in working memory appears to be consistent with a wide range of both human and animal data (Miller & Cohen, 2001). For example, in studies with monkeys, careful analysis of the responses of prefrontal cortex neurons during behavioral tasks suggests that what is being maintained in their sustained activity patterns is not just a simple perceptual representation of the input, but rather something like the task-relevant features or behavioral rules of the situation (for example, if the light is red, then press the left button; Miller et al., 2002). Because the information being maintained in the prefrontal cortex is the most relevant for performing the task at hand, it could potentially be used to bias how new information is interpreted and how actions are determined. Is there a way to test such an idea?

In fact, the goal-maintenance theory has been implemented and tested in computational modeling studies in which the storage and control mechanisms could indeed work together to produce the patterns of performance that humans and animals exhibit in working memory tasks (Braver et al., 2002; O'Reilly et al., 2002; Rougier et al., 2005). The theory goes a long way toward demystifying the concept of the central executive in working memory by showing how control of behavior can occur in a neurobiologically plausible manner. Nevertheless, it is important to realize that there may be many possible executive functions related to working memory—updating, integration of information, transformation, buffer allocation, attention, and coordination—and it is not clear how these could arise solely from the goal-maintenance model. It is likely, as discussed in the next chapter, that executive processes other than goal maintenance are implemented in the prefrontal cortex.

Comprehension Check:



1. What evidence suggests that information is maintained in working memory through activity-based storage?
2. How have studies of the prefrontal cortex informed cognitive theories of working memory?

5. CURRENT DIRECTIONS

The Baddeley-Hitch model and the idea of a “mental workspace” took us a long way in the exploration of working memory. However, the close examination of the role of the prefrontal cortex, particularly the goal-maintenance model and the interaction of storage and control functions, leads to considerations of other hypotheses. The original model makes a structural distinction between storage and control; if that distinction is not rigid, other possibilities arise.

5.1. The Episodic Buffer

Even good models of cognition need an update after a while, and Baddeley (2000) recently refined his model of working memory to account for some limitations associated with the original Baddeley-Hitch model. The more recent version has added a third storage buffer, termed the **episodic buffer**, as a system that can serve as both an auxiliary store when the primary ones are overloaded or disrupted, and also as a site in which to integrate diverse types of information such as verbal and spatial content within working memory. Another key aspect of the episodic buffer is that it appears to be a place where short-term memories of complex information such as temporally extended events or episodes can be stored (hence, the name “episodic”).

The inclusion of the episodic buffer into the working memory model appears to provide a nice solution to many peculiar findings that have accumulated over the years, findings that could not be easily accounted for by the original conception. As an example, read the following and then close your eyes and try to repeat it out loud: *The professor tried to explain a difficult cognitive psychology concept to the students, but was not completely successful.* You probably did pretty well at remembering most of the words. Now try this one: *Explain not but successful difficult a psychology the was to concept completely students cognitive to professor the tried.* Impossible, right? There is a huge difference between a meaningful 18-word sentence and one that has no meaning because the words are jumbled. What allows us to maintain such information in working memory when the number of words so vastly exceeds generally recognized capacity limits? One possibility, as Miller (1956) would have argued, is that we can chunk the information into larger, more meaningful units than single words. But how and where does such integration occur? At first blush, it seems that it might be in the phonological loop, because this holds verbal information. Yet the phonological loop is thought to use a sound-based code rather than a meaning-based one. Similarly, patients such as P.V., who are thought to have a completely damaged phonological loop, still show the sentence effect just described. P.V. has a word span of 1, but a sentence span of 5 words (Vallar & Baddeley, 1984). That is still lower than the normal range of 15 to 20, but it indicates that she might have been able to utilize a backup storage system that is more flexible with the type of information being stored. Perhaps the episodic buffer plays just such a role.

The episodic buffer is a relatively new idea, and so has not been put through many experimental tests as of yet. Moreover, the mixed nature of its function could indicate that it may actually be a part of the central executive rather than a storage component. Baddeley (2003) has indicated as much himself, which suggests that the separation of storage and control within working memory, so strongly advocated in the original version of the model, may be blurring in current conceptions. Such a view would fit well with the goal-maintenance account.

5.2. Person-to-Person Variation

A current focus of research on working memory is that of individual differences in working memory capacity. People vary widely in the ability to maintain items

in working memory, and especially in maintaining these items under conditions of interference. Because working memory appears to be so important for mental processes such as problem solving and thinking, it is not surprising that these individual differences are associated with success in academic examinations (such as the SAT tests) and the learning of new and complex cognitive skills (such as computer programming). Indeed, some researchers have suggested that working memory capacity is related to general fluid intelligence, defined as the ability to solve problems and reason in novel situations (Kyllonen & Christal, 1990). An important question, then, is to determine more precisely what varying component of working memory is critical for predicting cognitive success and general intellectual ability.

A standard task for measuring working memory capacity, such as the one presented in Figure 6–1, essentially asks how many items a participant can store in working memory in the face of distraction (Conway et al., 2005). If working memory capacity is defined by number of items, and the ± 2 following the magic number 7 reflects individual variability, we might imagine that someone with a capacity of nine items might have a strong advantage in carrying out complex cognitive tasks over someone with a capacity of five items. That is, someone who can keep more information available in working memory might be more efficient, forget less, and be less reliant on the slower and less flexible long-term memory system.

An alternative, and more recent, idea suggests that what is being measured in tasks like this may not be storage capacity per se but rather the ability to keep goal-relevant information actively maintained in the face of interference (Engle, 2002). In this view, high working memory capacity can refer to the ability to keep even a single goal active under conditions of high interference. Researchers have shown that this ability is distinct from short-term storage capacity and that this function, not short-term storage capacity, correlates strongly with fluid intelligence and cognitive abilities (Engle et al., 1999). Further, these researchers suggest that this function is implemented in prefrontal cortex, a notion consistent with the role of prefrontal cortex in maintaining information in the face of distraction. Evidence suggests that this ability may be the component of working memory capacity that varies most strongly from person to person.

This idea was tested in neuroimaging study that examined the brain response to distracting information occurring during performance of the *N*-back task (Gray et al., 2003). The distractors used were items that had recently been repeated but were not targets (for example, the second “F” in the sequence “B–T–R–F–T–F” where the task is to look for $N = 3$ matches). Participants measuring high in fluid intelligence were found to have a stronger activation response in the prefrontal cortex during distractor trials, even though there was no reliable difference among participants for nondistractors. Thus, people with high working memory capacities may be better able to keep goal-relevant information highly activated and ready for use when needed.

5.3. The Role of Dopamine

Researchers have found that patients suffering from certain forms of neurological or psychiatric illnesses have impaired working memory. These groups include patients

with schizophrenia, Parkinson's disease, and Alzheimer's disease. Given the critical role of working memory in cognition, it is of clinical importance to determine whether there might be any drug treatments that could improve working memory in such populations. Interestingly, a number of studies in both animals and humans suggest that the neurotransmitter *dopamine* is especially important for working memory, and that drugs that increase levels of dopamine in the brain or facilitate the action of dopamine can enhance working memory capabilities (Luciana et al., 1998; Sawaguchi, 2001). Conversely, drugs that block the action of dopamine have the opposite effect and interfere with working memory (Sawaguchi & Goldman-Rakic, 1994).

In addition to the clinical relevance of this work, it also may influence our understanding of how working memory is normally implemented in the brain, and what can cause it to go awry at times, even in healthy individuals. Some theoretical accounts have suggested that dopamine may be critically important for helping to maintain ongoing information in the face of interference by signaling when information in working memory should be updated (Braver & Cohen, 2000; Durstewitz et al., 1999; Servan-Schreiber et al., 1990). Neurophysiological research suggests that dopamine can help to amplify strong signals and attenuate weak ones (Chiodo & Berger, 1986). Such a mechanism might be very useful in working memory if we assume that task-relevant information carries a stronger signal than the background noise of interference. It is suggestive that the anatomy of the dopamine system is such that dopamine-producing cells have a strong connection to the prefrontal cortex—the brain region that may be most important for protecting maintained information from distraction. Thus, a reasonable hypothesis is that dopamine input to the prefrontal cortex might play a key role in providing that region with interference-protection capabilities. Finally, there is some indication that dopamine levels and activity are highly variable, both over time within an individual (King et al., 1984) and across a population (Fleming et al., 1995). An intriguing possibility is that variability (possibly genetically based) in the dopamine system might be the neural source of differences in working memory seen in different people (Kimberg et al., 1997; Mattay et al., 2003).

✓ Comprehension Check:

1. How does the addition of an episodic buffer handle findings that are problematic for the original Baddeley-Hitch model?
2. According to the executive attention account, what is the source of person-to-person variation in working memory capacity?

Revisit and Reflect

1. *How is working memory used in cognition?*

Working memory can be defined as the cognitive system that keeps task-relevant information stored in a highly active state so that it can be easily accessed, evaluated, and transformed in the service of cognitive activities and

behavior. A potentially useful metaphor is the RAM of a computer. Working memory is used pervasively in everyday cognition. Not only is working memory used to keep a point in mind while listening to someone else talk, but it is also used in tasks as varied as calculating a tip in a restaurant, executing driving directions, parsing complex sentences, and planning a chess move. Because working memory is so pervasive in cognition, person-to-person variation in working memory capacity may be the fundamental component of individual differences in a wide variety of cognitive abilities.

Think Critically

- Imagine that your working memory was impaired. What aspects of your daily life do you think would be most disrupted?
 - Do you think it is possible to “train” your working memory to be better? How might one go about doing this? Use the movie conversation as an example—how could you improve your performance in this kind of situation?
2. *How did the modern view of working memory arise?*

Early notions of working memory strongly linked it to consciousness; experimental research in the 1950s and 1960s focused on the characteristics of short-term storage and its distinction from long-term storage. Three primary findings emerged from this work: (1) 7 ± 2 chunks is the maximum capacity of short-term storage (although this number later proved to be an overestimate); (2) information may rapidly decay from short-term storage if not rehearsed; and (3) information in short-term storage can be very quickly accessed. The Atkinson-Shiffrin model provided a functional account of short-term storage as a necessary repository or gateway that enables efficient coding and access into long-term memory. However, later work revealed that normal storage in long-term memory can occur even with an impaired short-term memory system. The Baddeley-Hitch model reformulated the notion of short-term memory into the modern concept of working memory, which postulates multiple storage components and emphasizes the interaction with control processes.

Think Critically

- Do you think that working memory is just consciousness, and vice versa? Why or why not? Is “consciousness” the same kind of thing as information processing?
 - Short-term storage is thought to be severely limited in both capacity and duration. Can you think of any advantages this limitation might confer? What might the world be like if both capacity and duration were unlimited?
3. *What are the elements of working memory?*

The Baddeley model has three components: the phonological loop (which stores and rehearses verbal information), the visuospatial scratchpad (which enables mental imagery and navigation), and the central executive (which directs information to one or the other of the storage buffers and coordinates, integrates,

and manipulates that information). A number of lines of converging evidence from behavioral studies, neuropsychological patients, and neuroimaging data have suggested that visuospatial and verbal working memory involve distinct storage buffers.

Neuroimaging studies have provided some support for a distinction between maintenance and manipulation processes; manipulation of information seems to rely on lateral prefrontal cortex, whereas maintenance of information seems to rely more on ventral areas.

Think Critically

- How might studies of working memory in people who are blind or deaf (but who are fluent in sign language) inform our understanding of short-term storage buffers?
- One theory of the phonological loop suggests that it is based on our expertise at imitation. Can you think of any equivalent expertise we have that might be the basis for the visuospatial scratchpad?

4. *How does working memory “work” in the brain?*

The maintenance of information in working memory might be carried out through activity-based storage mechanisms involving the prefrontal cortex. Prefrontal neurons show sustained heightened activity during delay periods in working memory tasks. This prefrontal activity appears most critical in situations where the stored information has to be protected from sources of interference. Human neuroimaging studies have shown sustained prefrontal activity during the *N*-back task; moreover, this activity appears to increase in intensity with the number of items being simultaneously maintained. Detailed computational models have suggested that active maintenance in prefrontal cortex might arise from recirculating activity among local networks of neurons.

Think Critically

- Research using transcranial magnetic stimulation (TMS; see Chapter 1) has enabled studies to be conducted in which temporary and reversible “lesions” are produced in humans. What kind of effects might you predict if TMS were applied to the prefrontal cortex during different kinds of working memory tasks? How might this research be used to address unresolved questions regarding the nature of working memory?
- There have been reports of individuals with exceptionally large capacities for short-term storage, such as up to 100 digits (presumably due to increased chunk size). Imagine that you could scan the brains of such people while they performed working memory tasks such as the *N*-back or Sternberg item recognition task. What patterns would you predict?

5. *How might views of working memory change in the future?*

A wide variety of different models currently exist regarding the structure and components of working memory. Some, such as the Baddeley-Hitch model, focus

on the storage side, emphasizing the distinctions between types of storage content (verbal, spatial) and the role of rehearsal in keeping information activated. Other models, such as the goal-maintenance account, focus more on the control side of working memory, emphasizing how active maintenance of goal-related information can be used to constrain attention, thoughts, and action. The control of behavior is multifaceted and likely to involve a variety of mechanisms. An important direction for future research will be to determine the precise relationship between executive processes and working memory.

Think Critically

- Working memory capacity predicts performance on tests such as the SAT and GRE. Thus, why not just replace the current standardized testing with a simple measurement of an individual's working memory capacity, using a short test like that illustrated in Figure 6–1? What might be the possible advantages, disadvantages, and implications of such a decision?
- Imagine that a drug becomes available that has been proven to enhance working memory function in healthy young adults. Would it be ethical to allow this drug to be made widely available? If you were involved in making this policy decision, what factors would influence you?