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Revisit and Reflect

A CLOSER LOOK: Mechanisms of working memory storage in the monkey brain
DEBATE BOX: How are working memory functions organized in the brain?
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, that 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, and is thought to be critical for many higher cognitive abilities, such as planning, problem-solving and reasoning. This chapter describes current conceptions regarding the nature of working memory, its internal components, and how 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 (“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’s straightforward but nonetheless requires holding bits of information in mind until you can put together the pattern of the whole. 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 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 (Figure 1). To simplify: in 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 and the operating system of the computer are stored on the hard disk. To use this stored information—that is, to run the software—you must retrieve the program 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 software 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 software program can access any part of RAM. Second, the more RAM a computer has, the more complex and sophisticated programs 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 upon 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 neuroscience approaches to the
study of working memory, to be considered here, have in many ways revolutionized the types of questions that can be asked and provided new insights into how working memory works.

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**FIGURE 1:**

**DIAGRAM OF THE COMPUTER METAPHOR OF WORKING MEMORY SHOWING ANALOGY BETWEEN MEMORY AND COMPUTER COMPONENTS**

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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 ability, 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**, the amount of information that can be held accessible (Daneman & Carpenter, 1980), and that these differences are predictive of general intelligence (as measured by standard IQ tests), verbal SAT scores, and even the speed with which skill such as computer programming is acquired (Kane & Engle, 2002; Kyllonen & Christal, 1990).

A test such as those used to determine working memory capacity (also known as working memory span) is shown in **Figure 2**. (Why not take it yourself? Do the results accord with your view of your own working memory?) From tests like these, researchers have found a correlation between high performing working memory and a number of
indicators of success: higher scores on IQ tests and other general ability measures, greater effectiveness in solving novel problems; and faster learning of new skills. 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 part is the most critical for real-world cognitive 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 our cognitive repertoire.

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FIGURE 2:

EXAMPLE OF WORKING MEMORY SPAN TASK

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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, of course, 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 like 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 on-going cognition is not a new one, but ideas regarding the nature and function of short-term storage have evolved considerably over 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 idea that there is a distinct form of memory that stores information temporarily in the service of on-going cognition is not new. Indeed, 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 was the initial repository in which perceptual experiences could be stored and made immediately available to conscious attention, inspection, and introspection.
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 an active cognitive process being initiated. 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 cognitive 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. . . . this 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” (G. A. Miller, 1956). 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 series of digits, showed that regardless how long the series, correct recall of digits appears to plateau at about seven items (though for some people this plateau number is lower and for some it is 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 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 a 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. (Although the notion of a “magical number” is still very much a 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
maybe 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 like chunking or rehearsal (Cowan, 2001.)

Miller’s 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., showed grossly impaired long-term memory but relatively intact performance on immediate recall tasks (A. D. 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 it 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 consciously rehearsed. An experimental technique called the Brown-Peterson task was developed to explicitly test that idea (Figure 3) (Brown, 1958; Peterson & Peterson, 1959). Participants would typically be given a string of three consonants to memorize and then prevented from engaging in active memorization, 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 delay 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. These findings suggested the shortness of short-term storage. (Around this time investigations were also being conducted on an even briefer form of storage – termed sensory memory – that enables a perceptual trace of a stimulus to persist 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. This argument was bolstered by the fact that participants’ recall performance tended to be much better in the first few trials of the task (when such 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, Dalezman, & Eggemeier, 1976). The debate over whether information is lost from short-term memory because of decay or interference has not been resolved, and the question is still studied today (Nairne, 2002).

FIGURE 3:
DATA FROM BROWN-PETERSON TASK ILLUSTRATING DECLINE IN RECALL WITH DURATION

2.2.2. Ready accessibility
The high level of accessibility of information stored in short-term was demonstrated in a classic set of studies conducted by Saul Sternberg (Sternberg, 1966, 1969). 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 short 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 perceptually process the probe item; (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, quantity (2)—that is, 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 reaction 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 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 a reaction time of approximately 40 milliseconds (Figure 4). The hypothesis that information held in short-term memory could be accessed at high speed was certainly borne out by these findings.

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, sophisticated
mathematical modeling techniques show that similar linear curves could be found from a parallel scanning process that accesses all items simultaneously. In these models, the increase in reaction times is due to the decreasing efficiency of the parallel process as the number of items held in short-term memory increases (McElree & Dosher, 1989; Townsend & Ashby, 1983). But even assuming parallel scanning, which becomes less efficient as there are more items to be compared, the reaction time 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.

FIGURE 4:
DIAGRAM OF THE STERNBERG DATA SHOWING THE LINEAR RELATIONSHIP BETWEEN MEMORY SET SIZE AND RT

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 Atkinson and Shiffrin (Figure 5) (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, then, was to provide a means of controlling and enhancing the information that made it into long-term memory via rehearsal and coding strategies. The Atkinson-Shiffrin model was highly influential because it laid out a comprehensive view
of information processing and its various stages, and it is still referred to as the “modal model” of memory, the model most frequently cited.

FIGURE 5:

DIAGRAM OF THE ATKINSON-SHIFFRIN MEMORY MODEL SHOWING THE STRUCTURAL DISTINCTIONS BETWEEN MEMORY STORES

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 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 did not seem to be correct. Some patients with brain damage (typically to the parietal lobe) who showed drastic impairments in short-term memory nevertheless were able to learn new information in a fashion comparable to that of neurologically healthy people (Shallice & Warrington, 1970). This finding suggested 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. Baddeley and Hitch (1974) asked participants to make simple true–false decisions about spatially arrayed letters: for example, shown “B A” they were to decide if the statement “B does not follow A” were 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.

2.3. 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 (Figure 6). Three important characteristics differentiate it from the Atkinson-Shiffrin view.
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 internally represented information. Thus, in the “A”–“B” reasoning problem described above, working memory is required to (1) hold an internal trace 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 (2) enable comparison of the two sources of information, 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 workplaces for cognition.

Third, the model proposes (as implied above) at least two distinct short-term memories, 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, the two short-term stores and a control system, interact to provide a comprehensive workspace for cognitive activity.
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.

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 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 a great deal of research. Although the initial idea of a central controller interacting with dual short-term memory buffers has been retained over the years, certain aspects of the model have been further elaborated by the work of a number of investigators. In particular, there has been an intense focus of research on storage within verbal working memory—the phonological loop—since 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 (A. D. 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. In order 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 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 the opening vignette, it is likely that you would be using the phonological loop to rehearse the key points you want to make in your movie conversation, but also time-sharing this same system to help process your friends’ 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, it suggests that verbal working memory capabilities should depend upon 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, it suggests that 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, by possibly using visual imagery (i.e., 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 cognitive modules, and hence should be dissociable. All these hypotheses have been tested in experiments, and they 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**. Working memory performance when items have to be serially recalled is significantly poorer if the items to be maintained are phonologically similar (Conrad & Hull, 1964). 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.”

In the other part of the phonological loop, articulatory processing, or the “speaking” of presented items by the inner voice, is affected by the **word-length effect**. Recall performance is much 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 words that have long vowel sounds, such as “harpoon” and “voodoo,” than for words with short vowel sounds, such as “bishop” and “wiggle” (A. D. Baddeley, Thomson, & Buchanan, 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 undergone decay 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 they can recall 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, the phonological loop out of operation, phonological similarity and word length 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. (e.g., imagine that, in the movie conversation example at the beginning of the chapter, 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; silly, of course, but you can see why such conditions might make it almost impossible to rehearse your thoughts). Under these conditions, termed articulatory suppression, performance is significantly, though not catastrophically, impaired (demonstrating that working memory
is still working). But critically, neither the phonological similarity nor the word length effect is present—not a surprising result, since these effects are thought to be due to the phonological loop, which is rendered less useful by the conditions of the experiment (A. D. Baddeley, 1986; A. D. Baddeley, Lewis, & Vallar, 1984).

Converging evidence for the phonological loop model has come from neuropsychological studies, that is, psychological tests administered to neuropsychological patients. The patient P.V. was, at the time she participated in this research, 28 years old; she 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, Spinnler, Vallar, & Zanobio, 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 must first be processed phonologically before it can 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, but due to the defectiveness of this buffer, the information could not be appropriately transferred to the articulatory rehearsal system. A number of patients who, like P.V., have selective auditory-verbal short-term memory deficits have been identified. Their common pattern of deficits (and area of damage) suggest that the phonological store component of verbal working memory has been damaged in these patients, and that this component is localized within the left inferior parietal cortex (Vallar & Papagno, 1995).

Is there evidence that storage and rehearsal are functionally independent components of 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 similarity effect on performance was not influenced by word length, and vice versa (Figure 7) (Longoni, Richardson, & Aiello, 1993).

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FIGURE 7:
PLOT OF LONGONI DATA SHOWING INDEPENDENT EFFECTS OF WORD LENGTH AND PHONOLOGICAL SIMILARITY
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Of course, behavioral data can provide only indirect evidence for functional
independence. Results from neuroimaging studies provide a stronger case that separate brain systems support phonological storage and rehearsal.

In neuropsychological patients, there seems to be a relationship between left inferior parietal damage and phonological storage impairments on the one hand, and left inferior frontal cortex damage and articulatory rehearsal impairments on the other. (The left inferior frontal cortex, also known as Broca’s area, is known to be involved with language.) Neuroimaging studies have provided a means to examine these relationships in neurologically healthy participants. This look at the other side of the coin can show if in fact the same brain regions are the ones engaged during normal processing conditions. 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, Frith, & Frackowiak, 1993). The assumption was that the phonological loop system would be engaged to maintain the English letters but not utilized for the Korean characters (since the sounds represented by the characters were unknown to the participants). This latter 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 (Figure 8). Interestingly, activation was also observed in brain structures associated motor-related components of speech, even though the task did not require participants to overtly speak. The speech-related brain activity was thus thought to represent “internal speech” or subvocal rehearsal. In a second experiment, the investigators 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 if each letter in turn rhymed with B. Here the assumption was 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 8). Thus, behavioral and neuroimaging results converge to establish the dissociability of the storage and rehearsal components of verbal working memory.

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FIGURE 8:

PAULESU IMAGING DATA ILLUSTRATING INCREASED ACTIVITY IN LEFT PARIETAL AND LEFT FRONTAL CORTEX

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More recent neuroimaging studies suggest a more complex picture. For example, the duration of activation during the delay period of working memory tasks has been shown to vary in different subregions of Broca’s area (Chein & Fiez, 2001). The investigators hypothesize that the more dorsal region of Broca’s area is involved in the formation of an articulatory rehearsal program, and the more ventral region 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, of course, is what is the true function of the phonological loop in cognition? Surely it did not arise just to help us retain telephone numbers! It
seems intuitive that the phonological loop would have to play some role in language processing, since 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 (A. Baddeley, Gathercole, & Papagno, 1998), a challenge experienced both by children learning their first language and by adults learning a second 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 scaffolding us into learning 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). P.V. was found to be completely unable to learn the Russian equivalent of any words in her native Italian, despite extensive practice (A. D. Baddeley, Papagno, & Vallar, 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 (i.e., Italian words). But her impairment prevented her from being able to accomplish the short-term storage of phonologically unfamiliar items (i.e., Russian words) that apparently is needed to accomplish longer-term learning. Thus, the data support the idea that the phonological loop has 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. A classic experimental study examined these memory functions by having participants answer questions about an outlined capital letter F (Figure 9) (Brooks, 1968). Participants were instructed to “see” the letter in the mind’e eye 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) of the letter? To test whether the participants were using visuospatial representations to do the task, some were instructed to point to the word YES or NO printed irregularly on a page, or 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 (Figure 9).

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FIGURE 9:

BROOKS’S CAPITAL F FIGURE, AND TIME TAKEN FOR POINTING VS. VOCAL RESPONSE

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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 for planning movements of the eyes (or possibly other parts of the body), just as verbal working memory depends on brain systems involved with planning speech (A. D. 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 a person is rehearsing spatial locations in working memory (e.g., think of mentally visualizing driving directions: “TURN LEFT AT THE NEXT BLOCK, AND THEN RIGHT AT THE STOPLIGHT”), they are actually utilizing the same systems that would help you move your eyes or body towards that location. But 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 (E. 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 (e.g., think of being at a party and engaging in a conversation with one friend, keeping your eyes focused on them, while also paying attention to the gestures of another friend to your left out of the corner of your eye), we might also be able to keep remembered locations in memory by covertly focusing our attention on those remembered locations.

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 stored 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 (W. Awh, Jonides, & Reuter-Lorenz, 1998). 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 maintain the location of the cue in order to know how to respond to the probe. In another condition, it was the identity of the cue that had to be maintained. Additionally, during the delay participants had 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. 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 are functionally overlapping, by demonstrating that they both rely upon 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, an opposition that is not surprising given the contralateral organization of these brain regions (Figure 10) (E. Awh & Jonides, 2001; B. R. Postle, Awh, Jonides, Smith, & D'Esposito, 2004). These results suggest that spatial working memory is accomplished by enhancing
processing in brain regions that support visual perceptual processing of those locations. This is precisely the pattern that would be predicted by an attentional account, since it is well known that spatial attention enhances perceptual processing by modulating activity in sensory brain systems.

FIGURE 10:

AWH IMAGING DATA INDICATING ENHANCED ACTIVITY IN VISUAL REGIONS DURING MAINTENANCE PERIOD

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 non-verbal 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 cognitive operations seem to be inherently non-spatial, 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). In monkeys it has been found that this distinction is also present for working memory, with neurons in the dorsal region of the prefrontal cortex showing a selective response to stimuli during a spatial working memory task while neurons in the ventral prefrontal cortex showed a selective response during an object working memory task (Wilson, Scalaidhe, & Goldman-Rakic, 1993). In humans, neurological patients have shown selective impairments on non-spatial 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, Hammond, Levine, & Calvanio, 1988). The reverse pattern has also been observed, demonstrating a double dissociation (Hanley, Young, & Pearson, 1991). Imaging studies have also tended to show dissociations between brain systems involved in spatial and in object working memory (S.M. Courtney, Ungerleider, Keil, & Haxby, 1996; Smith et al., 1995), although these have been most reliable in posterior rather than prefrontal cortex (the region identified in monkey studies). The specific functional 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 controversial.

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
integral part of the model (1) determines when information is deposited in the storage buffers; (2) decides which buffer—the phonological loop for verbal information, 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. The central executive can be seen as controlling and allocating attention. In other words, it decides both how to expend cognitive resources and how to suppress irrelevant information that would consume those resources (A. D. 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 be indirectly related to working memory itself; see Chapter 8 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: participants are given two distinct tasks, one visuospatial and one auditory-verbal, to perform at the same time. (An example would be doing the “corners-of-the-F” task in Figure 8 while at the same time 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 selectively 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 are performed in isolation. The study of patient groups with cognitive deficits is a good One such study matched patients with early-stage
Alzheimer’s disease with healthy adults of the same age (A. D. Baddeley, Bressi, Della Sala, Logie, & Spinnler, 1991). The hypothesis was that much of the cognitive impairment exhibited by people in early stages of the Alzheimer’s can be conceptualized in terms of 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. Importantly, the difficulty of each task could be adjusted for each participant individually to enable them 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 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.

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 maintenance vs. manipulation in working memory: contrast the brain activity occurring in tasks where the information only has to be briefly stored and then recalled (or recognized), against a similar task in which the stored information also has to be mentally transformed in some way. Significantly increased activation was observed when participants in such a study had to arrange a sequence of letters alphabetically, as opposed to simply recalling them in the order given in which they were presented (D'Esposito, Postle, Ballard, & Lease, 1999). A further point: the increased activation was observed in the dorsal regions of prefrontal cortex. This result, and others, suggest that the prefrontal cortex is organized by the different processes of working memory, that
is, simple maintenance recruits ventral regions, and information is manipulated in more dorsal areas (Figure 11) (Owen, 1997; B.R. Postle & D'Esposito, 2000). However, this view is a controversial one (see BOX: DEBATE).

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FIGURE 11:
IMAGING DATA FROM D’ESPOSITO STUDY INDICATING INCREASED DORSAL PFC ACTIVITY UNDER THE MANIPULATION CONDITION

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3.4. Are there really two distinct storage systems?

It seems obvious that we have distinct internal codes for verbal and visual information. But what about the storage of information in working memory? Must verbal and visual information be maintained in two distinct buffers, as the Baddeley 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: when interference with this verbal task was verbal, performance was more impaired; when the interference was spatial, the impairment was less so (A. D. Baddeley, Grant, Wight, & Thomson, 1973). The implication? Competition between two verbal (or two spatial) tasks produced more-impaired performance, an argument 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 has involved the right hemisphere. Thus, the neuropsychological data are consistent with the idea that verbal and visuospatial working memory rely on distinct brain systems.
Imaging 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, Jonides, & Koepppe, 1996). This fits the general finding that language-related functions are more associated with the left hemisphere of the brain, while visual processing is more associated with the right. They have also indicated 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 in perform the task most effectively. This kind of flexible use of the storage buffers—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 is dependent upon 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

In any depiction of a model there are the boxes and the arrows connecting them. We’ve looked at the boxes in the working memory model, 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: 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?

4.1. Mechanisms of Active Maintenance

A place to begin is to ask what is the nature of the memory trace 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 traces occur as a relatively permanent strengthenings (or weakenings) of connections between neural populations. Using the vocabulary of neural net models, we can call these changes weight-based memory, since the memory trace takes its form in the strength or weight of neural connections. While weight-based memories are stable and long-lasting, they are latent, and 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 (R. C. O'Reilly, Braver, & Cohen, 1999). In activity-based memory, information is retained as a sustained or persistent pattern of activity in
specific neural populations. 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 having a thought that you are holding in your mind, such as the point you might want to make in the movie conversation example from the beginning of the chapter. While the information is in this state, in your working memory, it is highly accessible, and can directly influence what words you choose to speak, so you can make your points fluently. But what if instead, your point was lost from working memory? You’d then have to go retrieve it from long-term memory. The information is still around, stored in your brain, but less accessible, until it gets retrieved back into working memory. During the interim, you are likely to be at a loss for words, even when 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 have 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 presented and, after a delay—during which presumably the information associated with the cue must be held in short-term storage—a response is required. Many of these studies are oculomotor, that is, 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 trace observed in these oculomotor studies is held in the activity patterns of single neurons. In particular, certain neurons in the dorsolateral region of prefrontal cortex have shown transient increases in the activity level (as measured by increased firing rate) during presentation of the cue, while 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 12) (Funahashi, Bruce, & Goldman-Rakic, 1989). These sustained responses could not be due to perceptual stimulation: there was no perceptual stimulation during the delay.

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**FIGURE 12:**

**PLOT OF NEURONAL ACTIVITY IN THE DELAYED RESPONSE TASK WITH PREFRONTAL CORTEX NEURONS SHOWING STIMULUS-SELECTIVE INCREASES IN ACTIVITY DURING DELAY PERIOD**
This evidence is of course correlational. Can it be strengthened to show that the activity in these neurons actually serves as the working memory trace? Well, what happens when the animal *doesn’t* look at the area where the cue was displayed? Presumably, it didn’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 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 coded by the neurons in the lesioned area. The lesions had produced “mnemonic scotoma,” or memory-blindspots (Funahashi, Bruce, & Goldman-Rakic, 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 clinical neurosurgical procedures). Instead, the research tool is functional brain imaging, 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; S. M. Courtney, Ungerleider, Keil, & Haxby, 1997).

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 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, since 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
signalling the storage of very selective kinds of information, such as a particular spatial location. This result indicates a further degree of content-based organization of working memory, as discussed previously. Yet it is still not know how widespread such type of content-based organization is in the brain. For example, does it extend to more abstract forms of verbal information, such as semantic meaning? Likewise, it appears as if the neural populations signal information is being stored through a sustained increase of firing rate. But what happens when more than one item is being stored in working memory? How does the brain signal the increase in information?

In animal studies, this has 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 the effects on brain activity as a function of the number of items simultaneously 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 a subset 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 a task known as the \textbf{N-back}. Participants are presented with a continuous stream of items,
such as letters, and instructed to decide, as each item is presented, if it matches one that is 
$N$ items back in the series, where $N$ typically equals 1, 2, or 3 (another variant of the task 
requires participants to directly recall the item $N$ trials back in the series, rather than 
making a match decision). The value of $N$ is varied to examine how performance and 
brain activity varies with load. Thus, given the sequence

$$DFFBCFB$$

the participants may be asked to say yes or no to a match when $N = 1$ (that is, 
does each item in turn match the one immediately preceding it? Also say no if there are 
no preceding items); here the correct answers are no–no–yes–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–yes–yes–no. An elegant aspect of the $N$-back task is that the 
experimenter can hold constant the order of items presented: the only factor that is 
changed is the required response. This means that the possibility of what researchers call 
“confounding variables”—other, extraneous, factors that also change with the task 
condition—is eliminated.

Imaging 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 quite linear relationship (Figure 13) (T. S. 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 seems to require control or executive processes in addition to storage, and that these demands on the central executive also appear to increase with N. Both the identity of an item and its ordinal position must be stored, and then the test item matched. 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 in maintenance processes or executive processes.

A number of studies have tried to address this issue by examining brain activity while working memory works on simpler tasks such as item recognition (as in the task studied by Sternberg that was described above). Here the demands on maintenance far outweigh 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 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 prefrontal and parietal cortex specifically during maintenance (Jha & McCarthy, 2000). The overall picture is still complex, however; a given set size 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 gets selected for storage and also how the maintained information is used.

The imaging and neuronal recording studies provide strong support for the idea that sustained activity in selected neural populations may serve as the working memory trace. 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? Such information is critical 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 appears 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 in a “reverberatory loop” (Hebb, 1949). That is, each neuron in the circuit participates in 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. 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? The computer in fact as well as metaphor might point the way, and psychologists and neuroscientists have begun building small-scale neural models to investigate the mechanisms of working memory. In some of these, the simulated neurons are implemented as computer programs with properties that attempt to capture quite 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 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 that the behavior of model neurons can approximate quite well what has been seen in the experimental data (D. Durstewitz, Seamans, & Sejnowski, 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 activating decays away (Lisman & Idiart, 1995; Usher & Cohen, 1999). Likewise, if irrelevant signals leak into such a circuit, potentially from on-going perceptual input, this can also interfere with the process of reverberation and lead to a decay of the sustained memory signal over time (Brunel & Wang, 2001; D. Durstewitz et al., 2000). Thus, the models can be used to predict the types of task situations that will be most vulnerable to having maintained
information in working memory decay. A final benefit of these models is that they can be watched in real 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 Prefrontal Cortex: Storage or Control?

While 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 primates was recorded in both temporal and prefrontal cortex during performance of a delayed matching task (E. K. Miller, Erickson, & Desimone, 1996). In this variant of item-recognition, intervening distractor items were shown in the delay between presentation of the item and the matching probe. Both temporal and prefrontal cortex showed selective and sustained activation during the delay; however, after a distractor was presented, selective activation disappeared in temporal cortex but was maintained within prefrontal cortex (Figure 14; see BOX: A CLOSER LOOK). In studies that used a spatial variant of the task, the same pattern was observed between parietal and prefrontal activity, the distractors reducing parietal but not prefrontal response (Constantinidis & Steinmetz, 1996). Similar results in humans have been obtained through fMRI studies (Jiang, Haxby, Martin, Ungerleider, & Parasuraman, 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, while posterior brain systems might have different mechanisms for maintaining information over shorter intervals.

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**FIGURE 14:**

**PLOT OF THE MILLER STUDY SHOWING PFC NEURONS WITH STIMULUS SELECTIVE RESPONSES MAINTAINED ACROSS INTERVENING DISTRACTORS**

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In addition to the data suggesting that prefrontal cortex plays a role in maintaining information in the face of distraction, many human imaging studies have suggested that it is also involved in executive functions such as dual-task coordination or manipulation of information within working memory. Experimental neuropsychological research conducted on patients with frontal lobe damage seems to indicate an impairment of central executive functions rather than of working memory per se (see the discussion in Chapter 8) (Stuss & Benson, 1986). What does this say about the Baddeley 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 imaging data be reconciled with cognitive theory? One possible resolution might be segregated subregions of prefrontal cortex that carry out storage and control functions in distinct areas. 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 clearcut distinction, and moreover, they have not been consistently observed (Veltman, Rombouts, & Dolan, 2003).

There is another possibility: that prefrontal cortex is the brain region where goal-related information is represented and actively maintained (T. S. Braver, Cohen, & Barch, 2002; E. K. Miller & Cohen, 2001). In this **goal-maintenance model** (Figure 15), PFC serves *both* a storage and control function: the maintenance of information about a goal (storage) so that it may serve as a top-down influence that coordinates perception, attention, and action to attain that goal (control). The information stored in prefrontal cortex may be providing a context that aids the interpretation of ambiguous situations and the response to them. Just how might this work? Here’s an example.

Suppose you have a regular route you drive, perhaps from a job to your apartment or house. 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 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 prefrontal cortex, and this activation flows from prefrontal cortex to behavioral systems of 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.

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FIGURE 15:

DIAGRAM OF THE GOAL MAINTENANCE MODEL OF PFC FUNCTION SHOWING RECIRCULATORY ACTIVITY AND BIASING

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The goal-maintenance theory of prefrontal involvement in working memory appears to be consistent with a wide range of both human and animal data (E. K. Miller & Cohen, 2001). For example, 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 trace of the input, but rather something like the task-relevant features or behavioral rules of the situation (e.g., if the light is red, then press the left button, E. K. Miller, Freedman, & Wallis, 2002). Because what is being maintained in the prefrontal cortex is the information that is most relevant for
performing the task at hand, it could potentially be used bias how new information gets interpreted and how actions get 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 which that the storage and control mechanisms could indeed work together to produce the patterns of performance humans and animals exhibit in working memory tasks (T. S. Braver et al., 2002; R.C. O'Reilly, Noelle, Braver, & Cohen, 2002). The theory goes a long way toward de-mystifying 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, 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 there are types of executive processes other than goal maintenance within prefrontal cortex.

Comprehension Check

1. What is the evidence that suggests 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. Alternative Models and Current Directions

The Baddeley 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 prefrontal cortex—particularly the goal-maintenance model, and the interaction of
storage and control functions—leads to considerations of other hypotheses. The original Baddeley 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 theoretical models of cognition need an update after a while, and Baddeley recently has refined his theory of working memory to account for some limitations associated with the original Baddeley-Hitch model (A. D. Baddeley, 2000). 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 one is overloaded or disrupted, and also 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 of peculiar findings that have accumulated over the years, that could not be easily accounted for in the original theory. 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, 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 up. But what allows us to maintain such information in
working memory, when the amount of words so vastly exceeds standardly recognized capacity limits (which are at most $7 \pm 2$ items)? One possibility, as Miller would have argued, is that we can chunk the information into larger, more meaningful units than single words – maybe idea units. But how and where does such integration occur? It seems intuitive that it might be in the phonological loop, since this holds verbal information. Yet the phonological loop is thought to use a sound-based code rather than a meaning-based one. Likewise, patients like P.V. who are thought to have a completely damaged phonological loop still show the sentence effect: she has a word span of 1, but a sentence span of 5 (Vallar & Baddeley, 1984). That is still lower than the normal range of 15-20, but it indicates that she might have been able to utilize an back-up 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 new idea, and so has not been put through 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 has indicated as much himself (A. Baddeley, 2003), which indicates 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 described above.

5.2. The Embedded Process Model

An influential view of working memory that provides an alternative to the Baddeley model is the *embedded process model* (Cowan, 1988, 1999). In this model, a
distinction is made between three categories of memory: inactive long-term memories, activated elements of long-term memory and activated information maintained within the focus of attention. Information in the focus of attention is only a subset of the set of activated memory elements, and these in turn are only a small subset of the full complement of the stored knowledge in long-term memory. The embedded nature of the different types of memory are what give the theory its name (see Figure 16). Both activated long-term memory and information in the focus of attention are thought to be highly accessible, and so might be seen as being part of working memory. However, information not in the focus of attention decays relatively quickly, whereas active information that is directly attended can be maintained indefinitely. An interesting prediction of this model is that some information that may be held in working memory—the portion that is activated long-term memory but outside the focus of attention—may not be consciously accessible. The close linkage of working memory and long-term memory in this view accounts for data that have suggested that working memory capacity is affected by long-term memory factors, such as familiarity of information. The embedded process model, like the goal-maintenance account suggests that different types of information may be maintained differently. Goal-relevant information is likely to be maintained within the focus of attention, and as such may require distinct (prefrontal) mechanisms for its storage.

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**FIGURE 16:**

**DIAGRAM OF THE EMBEDDED PROCESS MODEL**

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5.3. **Person-to-Person Variation**

A current focus of research on working memory is that of individual differences in working memory capacity. We vary widely in our ability to maintain items in working memory, and especially in maintaining these items despite interference. Because working memory appears to be so important for higher cognition and thinking, it is not surprising that these individual differences are associated with success in academic examinations (like the SAT tests) and the learning of new and complex cognitive skills (like computer programming). Indeed, some researchers have suggested that working memory capacity is approximately synonymous with 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 the critical one for predicting cognitive success and general intellectual ability.

A standard task for measuring working memory capacity, such as the one presented in Figure 2, essentially asks how many items a participant can store in working memory in the face of distraction. 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 higher-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 “executive attention”—the ability to keep goal-relevant information actively maintained in the face of interference (R.W. 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. The investigators have shown that executive attention is distinct from short-term storage capacity and that it is executive attention, not short-term storage capacity, that correlates strongly with fluid intelligence and cognitive abilities (R. W. Engle, Tuholski, Laughlin, & Conway, 1999). Further, they 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.

This idea has been recently tested in an imaging study that examined the brain response to distracting information occurring during performance of the N-back task (Gray, Chabris, & Braver, 2003). Distractors were items that had recently repeated but were not task-specified targets (e.g., the second F in the following sequence “B-T-R-F-T-F” where the task is to look for N=3 matches). Individuals measuring high in fluid intelligence (which is highly similar to working memory capacity) were found to have a stronger activation response in the prefrontal cortex during distractor trials, even though there was no reliable difference among individuals for non-distractors. Thus people with high working memory capacities (or fluid intelligence), as defined by the executive attention model, may be better able to keep goal-relevant information highly activated and ready for use when needed.

5.4. The Role of Dopamine
In addition to patients suffering from certain forms of brain damage, researchers have found that a number of populations suffering from 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 higher cognition it is obvious 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 brain chemical dopamine is especially important for working memory. Drugs that increase levels of dopamine in the brain or facilitate the action of dopamine can enhance working memory capabilities (Luciana, Collins, & Depue, 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 the clinical relevance of this work, it also may impact our understanding of how working memory normally functions 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, or by signaling when information in working memory should be updated (T.S. Braver & Cohen, 2000; D. Durstewitz, Kelc, & Gunturkun, 1999; Servan-Schreiber, Printz, & Cohen, 1990). Neurophysiological research suggests that dopamine can act as a filter, amplifying strong signals and attenuating 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 prefrontal cortex—the brain region that may be most important for keeping maintained information protected from distraction. Thus, a reasonable hypothesis is that dopamine input to prefrontal cortex might be the neural mechanism that provides that region with interference-protection capabilities. Finally, there is some indication that dopamine levels and activity are highly variable, both over time within a person (King, Barchas, & Huberman, 1984) and across a population (Fleming, Bigelow, Weinberger, & Goldberg, 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, D'Esposito, & Farah, 1997; Mattay et al., 2003).

Comprehension Check

1. What distinguishes the embedded process model of working memory from the Baddeley 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. It serves as a “mental blackboard” that enables temporary storage and computation. 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, as in the movie conversation at the beginning of the chapter, 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 higher 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? Think about the movie conversation as an example.

2. *How did the modern view of working memory arise?*

Early notions of working memory strongly linked it to consciousness and attention; 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 items is the maximum capacity of short-term storage; (2) information may rapidly decay from short-term storage if not attended; (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. In response, the Baddeley-Hitch model reformulated the notion of short-term memory into the modern concept of working memory, postulating multiple storage components and emphasizing the interaction with control processes.

Think critically:

• Do you think that working memory is just consciousness, and vice versa? Why or why not?
• Short-term storage is thought to be severely limited in both capacity and duration. Can you think of any advantages this might confer? What might the world be like if both were unlimited?

3. What are the elements of working memory?

The Baddeley model has three components: the phonological loop (which stores and reinforces verbal information); the visuospatial scratchpad (which enables mental imagery and navigation); and the central executive (which directs information to one or other of the other two components and coordinates, integrates, and manipulates that information). A number of lines of converging evidence from behavioral studies, neuropsychological patients and brain imaging data have suggested that visuospatial and verbal working memory involve distinct storage buffers. Imaging studies have provided
some support for a distinction between maintenance and manipulation processes; manipulation of information seems to rely on lateral prefrontal cortex.

*Think critically:*

- How might studies of working memory in individuals who are blind or deaf (i.e., sign-language speakers) inform our understanding of short-term storage buffers?
- One theory of the phonological loop suggests that it is based out of 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 heightened sustained activity during delay (that is, storage) 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 the TMS technique 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. Imagine that you could scan the brains of such individuals while they performed working memory tasks, such as the N-back or Sternberg item-recognition task. What patterns might you predict you would find?

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

There are currently a wide variety of different theoretical models about the structure and components of working memory. Some, like the Baddeley 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 embedded process model, suggest that there is a special storage mechanism—the focus of attention—for information that is goal-relevant. Still others, like the goal-maintenance and executive-attention accounts, 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 involves a variety of mechanisms. An important direction for future research will
be to better determine the precise relationship between executive processes and working memory.

*Think critically:*

- Working memory capacity is thought to be strongly correlated with higher cognitive abilities and predictive of tests like the SAT and GRE. If this is true, 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 2? 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. Is it ethical to allow such a drug to be made widely available? If you were involved in making such a policy decision, what factors would influence your decision?
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FIGURE LEGENDS

Figure 1: The computer metaphor about the structure of working memory. In this metaphor, working memory (WM) corresponds to the RAM of a computer, while long-term memory (LTM) corresponds to the computer’s hard drive (HD). [ORIGINAL DRAWING]

Figure 2: A standard test of working memory capacity. In each line you need to determine whether the math problem is correct or not—say “YES” or “NO”. Then look at the word that follows the problem and memorize it. To do this test yourself, cut out a window in a blank sheet of paper so that it exposes only one line at a time. Move through each line quickly, saying “YES” or “NO” out loud to the math problem and then memorizing the word. After you have finished all of the lines, try to recall each word in order. The number you get correct is an estimate of your working memory capacity (or span). [ORIGINAL DRAWING]

Figure 3: Short-term recall related to delay interval in the Brown-Petersen task. Plotted is the accuracy of participants in recalling short consonant strings. Accuracy decays to about 50% by 6 seconds and almost to zero by 18 seconds. Source:

**Figure 4:** Recognition time related to memory set items in Sternberg item recognition task. Plotted is the reaction times of participants in making probe recognition judgments. As memory set size (the number of items to be memorized) increases from one to six, reaction time increases in a linear manner with about a 40 millisecond increase per additional item. Source: Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. In W. G. Koster (Ed.), *Attention and performance II*. Amsterdam: North-Holland.

**Figure 5:** 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. Source: Atkinson, R. C., & Shiffrin, R. M. (1968). Human memory: A proposed system and its control processes. In K. W. Spence (Ed.), *The psychology of learning and motivation: Advances in research and theory* (pp. 89-195). New York: Academic Press.

**Figure 7:** Independence of word length and phonological similarity. Accuracy of participants performing an immediate recall task with five words that were either phonologically similar (sounded the same) or dissimilar, and were either short (two-syllable) or long (four-syllable). Both similarity and long words decrease recall performance. But the parallel nature of the lines indicate that the two effects are independent. Source: [ADAPTED FROM] Longoni, A. M., Richardson, J. T. E., & Aiello, A. (1993). Articulatory rehearsal and phonological storage in working memory. *Memory and Cognition, 21*(1), 11-22.

**Figure 8:** Brain activation during verbal working memory. The left panel shows activation in left inferior frontal cortex, or Broca’s Area (green ellipse) and inferior parietal cortex (blue ellipse). The right panel indicates that the left frontal activity was above baseline during both a verbal working memory and rhyming task. The parietal activity was only above baseline for the memory task, suggesting it might be selective to phonological storage. Source: Paulesu, E., Frith, C. D., & Frackowiak, R. S. J. (1993). The neural correlates of the verbal component of working memory. *Nature, 362*, 342-345.

**Figure 9:** Visuospatial imagery and interference task. The left panel shows the “F” figure used in the Brooks task. Participants were instructed to imagine the figure. Then, starting at the asterisk they were to mentally traverse across each corner of the figure in a clockwise manner and indicate whether that corner was at the
extreme top or bottom of the figure. Right panel indicates time to respond when they had to speak each answer, or instead point to the correct word (YES or NO) written on a page. Pointing took much longer, indicating that the spatial movements interfered with the mental navigation process. Source: Brooks, L. R. (1968). Spatial and verbal components in the act of recall. *Canadian Journal of Psychology, 22*, 349-368.

**Figure 10:** Enhanced activity in visual brain regions during spatial working memory. The upper panel shows the spatial working memory task performed by participants, which required memorizing the spatial location of a vertical bar in order to later judge whether it was to the left or right of two probe bars presented after a delay period. During the delay the visual system was stimulated with a flashing checkerboard. The lower left panel shows visually-sensitive brain regions that increased in activity during the delay period (white color). The lower right panel indicates that activation was reliably greater in the hemisphere opposite to side of display where the cue was shown (right hemisphere for this example; also indicated in left panel with blue ellipse), reflecting the contralateral organization of the brain. Source: Postle, B. R., Awh, E., Jonides, J., Smith, E. E., & D'Esposito, M. (2004). The where and how of attention-based rehearsal in spatial working memory. *Brain Res Cogn Brain Res, 20*(2), 194-205.

**Figure 11:** Activity in prefrontal cortex during maintenance vs. manipulation in working memory. Shown are brain slices from a representative participant with
active brain regions in the prefrontal cortex (uppermost part of each slice) shown in white. The leftmost slices highlight ventral regions of prefrontal cortex and rightmost slices highlight dorsal prefrontal regions. The top row shows activity in the maintenance-only condition of the task, the middle row shows activity in the manipulation condition (alphabetization) and the lower panel shows regions that were significantly more active in manipulation than in maintenance. Ventral prefrontal cortex was active in both maintenance and manipulation, but dorsal prefrontal cortex was active only in manipulation. Source: D'Esposito, M., Postle, B. R., Ballard, D., & Lease, J. (1999). Maintenance versus manipulation of information held in working memory: An event-related fMRI study. *Brain and Cognition, 41*, 66-86.

**Figure 12:** Neuronal activity in monkey prefrontal cortex during a delayed response task. Right panel shows events in delayed response task: a cue (gray ellipse) is briefly presented in one of 8 spatial locations; during a delay period the monkey must maintain this location (dotted ellipse) in working memory; following a go signal (removal of the crosshair) the monkey makes an eye movement toward the remembered location. The right panel shows averaged activity traces during the task trial for a representative neuron in prefrontal cortex. Each trace represents activity during the trial where the cue was presented in the corresponding spatial location. In each trace the thin vertical bars represent trial events; the delay period occurs between the rightmost two bars. For the neuron shown, activity was selective to spatial location, such that it only increased during the delay when
the cue was presented directly below the cross-hair (270 degrees). Source: Funahashi, S., Bruce, C. J., & Goldman-Rakic, P. S. (1989). Mnemonic coding of visual space in the monkey's dorsolateral prefrontal cortex. *Journal of Neurophysiology, 61*(2), 331-349.

**Figure 13:** Working memory load effects in prefrontal cortex during the n-back task. Left panel shows brain surface with colored areas indicating regions of prefrontal cortex that demonstrated increased activity with working memory load. Right panel shows change in activation level as a function of n-back condition (N=1, 2 or 3) for a representative region (indicated with black ellipse in left panel). Activation linearly increases as N increases. Source: Braver, T. S., Cohen, J. D., Nystrom, L. E., Jonides, J., Smith, E. E., & Noll, D. C. (1997). A parametric study of prefrontal cortex involvement in human working memory. *Neuroimage, 5*(1), 49-62.

**Figure 14:** Neuronal activity in monkey prefrontal cortex during distractor periods. Left panel shows memory task, which requires memorizing a sample (the first object shown in a trial) and responding when a match appears after a variable number of intervening distractor objects. Right panel shows trace of average neuronal activity in prefrontal cortex during distractor periods following presentation of sample objects 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. Source: Miller, E. K.,

**Figure 15.** 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. Feedback connections enable the maintained activity to bias the internal associations that are activated in response to perceptual input, which enables the goal-information to provide control over thoughts and behavior. Source: [ADAPTED FROM] Braver, T. S., Cohen, J. D., & Barch, D. M. (2002). The role of the prefrontal cortex in normal and disordered cognitive control: A cognitive neuroscience perspective. In D. T. Stuss & R. T. Knight (Eds.), *Principles of Frontal Lobe Function* (pp. 428-448). Oxford: Oxford University Press.

**Figure 16.** The embedded-process model. In this model, activated memory is thought to be a subset of the total knowledge stored in long-term memory. In turn, information in the focus of attention is a subset of activated memory. Both of these latter components could be considered components of working memory, but we are only conscious of information in the focus of attention. Source: [ADAPTED FROM] Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system. *Psychological Bulletin, 104*, 163-191.
KEY TERMS

Working memory

The cognitive operations that enable the short-term storage and mental manipulation of information. Working memory serves as a mental blackboard – a temporary workspace for keeping information in a highly accessible state so that it can be inspected and transformed in service of complex cognitive tasks.

Working memory capacity

A measure that describes the maximum amount of information an individual can store in an accessible form within working memory. Working memory capacity is thought to be related to person-to-person differences in a number of cognitive abilities.

Primary memory

An older term used to describe working memory, first used by William James in the 19th century. The term emphasizes the need for a separate memory system that provides an initial storage site for perceptually experienced information which enables this information to remain accessible to consciousness.

Chunks

Higher-level groupings of information stored in working memory. Such groupings increase the effective storage capacity, by enabling multiple bits of information (e.g., the digits 3 1 4) to be treated as a single unit (e.g., the number 314).
Short-term memory

An alternate term for working memory that emphasizes the limited duration of this storage system, which distinguishes it from the more permanent long-term memory.

Brown-Peterson task

A task developed in the 1950s to examine the duration of storage within short-term memory. The task involves memorization of a short consonant string immediately followed by a distraction period of varying length before the string is recalled. A typical finding is that recall accuracy is close to zero after about 18 seconds.

Modal model

A theory of information processing, first developed by Atkinson and Shiffrin in the 1960s, that emphasizes the role of short-term memory as an entryway for information to pass through before entering long-term memory. According to this view, the function of short-term memory is to control and enhance the information that is stored in long-term memory via coding and rehearsal strategies.

Baddeley-Hitch model

A currently influential model of working memory, that emphasizes the need for short-term storage information to enable complex cognitive activities, such as reasoning and problem-solving. In the model there are two distinct short-term storage buffers, one
for verbal information and one for visuospatial information, which interact closely with
a control system that decides when information gets stored and how it is used.

**Central executive**

The control system component of the Baddeley-Hitch working memory model.

This central executive governs the operation of the two storage buffer systems.

**Phonological loop**

The storage buffer component of the Baddeley-Hitch working memory model that
is responsible for maintaining verbal information.

**Visuospatial scratchpad**

The storage buffer component of the Baddeley-Hitch working memory model that
is responsible for maintaining visuospatial information.

**Phonological store**

The sub-component of the phonological loop responsible for storage of verbal
information in the form of a sound-based (phonological) code.

**Articulatory rehearsal**

A sub-component of the phonological loop that is responsible for actively
refreshing information in the phonological store, so that it does not decay. It is thought
that the refreshment occurs by transferring the stored information from a sound-based
code to a speech-based (articulatory) code, and then back again, in a reverberatory, or loop-like manner.

**Phonological similarity effect**

The reduction in working memory performance that occurs when verbal items that have similar sounds (e.g., D, B, T, V) must be simultaneously stored. The effect is thought to be caused by confusions that arise when similar sound-based codes are activated for the different items within the phonological loop.

**Word length effect**

The reduction in working memory performance that occurs when storing items that take a long time to speak (e.g., university, individual). The effect is thought to be caused by the increased time required to translate such items into a speech-based code.

**Articulatory suppression**

The disruption of the phonological loop, and in particular the articulatory rehearsal process, caused by overtly producing irrelevant speech (e.g., saying the word “the” out loud repeatedly) while at the same time maintaining information in working memory.

**Spatial rehearsal**
The process of mentally refreshing spatial locations stored in the visuospatial scratchpad. Spatial rehearsal is thought to involve mental (covert) movement of the eyes or body toward the stored locations.

**Dual-task coordination**

The process of performing two distinct tasks, each of which typically involve storage of information in working memory. The coordination of storage demands is thought to require the engagement of the central executive.

**Maintenance vs. Manipulation**

Working memory tasks involving only maintenance require only that information be stored for a short duration and then recalled or recognized. In contrast, working memory tasks involving manipulation require that the stored information be mentally transformed in some way (such as alphabetizing verbal information) prior to recall or recognition.

**Content-based organization**

A theoretical account in which maintenance in working memory is thought to occur in different regions of the prefrontal cortex according to the content of information being stored (e.g., verbal, spatial or object).

**Process-based organization**
A theoretical account in which different working memory processes (storage and executive control) are thought to be carried out in different regions of the prefrontal cortex. This account contrasts with the content-based organization account in that different types of information are thought to be processed within the same brain regions.

**Weight-based memory**

A form of memory storage that occurs by strengthening (or weakening) the connections, or weights, between neural populations. This type of memory storage is thought to best characterize long-term memory because the changes are stable and long-lasting, but are only revealed when the relevant pathways are excited by input (e.g., a retrieval cue).

**Activity-based memory**

A form of memory storage that occurs through a sustained or persistent increase in activity within specific neural populations. This type of memory storage is thought best to characterize short-term, working memory because the information is more highly accessible but less permanent.

**Delayed response task**

An experimental task used frequently in animal research to study the neural basis of simple forms of working memory. The task involves a briefly presented cue that is removed during a short delay period, during which the cue information must be held in short-term storage in order to make the appropriate response to a later signal.
N-back task

An experimental task used frequently in human research to study how the brain responds to increases in working memory load – the number of items that must be simultaneously stored and manipulated. A typical version of the task involves presentation of a continuous series of items, with participants required to judge for each item whether it matches an item presented N items back in the series, where N equals 1, 2 or 3.

Reverberatory loop

An hypothesis about the neural basis of short-term storage in working memory in which a circuit of connected neurons recirculates activity among themselves, through a process of mutual communication, with each neuron both sending and receiving signals regarding the information being stored. The neurons in the circuit mutually support one another so that the stored information does not decay or degrade.

Goal-maintenance model

A theoretical account of how the storage and control functions of working memory might be integrated within the prefrontal cortex. The prefrontal cortex is thought to actively maintain goal-related information (storage) so that this information can serve as a top-down influence that coordinates perception, attention and actions necessary to attain the goal (control).
**Episodic buffer**

A third storage buffer, recently added to the Baddeley model of working memory. The episodic buffer may serve as a storage site in which complex, multi-modal information (such as temporally extended events or episodes) can be stored and integrated, and may also serve as an auxiliary buffer for when the primary one becomes overloaded or disrupted.

**Embedded process model**

An alternative model of working memory, which distinguishes between three components of memory, where each is an embedded subset in the one following it: activated information in the focus of attention, activated long-term memory, and inactive long-term memory. Both activated long-term memory and information in the focus of attention are thought to be highly accessible, and so similar to standard views of working memory; however, only information in the focus of attention is accessible to consciousness.

**Executive attention**

A component of working memory that relates to the ability to keep goal-relevant information actively maintained in the face of interference. Evidence suggests that this ability might be the component of working memory capacity that varies most strongly from person to person, and which might relate to individual differences in fluid intelligence and higher cognitive abilities.
Dopamine

A brain chemical that is thought to be especially important for working memory. Dopamine may help keep information active in the face of interference, by filtering out background noise, and may also be important for updating the contents of working memory.
A CLOSER LOOK: Mechanisms of working memory storage in the monkey brain

Space limitations prevent us from describing each experiment in detail, but to get an idea of the logic of experimentation it is useful to look at the details of at least one study cited in the text. For this purpose, we consider the Miller et al (1996) experiment just mentioned in the text.

Introduction

The investigators are 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 an electrode into neurons into the cortex of macaque monkeys. In one study, 135 neurons in 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). Recordings were conducted 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 visual line-drawn objects (see Figure 14). The monkey was instructed (through gradual, rewarded training) to release a lever when the currently presented object matched the “sample” – which was the first object presented in the trial. Between the sample and the match, anywhere from 0-4 intervening non-match objects might be presented, which were to be ignored.

**Results**

In both the temporal and prefrontal cortex, many of the neurons were found to be stimulus-selective, which means they showed a greater response when one object was presented as the sample relative to other objects. Importantly, this stimulus-selective response was retained when the sample was removed from the display. Moreover, in the prefrontal cortex neurons the stimulus-selective activity persisted even across the presentation of intervening distractor items, and so was present up until the presentation of the match item (see Figure 14). However, in the temporal cortex, the stimulus-selective response was abolished following the presentation of the first and subsequent distractors.

**Discussion**

The finding that neurons in 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 stimulus-selective response across intervening distractor items suggests that the two brain regions
play 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.
**DEBATE: How are working memory functions organized in the brain?**

The Baddeley 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? The prefrontal cortex is thought to be an important component of working memory, based on both neuroimaging studies in humans and neural recording studies in monkeys. 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 while 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 (different types of information 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 has tended to find that dorsal prefrontal cortex is engaged by working memory tasks that involve both maintenance and manipulation, whereas only ventral prefrontal cortex is active when the task requires only simple maintenance. Thus, the human neuroimaging data have been argued to support a **process-based organization** (storage vs. executive control processes are carried out in different regions). The resolution to the controversy is not yet clear, but some researchers have suggested the two sets of findings may not be fundamentally incompatible (Smith & Jonides, 1999).
Figure 1
Computer Metaphor of Memory
IS (5 x 3) + 4 = 17?  BOOK
IS (6 x 2) - 3 = 8?  HOUSE
IS (4 x 4) - 4 = 12?  JACKET
IS (3 x 7) + 6 = 27?  CAT
IS (4 x 8) - 2 = 31?  PEN
IS (9 x 2) + 6 = 24?  WATER

Figure 2
Test of working memory capacity
Figure 3
Peterson & Peterson

Typical Results for Percentage Recalled with the Brown/Peterson & Peterson Technique

Percent recalled

Recall interval (in seconds)
Sternberg's Mean results on the Memory Scanning Task
The Atkinson-Shiffrin Memory Model

Environmental Input

Sensory registers
  - Visual
  - Auditory
  - Haptic

Short-term memory (STM)
  - Temporary working memory

Long-term memory (LTM)
  - Permanent memory store

Response output
Figure 6
Baddeley-Hitch Working Memory Model

Phonological Loop → Central Executive ← Visuospatial Scratchpad
Figure 7
Independence of Word Length and Phonological Similarity

% Accuracy

Phonologically Dissimilar

Phonologically Similar

Short Words

Long Words
Figure 8
Activation of left frontal and left inferior parietal cortex during working memory
Figure 9
Figure used to demonstrate visuospatial imagery and interference
Figure 10
Enhanced activity in visual perceptual regions during spatial working memory
Figure 11
Activity in prefrontal cortex during maintenance and manipulation in WM

Ventral

Dorsal

Maint.

Manip.

Manip. > Maint.
Figure 12
Neuronal activity in monkey prefrontal cortex during delayed response task

Go -> Move eyes to cue location

Delay (Cue Absent)

Cue Present

Time
Figure 13
Working memory load effects in prefrontal cortex

Memory Load (n-back condition) vs. % Signal Change
Figure 14
Neuronal activity during distractors in prefrontal cortex
The goal-maintenance model

- **Reverberatory Loop**
- **Goal Information (Prefrontal Cortex)**
- **Biasing Effect**
- **Associations**
- **Response**
- **Input**
Figure 16
The embedded-process model

Long-Term Memory

Focus of Attention

Activated Long-Term Memory