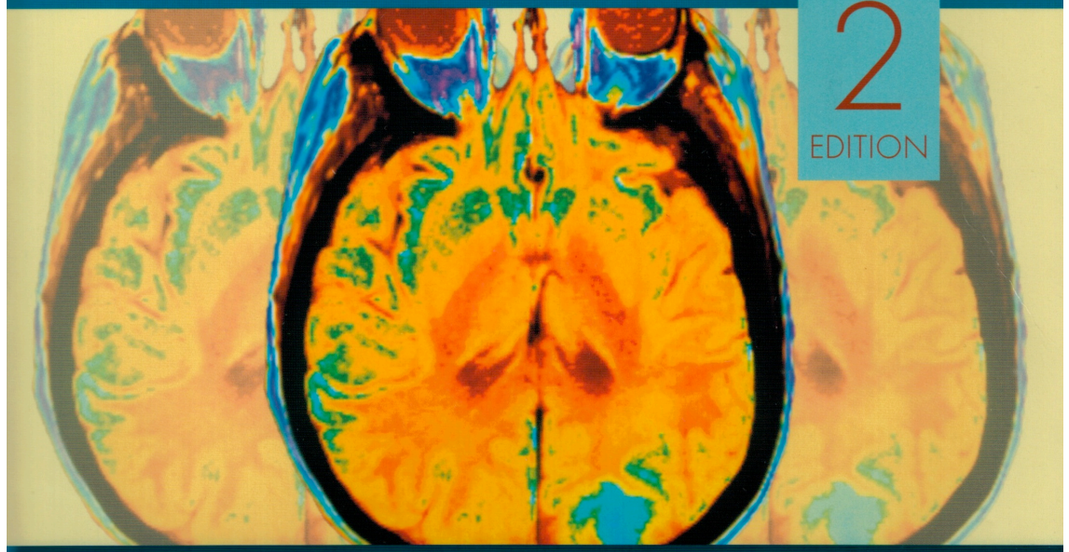
FUNDAMENTALS OF COGNITIVE PSYCHOLOGY

2 EDITION



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CHAPTER 4

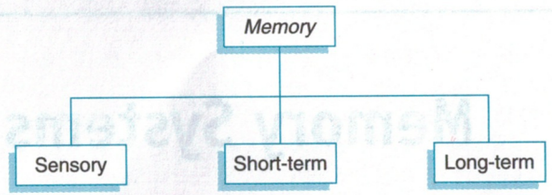
Memory Systems

The topic of this chapter has been studied intensely by psychologists since the pioneering work of Hermann Ebbinghaus more than a century ago (Ebbinghaus, 1885/1964). The intense interest in memory is hardly mysterious. The lives of individuals have meaning only because of memory. Our immediate and distant past defines who we are, what we believe, what we can do, and what we feel. Try to imagine what your life would be like if you lost all memory. Imagine no recollection of where you were born, where you grew up, what you did in school, where you work, whom you live with, what you look like, and even what you thought or did just moments ago. The loss of perception or attention would be tragic, but one would still possess a sense of identity so long as memory remained intact. The loss of memory, by contrast, would steal one's very life and personhood.

How is it possible to remember where you lived five years ago, what you were doing five days ago, or what you were thinking five seconds ago? The central story of memory research has been revealing the complexities of these commonplace achievements of recollection. As will be described here, the three-store model of memory asserts that memory must first be divided into sensory, short-term, and long-term (see Figure 4.1). The first level of a hierarchical system of memory comprises these three stores. As will be seen in this chapter and the next, each of these stores includes subcomponents. The short-term store also is linked with attention in a system called working memory, which will be discussed at the end of this chapter.

Memory involves more than these three separate storage systems. It also involves three basic processes that form mental representations and operate on them. Encoding concerns perceiving, recognizing, and further processing an object or event so that it can be remembered later. The way information is encoded into a mental representation makes a substantial difference in how well it is remembered, as will be seen. It is entirely possible that an event, for example, is forgotten because it was not well encoded in the first place. Encoding must be followed by the successful storage of the event's mental representation in long-term memory. An event may be encoded and held briefly in short-term memory. For it to be remembered over a long period of time, however, it must be stored in long-term memory. The failure to transfer information from short-term memory to permanent storage in long-term memory is another way memory can fail. Finally, retrieval concerns searching

Figure 4.1 A hierarchical memory system: Three basic stores.



long-term memory and finding the event that has been encoded and stored. An event may be encoded properly and stored successfully in long-term memory, yet if this event cannot be retrieved successfully, then it is inaccessible to consciousness.

Memory fails us in multiple ways. Schacter (2001) described seven common malfunctions of memory, which he referred to as the seven "sins" of memory. Transience refers to the rapid loss of memory over short periods of time. In this case, information fails to be transferred into long-term memory. Absent-mindedness refers to breakdowns in attention that prevent encoding the event in short-term memory in the first place. Blocking refers to an inability to retrieve information from long-term memory. Transience, absent-mindedness, and blocking are all, then, sins of omission, malfunctions that result in a loss of memory for information that we would like to remember.

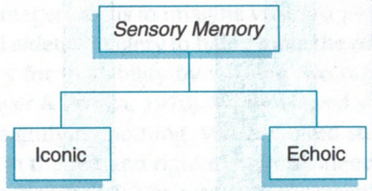
There are also sins of commission, in which we remember incorrect information or information that we would very much like to forget. For example, misattribution of the source of a memory can cause a person to confuse an event that he or she saw in a movie or even dreamed with an event actually experienced. Suggestibility refers to our tendency to become confused in our recollections because of comments made by others about what really happened. Eyewitness testimony about a crime can be incorrect because of misattribution and suggestibility, causing miscarriages of justice in our legal system. *Bias* refers to the way in which our current beliefs affect our reconstruction of the past. Retrieval from long-term memory is biased by the way we think and feel now about the event being remembered. The final sin—*persistence*—is not a distortion of memory but rather an unwelcome imposition of the past in full detail. Repeated retrieval of painful memories that we would much prefer to forget is another sin of commission that we are all familiar with. When a traumatic event persistently intrudes on consciousness, the result can be psychologically debilitating, as happens in post-traumatic stress disorder.

The seven sins of memory documented by Schacter (2001) will be encountered throughout the next three chapters. The sins of omission will be seen in this chapter's presentation of sensory, short-term, and long-term memory and in Chapter 5, where the focus will be on memory encoding processes. In Chapter 6, the focus will be on retrieval processes, and distortions of memory and the persistence of unwanted memories will be discussed.

SENSORY MEMORY

As introduced in Chapter 1, Atkinson and Shiffrin (1968) proposed that human memory is not unitary. According to the three-store model, it is necessary to distinguish among sensory, short-term, and long-term stores that differ in their capacity and duration of storage. Sensory memory refers to the brief persistence of stimuli following transduction. Its function is to permit stimuli to be perceived, recognized, and entered into short-term memory. Without sensory memory, events in the environment would be forgotten as soon as they registered in the nervous system. To date, research has focused on the kinds of sensory memory associated with sight and hearing rather than other sensory modalities such as touch (see Figure 4.2).

Figure 4.2 A hierarchical memory system: Components of sensory memory.

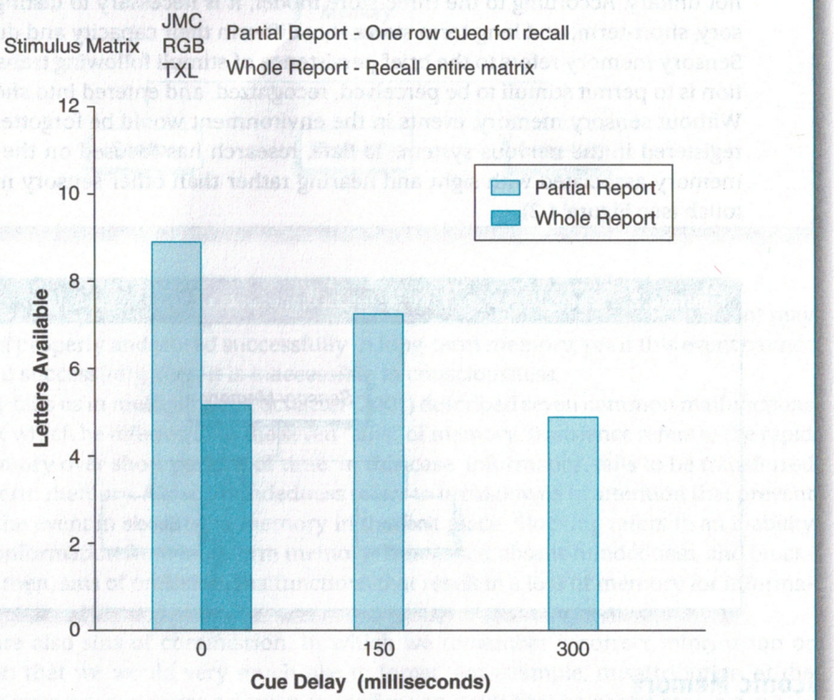


Iconic Memory

In vision, the brief persistence of sensory memory, called **iconic memory**, was investigated by Sperling (1960). An observer saw an array of nine letters presented for only 50 milliseconds using a device called a tachistoscope. A sample array is shown in Figure 4.3 along with the results of the experiment. When immediately asked to recall as many letters as possible, the typical participant managed to report four or five. Sperling called this the "whole report condition." He suspected, however, that all of the letters persisted briefly in iconic storage. But once the letters were located in space, their shapes were specified, and their names were recognized, some letters were lost. In terms of the three-store model, the letters may have been briefly available in iconic memory, but verbally reporting the letters required their conscious recognition and representation in short-term memory. By the time the observer named four or five, the others had faded from sensory storage and were no longer available for processing.

To test his hypothesis, Sperling (1960) arranged a partial report condition in which the observer had to report only the letters from a single row but did not know in advance which row. A high-pitched tone occurred after the 50-millisecond presentation to indicate that only the letters J-M-C needed to be reported. Similarly, a medium-pitched tone cued the middle

Figure 4.3 Partial report task used to study the capacity and duration oficonic memory.



SOURCE: Adapted from Sperling (1960).

row, and a low-pitched tone cued the bottom row. Sperling reasoned that if the observer could report all three letters from a single row without knowing in advance which row would be cued, then the true number of letters available in iconic memory equaled three times the number given under partial report. Sperling then delayed the onset of the partial report cue systematically from 0 to 1 seconds to examine how quickly the iconic storage was lost. As seen in Figure 4.3, with an immediate cue, the observer recalled on average about two and a half letters, implying that nearly all nine letters persisted in iconic storage. But within about 200 to 300 milliseconds, the estimated number of letters available dropped to four or five—no different from the number obtained in the whole report condition.

Sperling's work indicated that iconic memory has a large capacity—greater than what can be reported at once—and a duration of only about 250 milliseconds. Several later experiments by others suggest that the iconic store holds most, if not all, sensations registered

by the retina for a brief period of time (e.g., Averbach & Coriell, 1961).

Visual sensory memory is called iconic memory; it has a large capacity but a brief duration of about 250 milliseconds.

Schacter's (2001) concept of transience as a sin of memory refers to information that fails to be transferred from short-term storage to long-term storage. For most of us, transience in sensory memory is not a problem and persistence is rarely observed. There is, however, the rare case of eidetic imagery, more commonly known as photographic memory, in which details do persist for longer durations. Some college students find that they can remember images of textbook pages they have studied intensively, such that on tests they can retrieve seemingly accurate images of particular pages. Neisser (1981) found that such strong visual imagery skills are more common in children and are usually lost by the end of adolescence. A stringent test for eidetic imagery requires the ability to superimpose one pictorial image held in sensory memory onto another to form a third novel picture, such that what one perceives reflects both input images.

The only clear case of eidetic imagery ever documented was that of Elizabeth, an artist who used powerful visual imagery skills to imagine vividly a picture of her work in progress on a blank canvas; she used eidetic imagery to hallucinate the painting or drawing. Elizabeth was tested in the laboratory for this ability by viewing two random dot patterns, one presented to each eye (Stromeyer & Psotka, 1970). When viewed separately, the 10,000 dots in a pattern looked random, signifying nothing. When viewed stereoscopically (i.e., with the unique patterns presented to the left and right eye simultaneously), they merged to form a recognizable object such as the letter *T*. The researchers presented Elizabeth's right eye with a 10,000-dot pattern for 1 minute. Following a 10-second rest, she viewed the accompanying 10,000-dot pattern with her left eye and, when asked to superimpose the two, immediately reported seeing the letter *T* coming at her. She then looked at both patterns through a stereoscope and confirmed that her eidetic image of the *T* appeared exactly as it should. Note that this implies the ability to retain in memory the precise location of 10,000 random dots! Further tests showed that she could retain the right eye image for up to 24 hours before superimposing on it the left eye pattern. Thus, in this case one finds a strange persistence of sensory memory, an exception to the rule of transience.

Echoic Memory

The auditory system also stores sensations briefly in a component dubbed **echoic memory** by Neisser (1967). Experiments parallel to Sperling's partial report study have been conducted to test the capacity and duration of echoic storage (Darwin, Turvey, & Crowder, 1972; Moray, Bates, & Barnett, 1965). Using stereo headphones, Darwin et al. presented three separate sequences of letters to an individual: one to the left ear; one to the right ear; and one dichotically (to both ears), which is perceived in the center of the head. Using the same comparison of whole report (report all sequences) versus partial report (report the left, right, or center sequence only), the researchers concluded that more items were stored than could be reported, just as in the case of iconic memory. However, the duration of echoic memory seemed to be much longer, on the order of 2 seconds rather than

Auditory sensory memory is called echoic memory; its duration is brief, but aural stimuli such as speech are also stored for longer periods of time in short-term memory.

250 milliseconds, judging from the effects of delaying the partial report cue.

Many subsequent studies have addressed this discrepancy. In reviewing this work, Cowan (1988) concluded that the studies on echoic memory have actually tapped into two phases of storage. The first one is clearly sensory in nature and persists for about 250 milliseconds, comparable to the duration of iconic sensory memory (e.g., Massaro, 1970). The second phase lasts much longer, at least 3 or 4 seconds (Crowder, 1982). Auditory representations persisting for several seconds have been not only perceived but also recognized and named. Hence, the long phase observed in these studies is actually a result of storage in short-term memory (Penney, 1989).

SHORT-TERM VERSUS LONG-TERM MEMORY

All of us have experienced looking up a new telephone number in the directory and then repeating it silently until we reach for the telephone and dial the number successfully. Without silent rehearsal, the meaningless sequence of digits is easily lost from memory if we wait too long to dial or are interrupted. Subjectively, the number seems available only temporarily in a short-term store. Our experience is quite different from the automatic, well-learned recall of our own telephone number. Unlike a number in fragile short-term memory, our own number seems locked permanently in a long-term store from which it can be retrieved with ease. Other numbers less often used, such as that of a friend not called for years, can sometimes also be retrieved from a seemingly permanent form of memory, but only with great effort.

Introspection along these lines has suggested a distinction between short-term and long-term memory from the time of James's *Principles of Psychology* in 1890. James referred to immediate memory of events currently attended to as primary memory and all other memory as secondary. Atkinson and Shiffrin (1968) referred to these as short-term and long-term memory in their three-store model. A classic way to study the distinction between these two kinds of memory stores involves hearing or reading a list of words and then trying to recall them without any restrictions on the order of output. You can try this free recall task by reading aloud each word given in Box 4.1. After doing so, close the book and try to write down as many of the words as you can remember in whatever order you like. Next, check how many words you correctly recalled. In particular, make a note of how many of the first five words you recalled. Next, look at the items in the middle of the list, numbered 6 to 10. Finally, how many of items 11 to 15 did you recall?

Box 4.1 A Demonstration of the Free-Recall Method of Verbal Learning and Memory

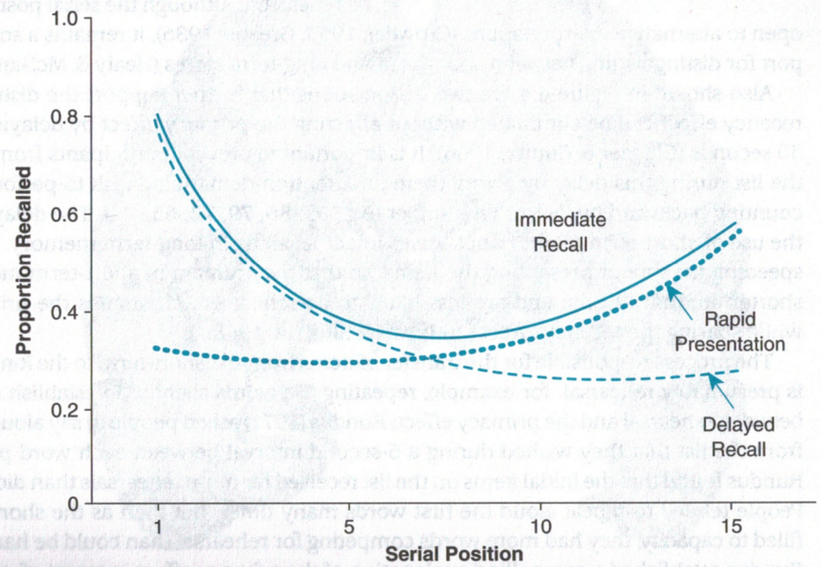
Read each word aloud at a rate of about one per second. Cover up each word as you read, to avoid rereading any items. Alternatively, you can ask a friend to read these words aloud to you. After reading or hearing the words, close the book and try to recall as many words as you can. Do not be concerned about the order of recall. You can write them down in whatever order you like.

1. brick
2. truck
3. stove
4. apple
5. door
6. book
7. ladder
8. rifle
9. pencil
10. lamp
11. goat
12. cabbage
13. baseball
14. tree
15. window

Serial Position Effects

The typical outcome of this free recall procedure, known as the **serial position effect**, is illustrated in Figure 4.4 with the curve labeled "immediate recall." The initial words on the list are

Figure 4.4 Serial position effects and the distinction between short-term and long-term memory.



recalled reasonably well, a phenomenon called the **primacy effect.** If you recalled most or all of the initial items on the list, then you showed a primacy effect. The words in the middle of the list are typically forgotten. Finally, the words at the end of the list are also remembered well; in fact, these are the words most likely to be recalled first. Were these the items you tended to write down first? Did you recall most or all of them? The high level of recall and early output is aptly labeled the **recency effect.** These effects have been known for more than a century (Nipher, 1878).

The serial position effect can readily be accounted for in terms of the Atkinson and Shiffrin model and related mathematical models (Murdock, 1974). Once a word was recognized, it passed from sensory memory to short-term memory. If it remained in short-term memory and was rehearsed, then the word was transferred to the long-term store. Because the short-term store has limited capacity, the initial items on the list remained in the short-term store longer than did the later items. Once the capacity of the store was exceeded, a new word entered only by displacing a previous word. So, the initial list items remained in short-term memory long enough to be transferred via rehearsal to long-term memory. Thus, the primacy effect arises from the retrieval of information from long-term memory. The recency effect, on the other hand, reflects retrieval from the short-term store. The final words on the list still reside in the short-term store and can be retrieved so long as recall is immediate; in other words, they did not need to be rehearsed. Although the serial position effect is open to alternative interpretations (Crowder, 1993; Greene, 1986), it remains a source of support for distinguishing between short-term and long-term stores (Healy & McNamara, 1996).

Free recall of a list of words reveals a serial position effect. The final items in the list are recalled first and well—the recency effect. The initial items in the list are also recalled well—the primacy effect. The three-store model attributes the recency effect to the short-term store and attributes the primacy effect to the long-term store.

Also shown in Figure 4.4 are two dissociations that further support the distinction. The recency effect can be eliminated without affecting the primacy effect by delaying recall for 30 seconds (Glanzer & Cunitz, 1966). It is important to prevent participants from rehearsing the list during this delay by giving them an attention-demanding task to perform, namely, counting backward by 7s from a number (e.g., 93, 86, 79, 72, 65, . . .). The delay eliminates the use of short-term memory but leaves intact recall from long-term memory. By contrast, speeding the rate of presenting the items, so that they remain in short-term memory for a shorter amount of time and are less likely to be rehearsed, eliminates the primacy effect while sparing the recency effect (Atkinson & Shiffrin, 1968).

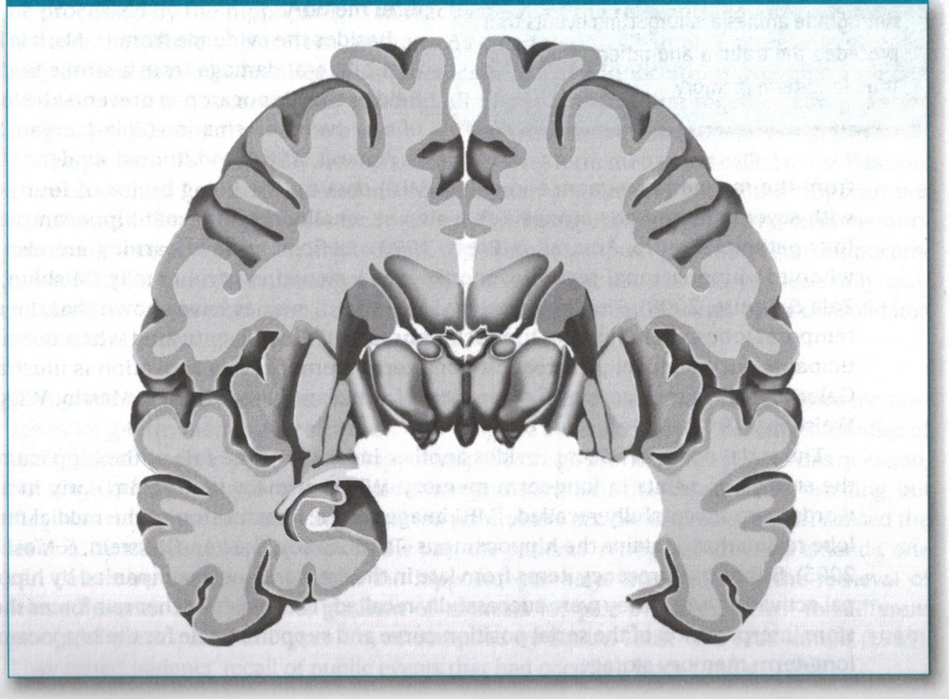
The process responsible for the transfer of items from the short-term to the long-term store is presumably rehearsal, for example, repeating the words silently. To establish a direct link between rehearsal and the primacy effect, Rundus (1971) asked people to say aloud any words from the list that they wished during a 5-second interval between each word presentation. Rundus found that the initial items on the list received far more rehearsals than did later items. People tended to repeat aloud the first words many times, but then as the short-term store filled to capacity, they had more words competing for rehearsal than could be handled. Thus, Rundus established a compelling explanation of the primacy effect in terms of rehearsal.

Neurological Dissociations

Another reason for distinguishing short-term memory from long-term memory came from the study of amnesia, specifically **anterograde amnesia.** This refers to difficulty in remembering events that occur after the onset of amnesia. **Retrograde amnesia,** on the other hand, refers to the loss of memory of events that occurred prior to the onset of the illness.

Anterograde Amnesia. In a famous case, a patient known by his initials, "H. M.," suffered from untreatable epilepsy. He finally found relief from violent seizures following the bilateral surgical removal of the frontal portions of the medial temporal lobe, including the hippocampus. Illustrated at the left of Figure 4.5 is a normal hippocampus in the left medial temporal lobes. At the right of the figure, bilateral lesions of the hippocampus are shown, similar to those produced in the anterior region of H. M.'s medial temporal lobe. Although the operation was a success in treating the epilepsy, H. M. suffered severe anterograde amnesia as a consequence.

Figure 4.5 The loss of the hippocampus in H. M. is illustrated at the right of the figure. At the left of the figure, the normal position of thehippocampal formation is shown for comparison. In H. M., the loss was bilateral, affecting both the right and left medial temporal lobes.



Milner (1966) described H. M.'s memory loss in the following words:

> He could no longer recognize the hospital staff, apart from Dr. Scoville himself, whom he had known for many years; he did not remember and could not relearn the way to the bathroom, and he seemed to retain nothing of the day-to-day happenings in the hospital. . . . A year later, H. M. had not yet learned the new address, nor could he be trusted to find his home. . . . He is unable to learn where objects are usually kept. (p. 113)

Milner (1966) and her colleagues used several tests to document in detail the nature of H. M.'s loss of memory. They found that he showed profound deficits in learning and remembering both verbal material, such as word lists, and nonverbal material, such as faces and sequences of lights. Specifically, Milner concluded that such anterograde amnesia reflected a failure to transfer information from short-term into long-term memory. Other cases of anterograde amnesia confirm this conclusion. Amnesia patients show a strong recency effect in recalling a list of words, much as do normal control participants (Baddeley & Warrington, 1970). Short-term memory per se is fine. However, the patients showed no primacy effect at all, as would be expected if their problem centered on difficulties in transferring new events into long-term memory.

Anterograde amnesia is forgetting events that occurred after brain trauma. It appears to reflect a disruption in the transfer of events to long-term memory during learning. Retrograde amnesia is forgetting events that preceded the trauma and reflects forgetting from long-term memory.

Besides the evidence from H. M., it is known that bilateral damage from a stroke to the CA1 field of the hippocampus prevents the learning of new event information (Zola-Morgan, Squire, & Amaral, 1986). Additional evidence comes from the magnetic resonance imaging (MRI) data on the living brains of four patients with severe anterograde amnesia that show a smaller than normal hippocampus in all four patients (Squire, Amaral, & Press, 1990). Deficits in new learning are also found when the hippocampal region of monkeys is lesioned experimentally (Mishkin, 1978; Zola & Squire, 2000). Finally, functional MRI (fMRI) studies have shown that the medial temporal lobes, including the hippocampus, are bilaterally activated when normal participants encode novel pictures into long-term memory. This activation is illustrated in Color Plate 4 in the section of color plates from a study reported by Martin, Wiggs, and Weisberg (1997).

The serial position effect provides another indicator of the role of the hippocampus in the storage of events in long-term memory. When primacy items from early in a list of words were successfully recalled, fMRI images revealed activation of the medial temporal lobe region that contains the hippocampus (Talmi, Grady, Goshen-Gottstein, & Moscovitch, 2005). By contrast, recency items from late in the list were not accompanied by hippocampal activation when they were successfully recalled. This result further reinforces the dual-store interpretation of the serial position curve and supports a role for the hippocampus in long-term memory storage.

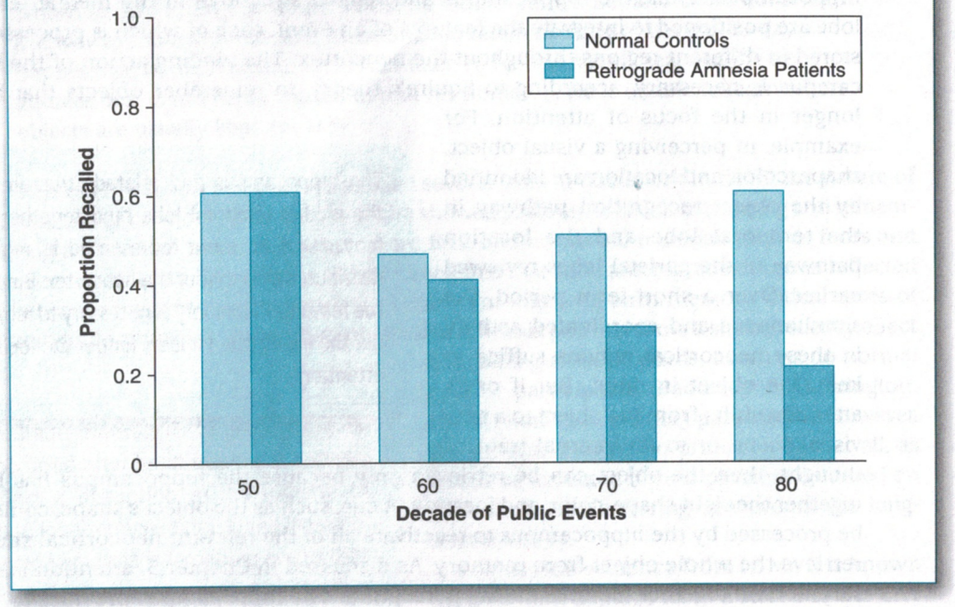
Squire (1992) theorized that the hippocampus binds together the various places in the neocortex that process different features of a new event, such as the shape, color, and location of a visual object. In primates, these areas of the neocortex project to the hippocampus. Thus, the hippocampus and related structures in the medial temporal lobe are positioned to integrate the features of an event, each of which is processed and stored in different regions throughout the neocortex. The binding action of the hippocampus is necessary, according to Squire's theory, to remember objects that are no longer in the focus of attention. For example, in perceiving a visual object, shape, color, and location are identified by the object recognition pathway in the temporal lobe and the location pathway in the parietal lobes reviewed earlier. Over a short-term period, the simultaneous and coordinated activity in these neocortical regions suffice to keep the object in mind. But if one's attention shifts from the object to a new visual scene or to an internal train of thought, then the object can be retrieved only because the hippocampus has bound together the right shape, color, and location. A cue, such as the object's shape, could then be processed by the hippocampus to reactivate all of the relevant neocortical sites and retrieve the whole object from memory. As discussed in Chapter 3, attention is necessary to bind together features during perception. The hippocampus provides an index of where in the neocortex one can find all of the features that together compose the memory representation of the object.

The hippocampus and related structures in the medial temporal lobe bind together the features of an event represented in regions distributed throughout the neocortex. Binding the features in memory is necessary to remember the event when it is no longer the focus of attention.

The process of successfully storing an event in long-term memory is called **consolidation**. Once an event is fully consolidated in long-term memory, then the task of the hippocampus in indexing and binding features is completed. Retrieving the event from long-term memory can then proceed without the involvement of the hippocampus. Activation of the hippocampus would be found in retrieving a recently learned event that has not yet been fully consolidated in neocortical areas, but not in retrieving an event that has been consolidated (McClelland, McNaughton, & O'Reilly, 1995).

Retrograde Amnesia. Given that the hippocampus is needed to bind together features for storage in long-term memory, one can ask how long the consolidation process takes. Studies of retrograde amnesia in patients with hippocampal damage provide an answer to this question. Not only do hippocampal lesions cause anterograde amnesia that disrupts new learning, but they also cause loss of events that occurred prior to the accidents or strokes that caused the lesions. By studying how far back in the past the patients' retrograde amnesia extends, one can determine the length of time the hippocampus stays involved with the retrieval of learned events. The temporal gradient of amnesia for past events is shown for different groups of participants in Figure 4.6, as compiled by Squire, Haist, and Shimamura (1989). They tested patients' recall of public events that had occurred from 1950 to 1985.

Figure 4.6 Recall of past public events in retrograde amnesic patients.



SOURCE: From Squire, L. R., Haist, F., & Shimamura, A. P. (1989). The neurology of memory: Quantitative assessment of retrograde amnesia in two groups of amnesic men. *Journal of Neuroscience*, 9, 828–839. Reprinted with permission of the Society of Neuroscience. Copyright 1989 by the Society of Neuroscience.

As can be seen, amnesic patients recalled just as many public events from the 1950s as did normal controls. However, the amnesic patients did progressively worse than the controls for the events from the 1960s, 1970s, and 1980s that occurred closer to the date they suffered hippocampal lesions. Presumably, the consolidation process had not yet been completed for these events, and so they were lost to retrograde amnesia.

Impaired Short-Term Memory. So far, the discussion of neuropsychological evidence has focused on problems that arise in storing and consolidating new events in long-term memory. Other evidence on the separation of short-term and long-term memory comes from cases with impaired immediate recall. Warrington and Shallice (1972) first documented what seems to be a defect in short-term memory per se in the patient "K. F." The normal span of short-term memory is about seven items. However, K. F. and others like him show a dramatically smaller short-term memory,

Evidence from patients suffering from anterograde amnesia, retrograde amnesia, and reduced short-term memory capacity supports the distinction between short-term and long-term memory.

particularly when auditory rather than visual presentation is used. K. F. could correctly repeat a single letter even after a 60-second delay. But a mere two letters spoken to him were rapidly forgotten. Three letters showed still greater loss over time, even for those presented visually.

Capacity

Long-term memory is nothing if not spacious. A lifetime of memories can readily be stored, and there are no known limits to how much one can experience, learn, and remember. By sharp contrast, short-term memory is notorious for its limits in storage capacity (G. A. Miller, 1956). This can be easily seen in a test of the span of short-term memory for digits, as illustrated in Box 4.2. How many digits were you able to recall correctly in the right order? For most individuals, five or six items can be recalled fairly easily, but eight or nine digits burden short-term memory. In fact, relatively few people accurately recall a nine-digit series, as required by the next to last digit set. But what about the final set? Although it also contains nine items, all nine are easily remembered.

Box 4.2 A Digit Span Test Demonstrating the Limited Capacity of Short-Term Memory

Cover the digit sets given below with a piece of paper and then uncover one set at a time. Read the set quickly, look away, and then try to recall it correctly by writing the numbers in the correct order on another sheet of paper.

6842

59317

274319

4952876

52968471

629479876

123456789

G. A. Miller (1956) recognized that the capacity limitation of short-term memory is a very real biological constraint. However, Miller further recognized that a nonbiological cultural process can overcome this limitation. He called the process chunking. It is easy to remember the final set of digits because they compose a single chunk: the ascending order of single-digit numbers. Meaningful patterns of information, often those grounded in the

cultural tool of language, allow a person to remember far more than seven individual items. By grouping meaningful information together, we form a coherent chunk of information.

Although the digit span results suggest a capacity limitation of seven chunks, other results place the capacity of short-term memory at only three to five chunks (Broadbent, 1975). The precise capacity of short-term memory varies depending on the task used to make the estimate and the materials used in the task (Cavanagh, 1972). Also, the higher estimates of capacity are distorted by contributions from rehearsal and long-term memory, on the one hand, and sensory memory, on the other (Cowan, 2001). When these factors are controlled effectively, it becomes clear that pure short-term memory capacity is limited to about four chunks.

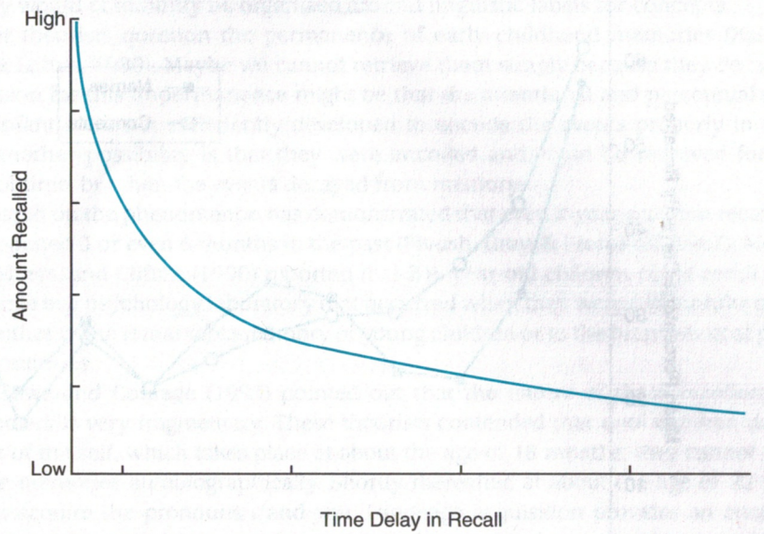
Duration

As noted earlier, you can retain a telephone number long enough to dial it by rehearsing the number silently. But what if someone interrupts the rehearsal or another task at hand distracts you from dialing? How long will the digits of the telephone number persevere? The answer appears to be about 20 seconds. Depending on the specific task and materials used to assess the duration, estimates range from as brief as 10 seconds to as long as 30 seconds (Cowan, 1988). Here lies the sin of memory called transience (Schacter, 2001).

The classic method for studying the duration of short-term memory is called the Brown-Peterson procedure after the pioneering research by J. A. Brown (1958) and L. R. Peterson and Peterson (1959). In this task, an individual listens to a series of three random consonants—a trigram—followed by the presentation of a three-digit number. As a distracting activity, the person counts backward by threes, speaking aloud to the pace of a metronome that clicks every half second. The counting continues for various unpredictable intervals ranging from 3 to 18 seconds; immediate recall without the intervening distraction also is tested at times. Forgetting over this brief interval can be closely approximated by a power function (see Figure 4.7) in which the rate of forgetting levels off as time increases. This is the classic forgetting curve that obtains regardless of whether the retention interval is 20 seconds, 20 weeks, or 20 years (Rubin & Wenzel, 1996). Thus, information in short-term memory is forgotten over a relatively brief time interval, even when it consists of only three chunks, which is below the capacity limit.

The duration of long-term memory must be measured in terms of years, not seconds. Once material is stored in long-term memory, it may well persist for a lifetime. Because of the difficulties in measuring such durations, a precise estimate cannot be given. We do know, from the remarkable studies by Bahrick and his colleagues (Bahrick, 1983, 1984; Bahrick, Bahrick, & Wittlinger, 1975), that the duration of long-term memory is at least 50 years. Memory for information acquired in high school or college was assessed many years after graduation. For example, the names and faces of classmates, foreign language vocabulary, and locations of buildings on a college campus were checked. Although much of the information was forgotten, Bahrick (1983) found clear evidence of apparently permanent storage even 50 years after graduation. For example, after 46 years, students could recall the names of campus buildings and correctly place them on a map of the campus.

Figure 4.7 The classic forgetting curve showing the loss of information from memory as a function of retention interval.

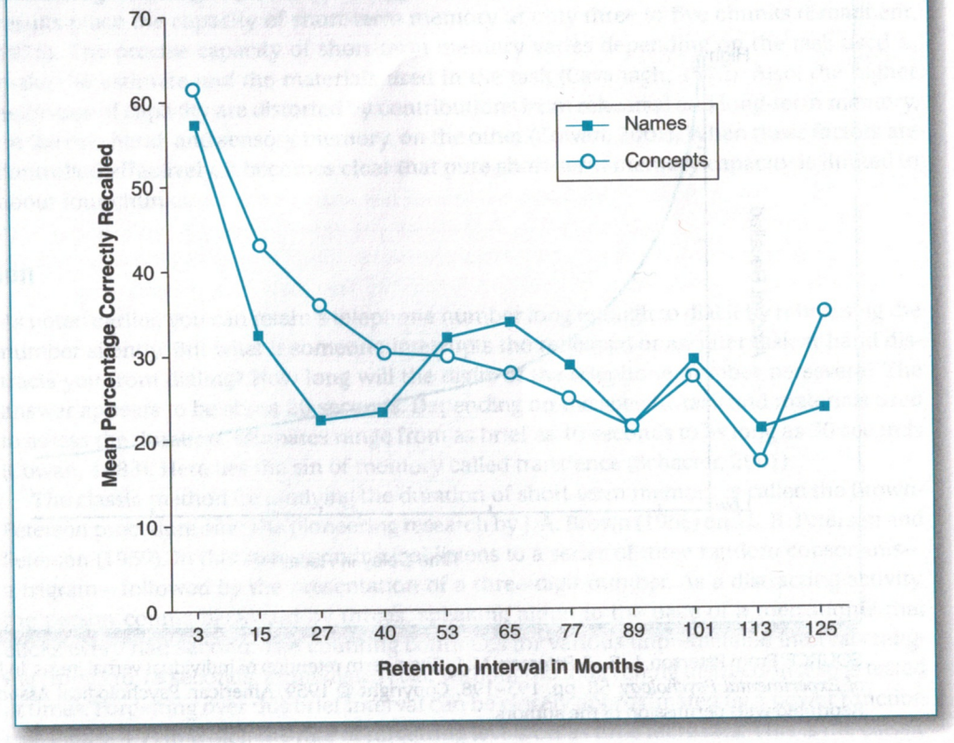


SOURCE: From Peterson, L. R., & Peterson, M. J., Short-term retention of individual verbal items, in *Journal of Experimental Psychology,* 58, pp. 193–198. Copyright © 1959, American Psychological Association. Reprinted with permission of the authors.

Conway, Cohen, and Stanhope (1991) measured what students remembered about their cognitive psychology class over a period of about 10 years. They tested their participants for the names of researchers and for concepts acquired by the students. Conway et al. controlled for the differences in the degree of original learning of the material by taking into account participants' grades received in the course. Accurate recognition of both names and concepts declined quickly over the first 40 months or so but then stabilized. It remained well above chance even 125 months later. It should not come as a surprise to any student that free recall of the same information showed more forgetting. Recognition is typically easier than recall. Still, even on the recall measure, Conway et al. found retention of about a third of the material after 10 years (see Figure 4.8).

The capacity of short-term memory is limited to about four chunks of information, and its duration is less than 30 seconds. The capacity limits of long-term memory are unknown, and its duration is measured in decades.

Figure 4.8 Long-term retention of facts about cognitive psychology.



SOURCE: From Conway, M. A., Cohen, G., & Stanhope, N., On the very long-term retention of knowledge acquired through formal education: twelve years of cognitive psychology, in *Journal of Experimental Psychology:* General,120,395–409, © 1991 American Psychological Association. Reprinted with permission.

What can you remember about your life when you were a baby? Although long-term memory can retain information for decades, our earliest experiences in life are virtually always forgotten. The inability to recall events from the first two or three years of life is called infantile amnesia (Howe & Courage, 1993; Spear, 1979). The reason for such amnesia is still unclear. One view is that the events of infancy are permanently stored but irretrievable. An alternative view is that these events were never encoded and stored adequately in the first place.

Freud (1900/1953) championed the first view. In psychoanalytic theory, repression of early, anxiety-provoking experiences was considered a defense mechanism to protect the ego. Freud used free association to unlock early memories. Another technique for doing so is hypnotic age regression, in which an individual presumably assumes the personality

held at an earlier age (Nash, 1987). Repression is not the only explanation for retrieval failure, however. Perhaps the events are coded by the infant in a way that is not linked to the retrieval cues used by an adult. For example, an infant would encode the world without using language to label objects and events, whereas an adult's attempts to search memory would commonly be organized around linguistic labels for concepts.

Other theorists question the permanence of early childhood memories (Kail, 1984; Loftus & Loftus, 1980). Maybe we cannot retrieve them simply because they do not exist. One reason for this impermanence might be that the attentional and perceptual systems of the infant were not sufficiently developed to encode the events properly in the first place. Another possibility is that they were encoded and could be retrieved for a brief period of time, but then the events decayed from memory.

Research on the phenomenon has demonstrated that even 2-year-olds can recall events that happened 3 or even 6 months in the past (Fivush, Gray, & Fromhoff, 1987). Moreover, Perris, Myers, and Clifton (1990) reported that 2½-year-old children could recall a single experience in a psychology laboratory that occurred when they were 6½ months old! That attests either to the remarkable memory of young children or to the bizarreness of psychology laboratories.

Yet Howe and Courage (1993) pointed out that the nature of these recollections by preschoolers is very fragmentary. These theorists contended that until children develop a concept of the self, which takes place at about the age of 18 months, they cannot possibly organize memories autobiographically. Shortly thereafter, at about the age of 22 months, children acquire the pronouns *I* and *you*. Language acquisition provides an enormously powerful tool for organizing memory as an autobiographical narrative (Nelson, 1990). The source of infantile amnesia most likely lies either in the initial absence of a self-concept or in the absence of language needed to support memory for experiences.

Other Distinguishing Criteria

The capacity and duration differences among sensory, short-term, and long-term memory are summarized in Figure 4.9. Besides these basic distinctions among memory stores, efforts have been made to identify other differences such as the codes used to store information, the causes of forgetting, and the means of retrieval. As first noted by Craik and Lockhart (1972), these criteria failed to dissociate the three stores. For example, it turned out that short-term and long-term memory rely on visual, acoustic, and semantic codes.

Figure 4.9 The different characteristics of sensory, short-term, and long-term memory.

	Differences in Memory Stores		
	Sensory	*Short Term*	*Long Term*
Duration	250 milliseconds	20 seconds	Years
Capacity	Large	4 chunks	Very large

Because of such similarities, Craik and Lockhart argued against a structural view of memory and in favor of a process view. Specifically, they suggested that memory representations are linked to the perceptual and higher-order cognitive processes that are involved during encoding and storing events. As we will see in Chapter 6, their focus on encoding processes has strongly influenced the direction of research over the past 30 years.

Coding. Sperling (1960) proposed that the format of iconic storage is precategorical. That is, only preliminary pattern recognition processes operate on the information, allowing one to locate items in space but not to name them or identify them as members of a category. Sperling argued this position on the basis of studies that included a matrix with half letters and half numbers. The observer failed to show any advantage with a partial report cue to name, say, only the letters, whereas the location cue of the top, middle, or bottom row resulted in nearly perfect recall. However, Merikle (1980) later showed that the haphazard arrangement of the letters and numbers forced the observer to process them one at a time. By carefully arranging the format and spacing of the display, Merikle demonstrated that categorical distinction between letters and numbers could be used to a degree. Thus, location and other physical features are processed faster than the semantic category to which a stimulus belongs, but it is hard to draw a firm line between iconic and short-term memory on the basis of the coding format. A similar difficulty exists for echoic memory (Penney, 1975, 1989).

In fact, even long-term memory uses sensory codes. Paivio (1971, 1983, 1991) marshaled an extensive body of evidence showing that people can verbally encode information into long-term memory using words or visually encode it using images. These representations are derived from and retain the qualities of perceptions received through our sensory modalities. Linguistic stimuli are coded verbally as words as a result of perceiving speech and writing. Nonlinguistic stimuli are coded as images of what one has seen, heard, felt, tasted, or even smelled. **Dual-coding theory** holds that information is best remembered when it is stored in long-term memory using both verbal and imaginal codes. As is discussed further in Chapter 5, if you were to learn the list presented in Box 4.1 by both forming an image of each item in your mind's eye and attending to the names, then your overall level of recall would improve.

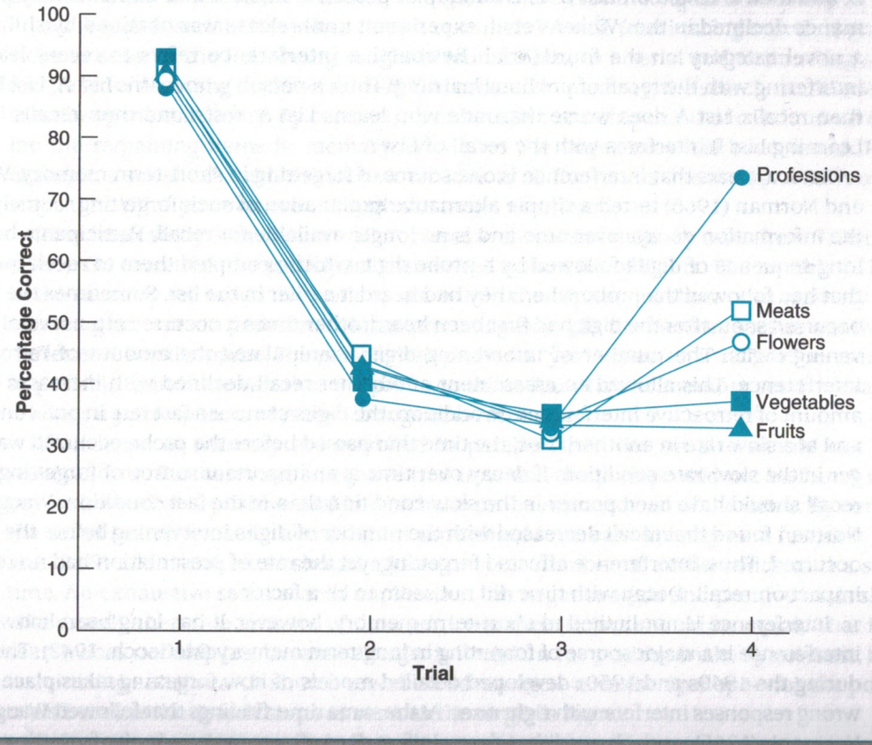
Initially, short-term memory appeared to be based on a sensory code, specifically the acoustic or articulatory code involved in vocalizing names. Intrusion errors in immediate recall typically reflected confusions in stimuli that sound alike or that are enunciated in similar ways (R. Conrad, 1964). For example, people often incorrectly recalled the letter *B* in tests of short-term memory when the correct item was *V*. Confusion based on a visual code of how letters looked—their orthographic similarity—rarely occurred. The letters *F* and *E* differ by only a single distinctive feature in visual coding, yet Conrad's participants failed to confuse them. The high rate of intrusion errors in short-term memory for stimuli that are pronounced alike is called the **phonemic similarity effect.** The acoustic alphabet (e.g., *Alpha, Bravo, Charlie, Victor*) used by the military and others avoids such acoustic errors by assigning a name for each letter that is unique in terms of the acoustic-articulatory code.

The phonemic similarity effect refers to the high rate of intrusion errors in short-term memory for stimuli that are pronounced alike.

Thus, when processing verbal material for later recall, people clearly use an acoustic-articulatory code. But it became clear from later research that short-term memory is not limited to this type of sensory code. Visual codes are used in short-term memory when people hold mental images in the mind's eye for several seconds (Brooks, 1968; Penney, 1975, 1989). Semantic codes are also used to store material in short-term memory (D. D. Wickens, 1972). To see the logic behind this conclusion, consider an experiment by D. D. Wickens, Dalezman, and Eggemeier (1976).

D. D. Wickens et al. (1976) presented three words on each trial, followed by backward counting to prevent their rehearsal. Each triad of words came from the same semantic category (types of fruit) on the first three trials. On the fourth trial, the researchers shifted the category in the experimental condition to vegetables, flowers, meats, or professions. The control condition received another triad of fruits. The results are shown in Figure 4.10.

Figure 4.10 Release from proactive interference showing semantic coding in short-term memory.



SOURCE: From Wickens, D. D., Dalezman, R. E., & Eggemeier, F. T. (1976). Multiple encoding of word attributes in memory. *Memory & Cognition, 4*(3), Figure 1, p. 308. Reprinted with permission of the Psychonomic Society.

Recall decreased systematically on the first three trials as it became more and more difficult to remember which specific fruits had been presented on a particular trial. Then, on the fourth trial, there was an improvement in recall for those receiving a new category. Notice that the degree of semantic similarity between fruits and the new categories accounted for the size of the improvement. This is striking evidence that semantic codes are used in short-term memory. The farther apart the categories are in meaning, the greater the release. This outcome shows convincingly that the semantic code of each triad is stored in short-term memory.

Forgetting. The decrease in correct recall observed on the first three trials in the D. D. Wickens et al. (1976) experiment illustrates an important cause of forgetting called interference. **Proactive interference** means that past learning interferes with the ability to learn and remember new information. For example, first learning a list of words (List A) would interfere with learning and recall of a second list (List B). Imagine an experiment in which we first presented List A, then presented List B, and then tested List B. Proactive interference is defined as poorer recall of List B relative to a condition that first rests, then receives List B, and then is tested on List B. The buildup of proactive interference explains why performance declined in the Wickens et al. experiment until release was obtained by shifting to a novel category on the fourth trial. **Retroactive interference** refers to recent learning interfering with the recall of previous learning. Thus, a person who learns List A, List B, and then recalls List A does worse than one who learns List A, rests, and then recalls List A. Learning List B interferes with the recall of List A.

So, it appears that interference is one source of forgetting in short-term memory. Waugh and Norman (1965) tested a simple alternative explanation of such forgetting, namely, that the information decays over time and is no longer available for recall. Participants heard a long sequence of digits followed by a probe digit, which prompted them to recall the digit that had followed the probe when they had heard it earlier in the list. Sometimes the probe occurred soon after the digit had first been heard; other times it occurred after several intervening digits. The number of intervening digits manipulated the amount of retroactive interference. This allowed an assessment of whether recall declined with increases in the amount of retroactive interference. In addition, the digits came at a fast rate in one condition and at a slow rate in another; thus, the time that passed before the probe occurred was longer in the slow-rate condition. If decay over time is an important source of forgetting, then recall should have been poorer in the slow condition than in the fast condition. Waugh and Norman found that recall decreased with the number of digits intervening before the probe occurred. Thus, interference affected forgetting, yet the rate of presentation had no reliable impact on recall. Decay with time did not seem to be a factor.

Interference is not limited to short-term memory, however. It has long been known that interference is a major source of forgetting in long-term memory (McGeoch, 1942). Theorists during the 1940s and 1950s developed detailed models of how forgetting takes place when wrong responses interfere with right ones. At the same time, findings that followed Waugh and Norman's (1965) work showed that decay in fact does play some part in the forgetting found in short-term memory, in addition to interference (Baddeley & Scott, 1971; Reitman, 1974). There is more to forgetting than just decay and interference, as will be seen in Chapter 6, but for now the essential point is that the loss of information from short-term and long-term memory can take place in similar ways.

Consistent with this point, Rubin and Wenzel (1996) examined 210 published data sets that looked at short-term and long-term forgetting with retention intervals of seconds, days, weeks, and months. In all cases, forgetting followed the same function, as illustrated in Figure 4.7. It does not matter whether the time scale was short or long; the course of forgetting looks the same. The only exception was with respect to autobiographical memories—events with personal meaning for the individual—which were retained well even for long periods of time.

Retrieval. Just as short-term and long-term memory are difficult to distinguish on the basis of forgetting, the retrieval processes involved may also overlap. A **serial search** means that the items in memory are somehow ordered and are examined one at a time, starting with the first item and proceeding to the next. A **parallel search,** by contrast, means that all items in memory are examined simultaneously, not serially. Obviously, a parallel search process would result in much more efficient retrieval of information, especially when the amount of information that must be searched is large, as is the case in long-term memory.

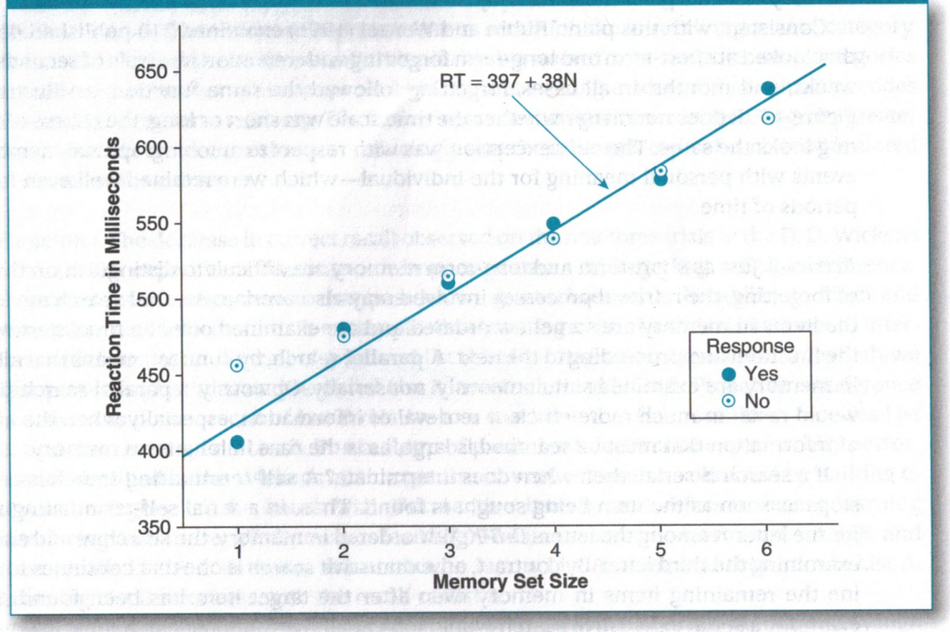
If a search is serial, then when does it terminate? A **self-terminating search** is one that stops as soon as the item being sought is found. Thus, in a serial self-terminating search for the letter *K* among the letters *D-B-K-X-M* ordered in memory, the search would end after examining the third letter. By contrast, an **exhaustive search** is one that continues to examine the remaining items in memory even after the target item has been found. In our example, a serial exhaustive search would look at all five letters one at a time. It would not stop at the third position even though the target was found.

The classic study of these retrieval processes in short-term memory came from S. Sternberg (1966). On each trial, the participant memorized a short list of letters. The number of letters in the memory set varied from one to six, within the capacity of short-term memory. Next, Sternberg presented a probe letter. In the preceding example, the memory set size was five and the letter *K* was the probe. The person then pushed a "yes" button or a "no" button as rapidly as possible to indicate whether the probe could be found in the memory set. For example, *K* brings a yes response, whereas *L* brings a no response.

If all items in memory are searched in parallel, then the set size should not affect retrieval time. Furthermore, a negative trial in which the probe could not be found would be no slower than a positive trial in which the probe matched one of the items. By contrast, if a serial search is used, then reaction time should increase linearly as a function of set size. Each additional letter should add a constant number of milliseconds to the search time. An exhaustive serial search implies that the negative trials and positive trials should take exactly the same amount of time per item; their slopes should be equal. That is, the search does not stop just because a target is found on the positive trials. By contrast, a self-terminating serial search should reveal an advantage—a less steep slope—for the positive trials because the search stops as soon as the target is found.

S. Sternberg's (1966) results indicated that retrieval from short-term memory involves a serial exhaustive search (see Figure 4.11). A linear equation is fit to these data with a *y*-axis intercept of 397 milliseconds and a slope of 38 milliseconds. The search time increased

Figure 4.11 Evidence for a serial exhaustive search of short-term memory.



NOTE: RT = reaction time.

SOURCE: Reprinted with permission from Sternberg, S., High-speed scanning in human memory, in *Science, 153,* 652–654. Copyright © 1966 AAAS.

linearly with set size, and both positive and negative trials showed identical search times per item. This outcome is counterintuitive in that a self-terminating search seems more logical. Why bother searching all items in memory even after the target has been found? The answer may be related to the extremely rapid rate at which we search our short-term memory. The slope of the function is only 38 milliseconds, which is the extra time needed to examine each additional letter in the memory set.

The story is not this simple, however. The research spawned by S. Sternberg's (1966) results eventually led to the conclusion that a parallel search probably best characterizes short-term memory (Greene, 1992). Retrieval from long-term memory is also often parallel. It is impossible to explain the rapid speed with which humans are able to retrieve events, facts, and conceptual knowledge if every item in memory is searched in a serial manner. Even a self-terminating search does not help much, given the vast amount of information stored in long-term memory. At the same time, searches in long-term memory may proceed in a serial manner. For example, which letter comes five letters after *K* in the English alphabet? To arrive at the answer probably involves searching forward from *K* to *L, M, N,* and *O,* not directly retrieving P. Thus, it is not possible to distinguish between short-term and long-term memory on the basis of retrieval processes.

Conclusion

The three-store model has fueled major advances in our understanding of human memory. Despite significant challenges to the model, its core assertion that sensory, short-term, and long-term stores can be distinguished in terms of storage capacity and duration still stands and accounts for an impressive range of evidence (Estes, 1988; Healy & McNamara, 1996). Yet, the inability to distinguish short-term from long-term stores on the basis of coding, mechanisms of forgetting, and procedures for searching memory during retrieval raises questions about the validity of this cognitive architecture (Crowder, 1993). An alternative model assumes that short-term memory is the activated portion of long-term memory rather than a separate store. As will be seen in the next section, research has revealed how the short-term store is put to work in learning, comprehending, and other cognitive tasks. In this context, one view of short-term memory regards it as separate from long-term memory, whereas another sees it as a subset of the same store. Even so, the distinction between sensory stores and long-term stores remains valid. The very brief persistence (250 milliseconds) of iconic and echoic information is plainly separate from long-term storage.

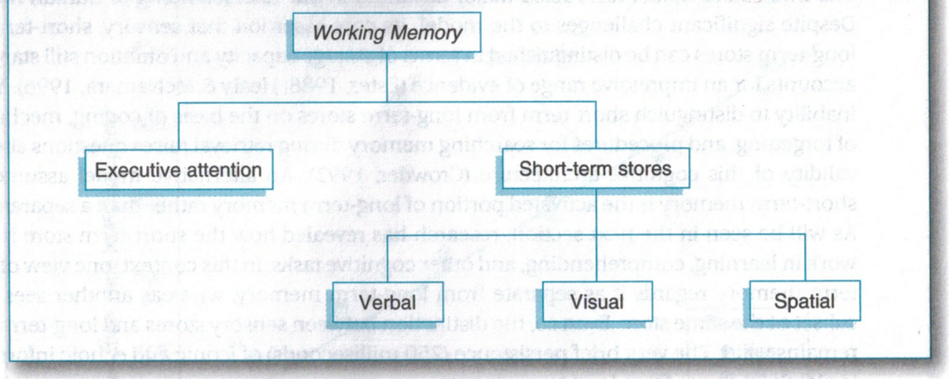
WORKING MEMORY

The short-term store explained how people are able to retain a list of words, digits, or other simple stimuli over a time span of several seconds. However, this theoretical construct does not seem adequate to explain the kind of retention of information that is needed in more complex cognitive tasks. For example, individual differences in reading ability are not strongly correlated with measurements of how many digits an individual can retain (Daneman & Carpenter, 1980). When you read this or any other book, remembering the meaning of a previous sentence helps you comprehend the meaning of the next sentence. Similarly, when carrying on a conversation, you need to hold in mind the assertions just made by your partner in order to formulate a response. Everyday cognitive tasks, such as reading and conversing, involve processing the information held in short-term memory to create a train of thought.

A system more complex than the short-term store was required to adequately explain performance in tasks that required a sustained train of thought. **Working memory** refers to the system for temporarily maintaining mental representations that are relevant to the performance of a cognitive task in an activated state. It includes short-term stores for mental representations that are coded in specific ways, as shown in Figure 4.12. Although these stores might be separate from long-term memory, another possibility is that working memory is best viewed as the representations that are currently active in long-term memory (Cowan, 1988). Working memory also includes executive attention, which controls the mental representations held in short-term or active memory. As noted in Chapter 3, executive attention is a supervisory attentional system that inhibits some mental representations and activates others.

The term *working memory* stresses that the system is needed to accomplish cognitive work. The span of working memory is measured in a dual-task situation that demands attention be paid to more than remembering a list of words. For example, in the reading span test, participants must read and understand a series of sentences in addition to remembering the

Figure 4.12 A hierarchical memory system: Components of working memory.



SOURCE: CDIR (Current directions in Psychological Science). The Attentional blink: The Brain's "eyeblink"...v.3, p. 86–89. Reprinted with permission of Blackwell Publishing.

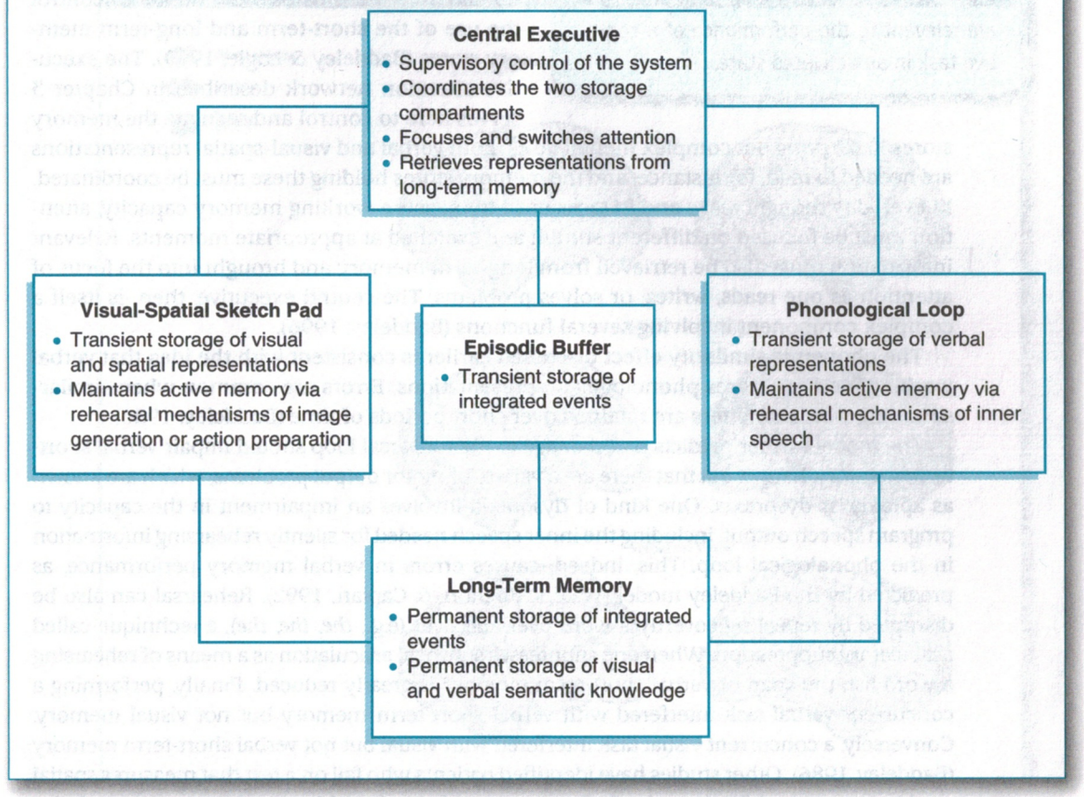
last word of each sentence (Daneman & Carpenter, 1980). In the operations span test, participants must perform a series of mental arithmetic problems in addition to remembering the words paired with each problem (Engle, Cantor, & Carullo, 1992). Unlike the digit span test, these tests of working memory capacity require actively processing task-relevant information at the same time that material is held in short-term storage. Because reading span and operations span tests require coordinating two tasks at once, they require executive attention. Individuals with a larger capacity of executive attention attain higher span scores, as do those with greater short-term storage capacity. Working memory span successfully predicts individual differences in performance in a wide range of complex cognitive tasks, including reading, writing, reasoning, and problem solving (Engle, Tuholski, Laughlin, & Conway, 1999).

Multiple-Component Model

Numerous alternative models of working memory have been proposed, but they typically share the assumption that working memory consists of multiple components (Shah & Miyake, 1999). The earliest and highly influential multicomponent model was proposed by Baddeley (1986). The model initially posited two short-term stores that specialize in the transient retention of verbal information, on the one hand, and visual or spatial information, on the other. These components were called the phonological loop and a visual-spatial sketch pad, respectively. The phonological loop is further fractionated into a passive memory store and a rehearsal loop that refreshes the activation of items held in the store. The phonological loop, then, allows one to maintain verbal information over time by repeating it covertly—silently articulating the letters or words. The visual-spatial sketch pad maintains representations used in visual imagery. It permits one to rehearse information by visualizing it or to imagine a problem and then seek a solution to it in the mind's eye (see Figure 4.13).

A third transient storage component was later added in a revised version of the model (Baddeley, 2001). This component, called an episodic buffer, stores integrated

Figure 4.13 A multicomponent model of working memory.



SOURCE: Adapted from Baddeley, A. D. Is working memory still working? *American Psychologist*, *56*, 849–864. Copyright © 2001, The *American Psychological* Association. Reprinted with permission.

representations that bind visual, spatial, and verbal codes from the other short-term stores together with information held in long-term memory. When features are bound together during perception, an integrated event representation is temporarily held in the episodic buffer and is available to conscious awareness. Complex events or scenes that combine multiple sources of information can thus be held and manipulated in working memory. Our ability to think about the past, plan for the future, and solve problems relies on actively maintaining such episodic representations. The episodic buffer, therefore, links the long-term memory system with a separate short-term memory system. Other alternative models handle the need for this linkage by assuming that working memory consists of the currently active subset of long-term memory representations (Cowan, 1988).

Working memory is the system that temporarily maintains mental representations that are relevant to the performance of a cognitive task in an activated state.

The final component of working memory is the central executive. This is the executive attentional component whose function is to control the use of the short-term and long-term memory stores (Baddeley & Logie, 1999). The executive attention network described in Chapter 3 serves here to control and regulate the memory stores in carrying out complex mental tasks. Both verbal and visual-spatial representations are needed to read, for instance, and the memory stores holding these must be coordinated. In everyday thought tasks and in tasks used to measure working memory capacity, attention must be focused on different stimuli and switched at appropriate moments. Relevant information must also be retrieved from long-term memory and brought into the focus of attention as one reads, writes, or solves problems. The central executive, then, is itself a complex component involving several functions (Baddeley, 1996).

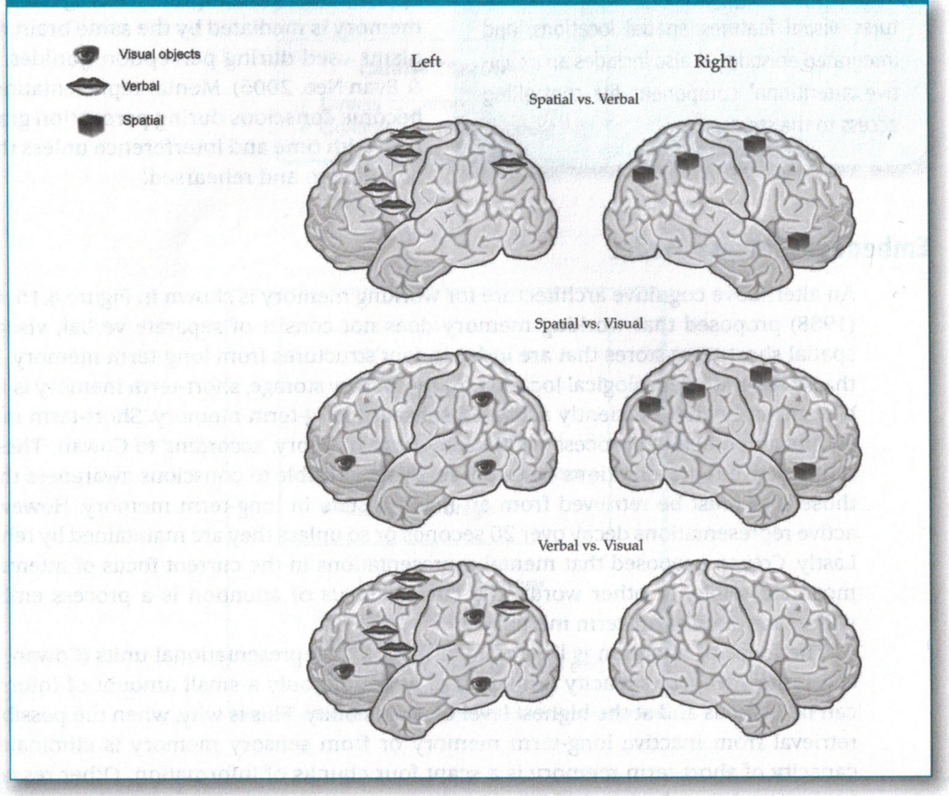
The phonemic similarity effect discussed earlier is consistent with the idea that verbal working memory stores phonological representations. Errors are common when similar-sounding words or letters are retained over short periods of time (Baddeley, 1986).

The model further predicts that damage to the rehearsal loop should impair verbal short-term memory. It turns out that there are a variety of motor output problems, which are known as apraxia or dyspraxia. One kind of dyspraxia involves an impairment in the capacity to program speech output, including the inner speech needed for silently rehearsing information in the phonological loop. This, indeed, causes errors in verbal memory performance, as predicted by the Baddeley model (Waters, Rochon, & Caplan, 1992). Rehearsal can also be disrupted by repeating covertly a word over and over (e.g., *the, the, the*), a technique called articulatory suppression. When one suppresses subvocal articulation as a means of rehearsing a word list, the span of verbal short-term memory is greatly reduced. Finally, performing a concurrent verbal task interfered with verbal short-term memory but not visual memory. Conversely, a concurrent visual task interfered with visual but not verbal short-term memory (Baddeley, 1986). Other studies have identified patients who fail on a test that measures spatial working memory ability but who do fine on a test of visual or object working memory relative to normal controls (Della Sala, Gray, Baddeley, Allamano, & Wilson, 2000). A double dissociation has been demonstrated on these tests. That is, separate patients show the reverse pattern, failing the test of visual working memory and succeeding on the spatial test.

Neuroimaging has recently demonstrated that different regions of the brain are involved in the multiple components of working memory. From a large literature based on animal testing, it is known that the prefrontal cortex is a necessary neural substrate for working memory (Goldman-Rakic, 1995). The neuroimaging findings confirm this point and further show some other regions involved. These studies use the method of subtraction to isolate the processes involved in maintaining different kinds of information in working memory such as verbal, spatial, and visual object representations. For example, in the verbal condition, participants try to retain a set of four letters in memory and are presented with a test probe that either was or was not in the set. Working memory for locations in space and for the shape of objects was also assessed.

The data are summarized in Figure 4.14 by first showing the sites in the left and right hemispheres that showed the greatest PET activation in the spatial versus verbal conditions.

Figure 4.14 Dissociating verbal and spatial working memory with positron emission tomography (PET) data.



SOURCE: From Smith, E. E., & Jonides, J., Working memory: A view from neuroimaging, in Cognitive Psychology, 33, copyright © 1997. Reprinted with permission from Elsevier.

The verbal condition activated a region associated with Broca's area and motor areas in the frontal cortex associated with speech production and the covert rehearsal loop. A region in the left posterior parietal lobe was also activated, presumably as a result of storing the phonological representation that was refreshed via rehearsal. By contrast, the spatial condition activated regions in the right parietal and frontal cortex.

As shown in the middle row of Figure 4.14, the results have further shown that maintaining visual objects in working memory activates still different cortical regions in the left hemisphere (Smith & Jonides, 1997). In other words, the visual and spatial components of working memory must also be dissociated. One component stores visual objects and another stores their spatial location, a result that is consistent with the separate

Working memory includes components for transiently storing phonological or verbal features, visual features, spatial locations, and integrated episodes. It also includes an executive attentional component for controlling access to the stores.

"what" versus "where" pathways of perceptual analysis discussed in Chapter 1. In fact, it appears that the temporary storage of working memory is mediated by the same brain mechanisms used during perception (Jonides, Lacey, & Evan Nee, 2005). Mental representations that become conscious during perception gradually fade with time and interference unless they are attended to and rehearsed.

Embedded-Process Model

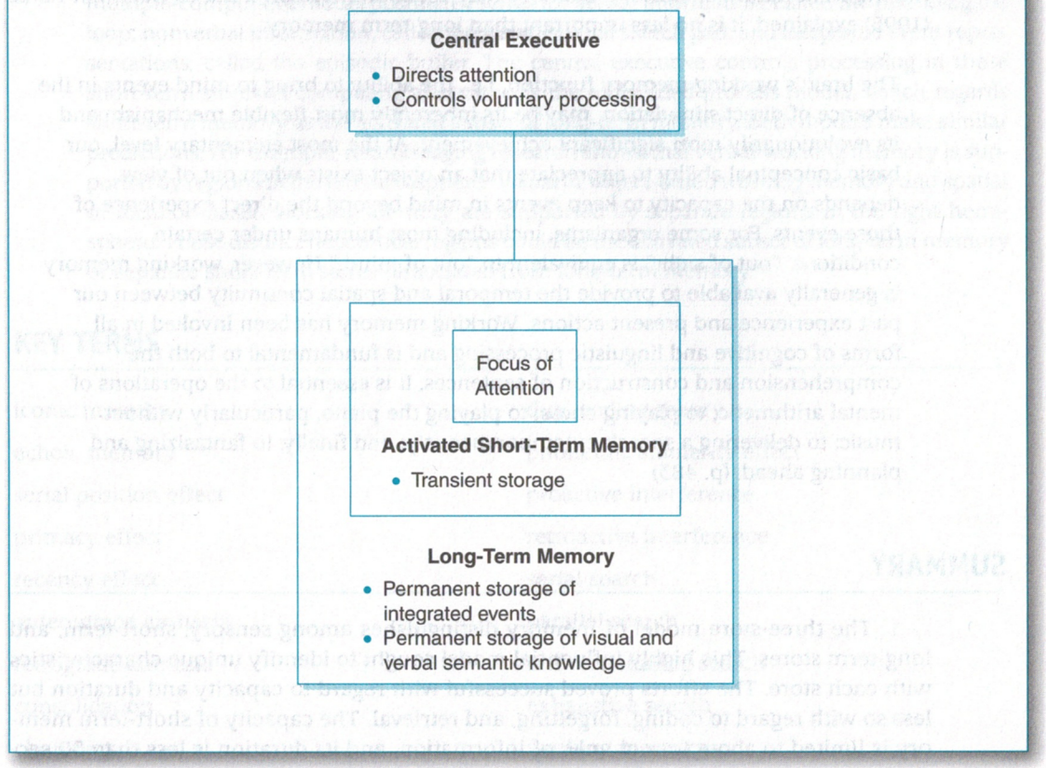
An alternative cognitive architecture for working memory is shown in Figure 4.15. Cowan (1988) proposed that working memory does not consist of separate verbal, visual, and spatial short-term stores that are independent structures from long-term memory. Rather than a separate neurological location for temporary storage, short-term memory is instead the currently and transiently activated subset of long-term memory. Short-term memory is thus an embedded process within long-term memory, according to Cowan. These currently active representations are more readily accessible to conscious awareness than are those that must be retrieved from an inactive state in long-term memory. However, the active representations decay over 20 seconds or so unless they are maintained by rehearsal. Lastly, Cowan proposed that mental representations in the current focus of attention are most accessible. In other words, the current focus of attention is a process embedded within activated short-term memory.

The focus of attention is limited to at most four representational units (Cowan, 2001). Given the stringent capacity limitation of attention, only a small amount of information can be in focus and at the highest level of accessibility. This is why, when the possibility of retrieval from inactive long-term memory or from sensory memory is eliminated, the capacity of short-term memory is a scant four chunks of information. Other researchers have argued that the focus of attention is even narrower—only a single unit—although it can appear to be larger because of rapid, transient chunking of representations into a higher-order structure that is maintained in short-term memory (McElree, 2001; Oberaurer & Kliegl, 2006). Regardless of which view is held, it is clear that the capacity of short-term memory is more limited than that of long-term memory.

Because long-term memory involves verbal, visual, and spatial codes for storing information, the neuroimaging findings can be interpreted in a different light. According to the embedded-process model, these are the neocortical regions of long-term memory that are temporarily active while performing a verbal, visual, or spatial working memory task. The effect of phonological similarity can be equally well interpreted as acoustic confusion among verbal codes in either long-term memory or a separate phonological store of short-term memory. The effect of articulatory suppression is also explained by both models as a disruption of the rehearsal process.

Although the multiple-component and embedded-process models account equally well for many basic findings, Chein and Fiez (2010) recently suggested that they differ in their

Figure 4.15 An embedded-process model of working memory.



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.

predictions regarding the effect of irrelevant speech versus nonspeech on short-term recall. Imagine studying a list of seven letters presented visually while hearing and trying to ignore irrelevant background sounds. The multiple-component model predicts that irrelevant speech will occupy space in the phonological store that would otherwise be available for holding the letters. However, bursts of white noise are not phonological and so at most could distract executive attention and possibly disrupt recall. By contrast, the embedded-process model predicts that both kinds of irrelevant background sounds should be equally disruptive to recall for the same reason—both distract focal attention from the letters. This latter prediction was confirmed by Chein and Fiez; moreover, fMRI findings revealed the same reduction in activity in regions associated with working memory for both irrelevant speech and irrelevant nonspeech.

Conclusion

Relative to our ability to learn and retrieve events stored in long-term memory years ago, the transient nature of working memory may seem unimpressive. But as Goldman-Rakic (1995) explained, it is no less important than long-term memory:

> The brain's working memory function, i.e., the ability to bring to mind events in the absence of direct stimulation, may be its inherently most flexible mechanism and its evolutionarily most significant achievement. At the most elementary level, our basic conceptual ability to appreciate that an object exists when out of view depends on the capacity to keep events in mind beyond the direct experience of those events. For some organisms, including most humans under certain conditions, "out of sight" is equivalent to "out of mind." However, working memory is generally available to provide the temporal and spatial continuity between our past experience and present actions. Working memory has been invoked in all forms of cognitive and linguistic processing and is fundamental to both the comprehension and construction of sentences. It is essential to the operations of mental arithmetic; to playing chess; to playing the piano, particularly without music; to delivering a speech extemporaneously; and finally, to fantasizing and planning ahead. (p. 483)

SUMMARY

1. The three-store model of memory distinguishes among sensory, short-term, and long-term stores. This highly influential model sought to identify unique characteristics with each store. The efforts proved successful with regard to capacity and duration but less so with regard to coding, forgetting, and retrieval. The capacity of short-term memory is limited to about four chunks of information, and its duration is less than 30 seconds. The capacity limits of long-term memory are unknown, and its duration is measured in decades.

2. The hippocampus plays a critical role in storing events in long-term memory. The hippocampus, a structure in the medial temporal lobe of the brain, binds together neural activity from locations distributed across the neocortex during learning. Until an event is consolidated in long-term memory, the hippocampus is needed to index the locations of the distributed memory representation. Damage to the hippocampus causes severe anterograde amnesia, meaning that recent new events cannot be stored in long-term memory.

3. Free recall of a list of words reveals a serial position effect. The last items in the list are recalled first and well—the recency effect. The initial items in the list are also recalled well—the primacy effect. The three-store model attributes the recency effect to the short-term store and attributes the primacy effect to the long-term store. The model also accounts for evidence from patients suffering from anterograde and retrograde amnesia and from reduced short-term memory capacity.

4. Working memory refers to the system for temporarily maintaining mental representations that are relevant to the performance of a cognitive task in an activated state. It involves short-term memory stores plus attentional control over processing in a cognitive task. The multiple-component model postulates stores for verbal information, called the phonological loop; nonverbal information, called the visual-spatial sketch pad; and integrated event representations, called the episodic buffer. The central executive controls processing in these short-term stores. A competing alternative is the embedded-process model, which regards short-term memory as the activated subset of long-term memory. Both models make similar predictions. For example, neuroimaging research shows that verbal working memory is supported by regions in the left hemisphere. Visual or object-based working memory and spatial or location-based working memory are supported by separate regions in the right hemisphere. These distinct neocortical regions could be the activated subset of long-term memory or separate short-term stores dissociated from long-term memory.

KEY TERMS

iconic memory
echoic memory
serial position effect
primacy effect
recency effect
anterograde amnesia
retrograde amnesia
consolidation
chunking
dual-coding theory
phonemic similarity effect
proactive interference
retroactive interference
serial search
parallel search
self-terminating search
exhaustive search
working memory