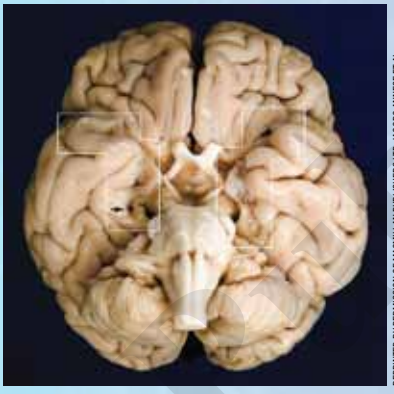
18 Learning and Memory

PORTRAIT The Mystery of Memory

In 1953, when Henry Gustav Molaison, better known as Patient H.M., was 27 years old, he underwent elective surgery to relieve intractable epilepsy. When William Scoville operated on H.M., he inadvertently opened one of the most widely studied cases of memory impairment in neuropsychological history (Scoville and Milner, 1957). H.M.'s disorder was documented in more than 100 scientific publications during his lifetime.



REPRINTED BY PERMISSION OF MACMILLAN PUBLISHERS LTD. JACOPO ANNESE ET AL. POSTMORTEM EXAMINATION OF PATIENT H.M.'S BRAIN BASED ON HISTOLOGICAL SECTIONING AND DIGITAL 3D RECONSTRUCTION, *NATURE COMMUNICATIONS* JAN 28, 2014; 5: 3122. FIGURE 1

H.M. experienced generalized epileptic seizures that had grown progressively worse in frequency and severity despite very high doses of medication. Scoville performed a bilateral medial-temporal-lobe resection in an attempt to stop the attacks. Afterward, H.M's seizures lessened, but he experienced severe amnesia that persisted until his death on December 2, 2008 (Annese et al., 2014). A postmortem photo of H.M.'s brain, in ventral view, clearly shows areas of scarring from the operation in both hemispheres (white outlines), including a mark visible on the parahippocampal gyrus of the right hemisphere (black arrow) produced by oxidation of one of the surgical clips Scoville inserted.

H.M.'s IQ was above average (118 on the Wechsler Adult Intelligence Scale), and he performed at normal on perceptual tests. H.M.'s memory of events that took place before the surgery was good, as was his capacity to recall remote events such as incidents from his school days or jobs that he held in his late teens or early twenties. For events that occurred after his surgery, H.M.'s memory was extremely limited: he was unable to describe the work he was doing after 6 months of employment, find his way to the house he had moved into after surgery, or even remember that he had just eaten a meal.

Given what was known about memory before H.M.'s experience, the discovery that **amnesia**, partial or total memory loss, can result from a localized brain lesion was a surprise. Perhaps even more surprising was that H.M. was unimpaired in learning some things, including motor skills; remembering faces; and retaining short-term memories, such as remembering a telephone number or a name for a short period of time (Milner et al., 1968).

The case of H.M. reveals two novel things about memory. First, many kinds of memory exist, each mediated by different neural systems, and second, selective brain damage can result in the loss of memory abilities.

The study of H.M.'s amnesia and of other patients with brain damage reveals that our multiple memory systems, charted in **Figure 18.1**, constitute largely independent neural processes. *Long-term memories* are of three general types—explicit, implicit, and emotional—each supported by different brain pathways. *Short-term memory* calls on a separate set of neural pathways. In this chapter we describe these different memory systems, their neural substrates, and the insights that knowledge about the many kinds of memory brings to our understanding of our own memories. We begin by surveying the effects of amnesia on learning and remembering.

18.1 Learning, Memory, and Amnesia

In his classic book, *Remembering*, Fredric Bartlett emphasized that remembering cannot be regarded as the mere revival of previous experience; rather, remembering is an active process of reconstruction. "So long as the details which can be built up are such that they would give a 'reasonable' setting," Bartlett stated, "most of us are fairly content, and are apt to think that what we build we have literally retained" (Bartlett, 1932, p. 176).

Daniel Schacter and Donna Addis (2007), who use the term *gist* to describe the objective of reconstructing a memory, make the point that the gist serves the adaptive purpose of allowing us to anticipate and respond to situations in the future in ways that benefit from our past experiences. Thus, memory does not just allow us to recreate the past, it is prospective in allowing us to imagine or anticipate the future and so respond adaptively "next time." Because the gist is adaptive, details are often unimportant. As such, the shortcut nature of the gist renders it prone to errors of commission as well as of omission. Schacter describes such errors as the seven sins of memory.

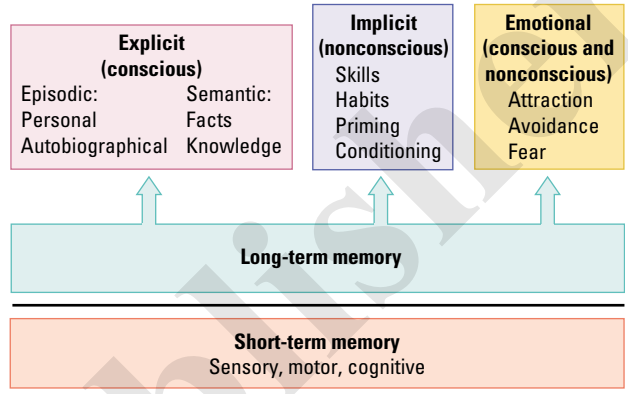


Figure 18.1 ▲

Multiple Memory Systems The broadest classification of memory distinguishes transient *short-term memory* for recent sensory, motor, or cognitive information from relatively permanent *long-term memory*. Conscious, long-term memories may be *explicit*—events and facts that you can spontaneously recall—and either *episodic*, for personal experiences (your first day at school), or *semantic*, for facts (England is in Europe). *Implicit*, nonconscious memories (say, riding a bicycle) consist of learned skills, conditioned responses, and events recalled on prompting. *Emotional memory* for the affective properties of stimuli or events (your first kiss) is vivid and has characteristics of implicit and explicit memory.

An adaptive "sin" that experimental control participants commit far more often than amnesic subjects illustrates the sacrifice in accuracy that gist formation incurs. Participants are given a study list of words (*tired*, *bed*, *awake*, *rest*, *dream*, *night*, *blanket*, *dose*, *slumber*, *snore*, *pillow*, *peace*, *yawn*, and *drowsy*). A presented lure word (for example, sleep) is related to the words on the study list. On a subsequent old–new recognition test containing studied words (for example, tired and dream), new words unrelated to the study list (for example, butter) as well as new lure words related to the study-list items, such as *mattress*, are presented.

Controls frequently claim that they have previously studied the lure words. Amnesic patients with damage to the hippocampus and related structures in the medial temporal lobe show significantly reduced false recognition of nonstudied words that are related, either semantically or perceptually, to previously studied words. Apparently, controls form and retain a well-organized semantic or perceptual gist of a list of related study items. This gist causes them to respond to lure words but also allows them to reject unrelated words, whereas amnesic subjects may form a better list memory but retain only a weak or degraded gist.

The notion that we have multiple memory systems allows for other errors caused by favoring one kind of memory over others. For example, witnesses at an accident can usually give the gist of what they observed. They can note the temporal and spatial sequence of the action, identify the participants, and note the autobiographical framework of how they became an observer.

Yet when quizzed on the details, the fallibility of memory becomes apparent. Each observer may recall details not remembered by others. In addition, recollection can be distorted. Observers can be *primed* (sensitized) by other witness's stories and by photographs or videos of the occasion to remark, "Oh yes, I remember that also," even when the stories, photographs, or videos are distorted.

A simple example of the relation between such perceptual bias and memory reconstruction is illustrative. If people are asked to draw an upright glass half

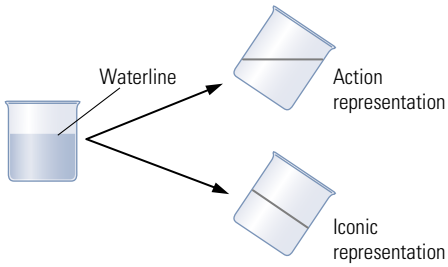


Figure 18.2 ▲

Perception Affects Memory Those who encode a glass of water as an action image will render the waterline horizontally, whereas those who encode it as an icon will render the waterline at a slant, rotating it with the glass.

full of water as a tilted glass, some represent the glass with the water level in a horizontal position while others represent it with the waterline tilted (**Figure 18.2**). The former suggests encoding a spatial or action representation of the image, whereas the latter suggests encoding the representation as an icon. In Section 12.2 we report a sex difference in the representation of this image, with females more likely to report the icon and males the action. Both are accurate, but obviously quite different, perceptions.

As a student, you may have problems with different kinds of memory when studying for and taking examinations. A rule of thumb is that you remember things in the way that you learned them. If you learn the gist, you will not do well when asked for details. If you just read over material or underline important passages or both, you will not do well when asked to recount the material in detail.

You can prevent the unpleasant experience of "I knew the information but had a mental block when I had to produce it" by performing the same operations during the study phase that will be required of you during the test phase. Effective studying consists of practicing for an exam as it will be administered. These sessions usually require top-down rather than bottom-up processing if examiners are interested in more than the gist, and they usually are.

Varieties of Amnesia

The first evidence that the temporal lobes might play a role in human memory preceded H.M. by 50 years, when Vladimir Bekhterev (1900) autopsied the brain of a patient who had shown a severe memory impairment. He discovered a bilateral softening in the medial temporal cortex. The bilateral surgical excision made in H.M.'s brain, illustrated in **Figure 18.3**, shows just how small a region of damage to the medial temporal lobes can produce severe amnesia.

Other patients with bilateral temporal cortex damage, whom Brenda Milner (1970) and her coworkers had described in the 1950s, confirmed not only the temporal lobe's role in memory but also the special contributions made by different structures within the temporal lobes to different kinds of memory.

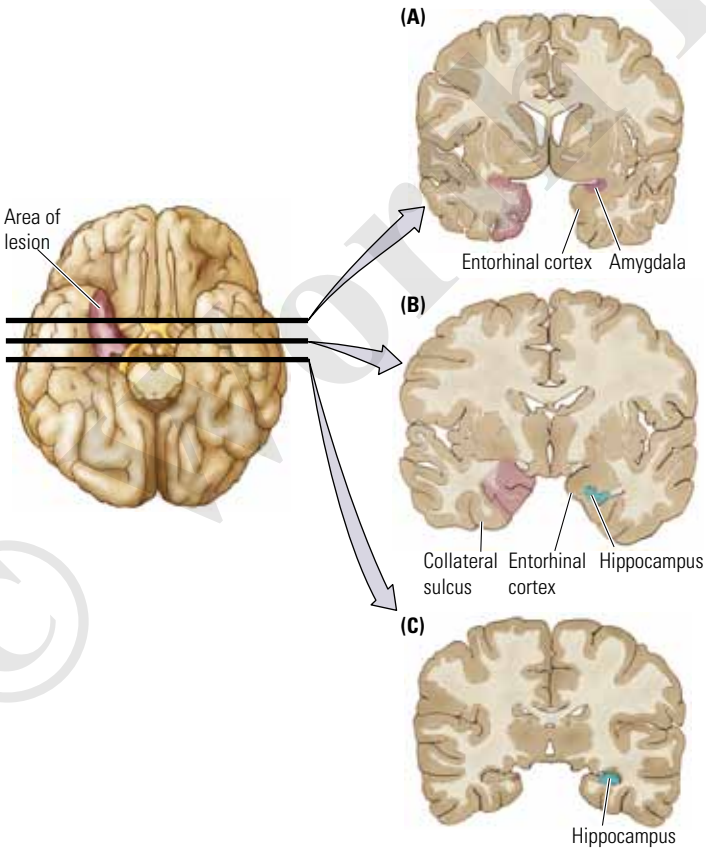


Figure 18.3 ◄

Extent of H.M.'s Surgery (Left) H.M.'s brain viewed ventrally, with the area of only the right-hemisphere lesion shown, in purple. (Right) In sections A, B, and C, which are based on MRI scans made in 1997, the left hemisphere (right sides of the diagrams) is intact to show the relative locations of affected medial temporal structures. Because the lesion, shaded purple on the left in each diagram, ran along the walls of both medial temporal lobes, the extent of damage in H.M.'s brain can be seen in the right hemisphere in several cross sections. (Research from Corkin et al., 1997.)

Recall from Section 15.3, for example, that damage to the inferotemporal cortex (area TE) specifically interferes with conscious recall of information, the extent of the memory disturbance increasing in direct proportion to the amount of temporal-lobe damage. Other causes of amnesia, and presumably other ways of disrupting or damaging the medial temporal lobe and its pathways, also offer insight into the neural bases of learning and memory.

Childhood Amnesia

We have all experienced amnesia to some degree. The most dramatic example of forgetting common to us all is **childhood** (**infantile**) **amnesia**, an inability to remember events from infancy or early childhood. The early years of life are generally regarded as critical in our development. We acquire many skills, including language, and much knowledge in those years but for the most part do not remember the experiences through which we acquired them. One reason for this failure to remember is that memory systems mature at different rates. Personal memories of our early years may be lost because the system central to storing adult episodic memory is not yet mature.

Another reason that childhood memories may be lost is that the brain plays an active role in deleting them, perhaps to make room for new memories. Katherine Akers and colleagues (2014) find that childhood amnesia also occurs in some nonhuman animals. During the period for which amnesia occurs in experimental mice, for example, many new neurons are being added to the hippocampus. In precocial species, including the guinea pig, hippocampal neurogenesis is largely complete before birth, and they do not display infantile amnesia. The investigators suggest that as new hippocampal neurons form new connections, they participate in forming new memories, but in doing so they disrupt neural circuits that support memories already acquired. More-permanent memories are formed only after the acquisition of new neurons by the hippocampus slows.

Amnesias Rare and Common

Adults also forget, as witnessed by occasional reports of people who turn up far from home with no knowledge of their former lives but with skills and language intact. Referred to as a **fugue state**, memory loss of personal history is sudden and usually transient. *Fugue* means "flight," and one interpretation is that the person has in effect fled a former life to form a new one. Perhaps the basis of the fugue state is the temporary suppression of medial-temporal-lobe memory systems.

Damage to restricted brain areas can cause amnesia that takes very curious forms. Clinical reports describe people who become amnesic for the meaning of nouns but not verbs, and vice versa, or amnesic for recognizing animals but are not *prosopagnosic* (amnesic for human faces). Simona Siri and colleagues (2003) describe a patient with herpes simplex encephalitis who was severely amnesic for fruits and vegetables but less so for animals and birds, suggesting a partial dichotomy in memory between plant and animal categories.

We all experience little everyday amnesias: we forget people's names or faces or where we put our keys. This kind of forgetting can increase with advancing age, in so-called senior moments. Its onset is typically characterized by amnesias for the names of people we do not often meet and for items we encounter in news media and in conversation. For some people, memory disorders of aging can become incapacitating, as happens in *Alzheimer's disease*, characterized

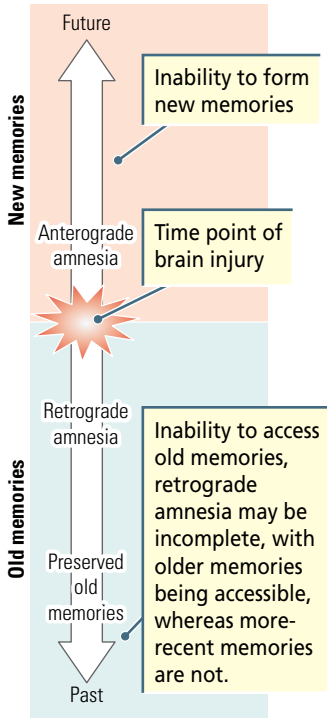


Figure 18.4 ▲

Varieties of Amnesia

Among the possible consequences of brain injury on old and new memories, retrograde amnesia may be incomplete, with older memories being better preserved than newer memories.

by the extensive loss of past memories and accompanied by neuronal loss that begins in the medial temporal lobe and then extends to other brain areas (see Section 27.7).

Anterograde and Retrograde Amnesia

H.M.'s memory, like that of other amnesic patients, consists of two parts. H.M. was unable to acquire new memories, a condition called **anterograde amnesia**, but he lost only some memories that must have been accessible to him before his surgery, a form of memory loss called **retrograde amnesia** (**Figure 18.4**).

The term *anterograde* refers to the future with respect to the time at which a person incurred damage to his or her brain. Because so many aspects of his ability to learn and remember appeared to be affected, H.M.'s severe anterograde amnesia is referred to as *global anterograde amnesia*. He was impaired in spatial and topographic learning and in learning about the events that took place around him, including the death of his loved ones. He showed sparse learning of new words and remembered only a few events or people who had made news after his injury. As H.M. himself said, "Every day is alone in itself, whatever enjoyment I've had, and whatever sorrow I've had."

The term *retrograde* signifies that memory loss extends back in time relative to the time of brain injury, as shown in Figure 18.4. H.M.'s retrograde amnesia was not as complete as his anterograde amnesia; he remembered many things he had learned before his surgery. He knew who he was; he could read, write, and speak; and he retained most of the skills he acquired before his surgery. Typically, memory is much better for events that took place earlier in life than for more-recent events. H.M. knew the way to the house where he lived before his surgery, for example.

For other patients, the extent of anterograde and retrograde amnesia can be quite variable (Smith et al., 2013). Both anterograde and retrograde amnesia occur in other clinical conditions, such as Alzheimer's disease. As the condition progresses, retrograde amnesia becomes more and more severe until almost all memory is affected.

Time-Dependent Retrograde Amnesia

Traumatic brain injury (TBI) commonly produces **time-dependent retrograde amnesia**, with the injury's severity determining how far back in time the amnesia extends. For example, after a head trauma, a transient loss of consciousness followed by a short period of confusion and retrograde amnesia is typical. The retrograde extent of the amnesia (the period of personal history it covers, extending from the present to the more-distant past) generally shrinks with the passage of time, often leaving a residual amnesia of only a few seconds to a minute for events immediately preceding the injury.

The duration of such posttraumatic amnesias can vary, however, as described in the opening Portrait of L.D. in Chapter 1. In a classic study, in one group of patients with severe head injuries, 10 percent had duration of less than 1 week, 30 percent had duration of 2 to 3 weeks, and the remaining 60 percent had duration of more than 3 weeks (Whitty and Zangwill, 1966). Sometimes isolated events, such as the visit of a relative or some unusual occurrence, are retained as islands of memory during this amnesic period.

Three Theories of Amnesia

The peculiar uncoupling of anterograde and retrograde amnesia presents a puzzle. What makes the memory systems underlying these two forms of amnesia partially independent? Three differing theoretical views each use the same evidence, from case and group studies of patients who have sustained medial-temporal-lobe damage and from extensive testing of learning and memory in animals.

System Consolidation Theory

As articulated by Larry Squire and Peter Bayley (2007), **system consolidation theory** states that the hippocampus *consolidates* new memories, a process that makes them permanent. When consolidation is complete, the memories are stored elsewhere in the brain. That is, memories are held in the hippocampus for a time, then gradually consolidated in a new location, the neocortex.

Consolidation theory explains why older memories tend to survive cases of hippocampal damage—they have been transferred elsewhere for storage—whereas more-recent memories are likely to be lost—they still reside in the hippocampus. If damage is limited to the hippocampus, retrograde amnesia may extend back for only a few years because only recently acquired memories remain there. As more of the temporal lobe, a region where longer-term memories are stored, is affected, retrograde amnesia can extend back for one to two decades or longer, depending on lesion size.

Multiple-Trace Theory

Lynn Nadel and Morris Moscovitch (1997) propose that **multiple-trace theory** accounts for individual differences in amnesias:

- **In any learning event memories of many types are encoded in parallel in different brain locations.** For example, autobiographic memory depends on the hippocampus and frontal lobes; factual semantic memory depends on temporal-lobe structures; and general semantic memory, on the remaining cortical areas.
- **Memories change throughout a person's life as they are recalled, reevaluated, and restored.** Autobiographic events, for example, through being recalled and discussed, can also be stored as factual memory and perhaps even as general memory (Cabeza and Moscovitch, 2013). Thus, the very process through which memories change as they are reused places them in different brain locations. This transformation results in memory that is recoded with use and thus changed from one type to another.
- **Different kinds of memory, being stored in different locations, are differentially susceptible to brain injury.** Because of this memory organization, after brain injury usually only some aspects of memory will be affected, and more important, older memories will be more resistant to disruption than newer memories.

Reconsolidation Theory

As described by Natalie Tronson and Jane Taylor (2007), **reconsolidation theory** proposes that memories will rarely consist of a single trace or neural substrate. We frequently recall memories, think about them, and discuss them

with others. In storytelling or gossiping, a memory is not only recalled but also shared and elaborated on by others.

Each time a memory is used, it is reconsolidated: the memory reenters a labile phase and is then restored as a new memory (Schwabe et al., 2014). Each use of memory is associated with a new phase of storage, resulting in many different traces for the same event. Reconsolidation complicates the study of amnesia because spontaneous recall and even investigating a subject's memory will change the memory that is the object of investigation. Case in point: a witness's memory for an accident consists of multiple traces, one for each time the accident is recalled. And the difficulty in studying childhood amnesia lies in separating memories that an individual recalls for the first time from those he or she has recalled numerous times and those that have been contributed to by reminders from others, such as a parent (Wang and Peterson, 2014).

These three theories suggest that memory storage or memory type or frequency of use contributes to the extent of amnesia. Because of the complexity of memory storage, we can expect wide individual differences in the degree to which people display anterograde and retrograde amnesia after a traumatic event. In the sections that follow, we describe the three categories of long-term memory—explicit, implicit, and emotional—in detail, and then turn to the characteristics of short-term memory.

18.2 Long-Term Explicit Memory

Explicit memory for events and facts is conscious and intentional and consists of personal experiences, or *episodic memories* (what you did last night) and fact-based *semantic memories* ($2 \times 2 = 4$, for students who memorized the times table). Both types of explicit memory depend on conceptually driven top-down processing, in which a person reorganizes the data to store it. Later recall of information is thus greatly influenced by the way in which the information was originally processed.

Episodic Memory

Episodic (autobiographic) memory, a person's recall of singular events, is uniquely different from other neurocognitive memory systems in that it is memory of life experiences centered on the person himself or herself—a life history. The following excerpts illustrate a simple test for the presence of autobiographic memory. In reading through it, note the neuropsychologist's persistence in trying to determine whether the subject, G.O., can recall a single personal event or experience. Had he not been so persistent, G.O.'s impairment in episodic memory might well have been missed.

> *Do you have a memory of when you had to speak in public?*
>
> Well yes, I'm a call centre trainer with Modern Phone Systems; so I did a lot of speaking because I did a lot, a lot of training all across Canada. I also went to parts of the States.
>
> *Do you remember one time that you were speaking? Can you tell us about one incident?*

Oh yes! Well I trained thousands and thousands of clients on a wide variety of topics including customer service, inbound and outbound telemarketing. Handling difficult customers.

. . .

So what we're looking for is one incident or one time that you gave a training session or any other speeches that you want to tell us about. A specific incident.

Oh well I customized a lot of material for many, many companies. And I also did lots of training at the home office.

OK, so what we're asking is do you remember one time that you gave a talk?

Oh! yes I do.

One specific time not over a series of times, one time, can you tell us about that?

Oh sure yes, it was at the home office and yes, many many people were there.

. . .

I'm getting the impression that you have a really good memory for all the training that you've done but you don't seem to be able to come up with a specific talk that maybe stands out in your mind for any reason? Would you agree with that?

Oh yes well I always trained customer service.

So there was no talk that maybe something went wrong or something strange happened?

No, No I was a very good trainer. (Levine, 2000)

Autonoetic Awareness of Time

One function of autobiographical memory is providing us with a sense of continuity. Endel Tulving (2002) terms this *autonoetic awareness*, or self-knowledge, which allows us to bind together the awareness of our self as a continuous entity through time. Autonoetic awareness further allows us to travel in subjective time, either into the past or into the future. Patients with hippocampal and frontal cortical injury often lose self-knowledge and have real difficulty in daily living resulting from a deficit of behavioral self-regulation and the ability to profit from past experience in making future decisions (see Section 16.2). Tulving proposes that "time travel" is a memory ability that characterizes humans but not nonhuman animals and depends on maturation and so will not be found in babies and young children.

Tulving's patient Kent Cochrane, usually referred to as patient K.C., illustrates the effects of losing autobiographic memory. At age 30, as a result of a motorcycle accident, K.C. had a serious TBI with extensive lesions in multiple cortical and subcortical brain regions, including the medial temporal lobes, and consequent severe amnesia. Nevertheless, most of K.C.'s cognitive capabilities were intact and indistinguishable from those of typical, healthy adults.

His intelligence and language were at normal; he had no problems with reading or writing; his ability to concentrate and to maintain focused attention were standard; his thought processes were clear; he could play the organ, chess, and various card games; his ability to visualize things mentally was intact; and his performance on short-term-memory tasks was at normal. K.C. knew many objective facts concerning his own life, such as his date of birth, the address of his

home for the first 9 years of his life, the names of some of the schools that he attended, the make and color of the car that he once owned, and the fact that his parents had owned and still owned a summer cottage.

He knew the location of the cottage and could easily find it on a map. He knew the distance from his home to the cottage and how long it took to drive there in weekend traffic. He also knew that he had spent a lot of time there. His knowledge of mathematics, history, geography, and other school subjects, as well as his general knowledge of the world, was not greatly different from that of others at his educational level.

Along with all these typical abilities, however, K.C. had dense amnesia for personal experiences. He could not recollect any autobiographic events, whether one-time happenings or repeating occurrences. This inability to remember any episodes or situations in which he was present covered his whole life from birth, although he did retain immediate experiences for a minute or two. In short, he could not "time travel," either to the past or future. He could not say what he would be doing later in the day, the next day, or at any time in the rest of his life. In short, he could not imagine his future any more than he could remember his past.

Because the damage to K.C.'s brain was diffuse, it is difficult to say which constellation of injuries accounted for his asymmetrical retrograde amnesia, in which episodic memory is lost but semantic memory is spared. Brian Levine and his coworkers (1998) described similar symptoms for M.L., whose lesion was more localized.

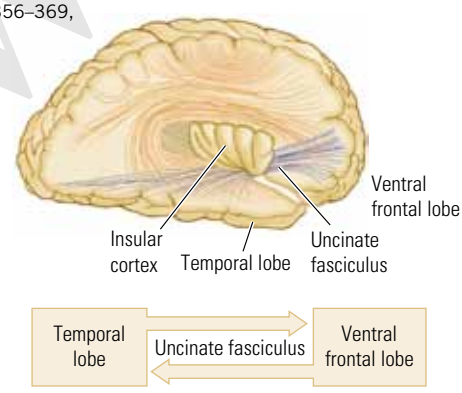
Densely amnesic for episodic experiences predating his injury, M.L. showed damage to the right ventral prefrontal cortex and underlying white matter, including the **uncinate fasciculus**, a fiber pathway that connects the temporal lobe and ventral prefrontal cortex (**Figure 18.5**). Because H.M. also displayed a complete loss of autobiographic memory both from before and after his surgery, autobiographic memory must depend on the medial temporal lobe as well as the ventral prefrontal cortex and the connections between them made by the uncinate fasciculus.

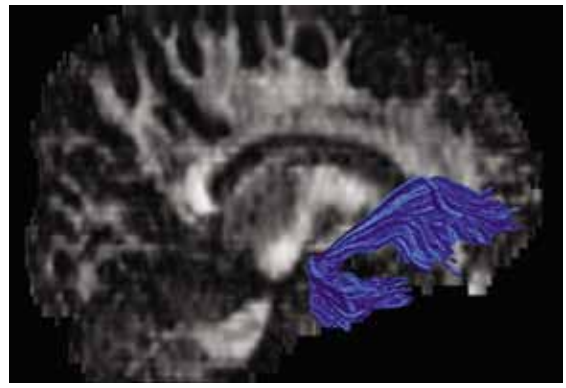
Semantic Memory

Knowledge about the world—all nonautobiographical knowledge—is categorized as **semantic memory**. It includes the ability to recognize family, friends, and acquaintances; information learned in school, such as specialized vocabularies and reading, writing, and mathematics; and knowledge of historical events

Figure 18.5 ▼

Brain Regions of Episodic Memory (Left) The ventral frontal and temporal lobes are reciprocally connected by the uncinate fasciculus pathway, shown in blue in the adjacent diffusion tensor image (right). (Diffusion tensor image from Field, A. S. Diffusion tensor imaging of cerebral white matter. *American Journal of Neuroradiology* 25:356–369, 2004, Fig. 7B.)





and of historical and literary figures—for example the answer to the question, Who was Charles Darwin?

Tulving's patient K.C. retained his semantic memory. He recalled the information he learned in school, he remembered that his parents had a cabin, and he knew where it was. He also remembered the games he learned before his injury, and he played them well. Similarly, H.M. retained semantic memory from before his surgery, and he acquired some semantic memories after his surgery—he knew that he had had brain surgery, for example. Not only is semantic memory different from episodic memory, it does not depend on the medial-temporal-lobe–ventral-prefrontal-lobe memory system that subserves episodic memory. Rather, semantic memory depends on the temporal- and frontal-lobe regions adjacent to the neural regions that subserve episodic memory.

Neural Substrates of Explicit Memory

Growing evidence indicates that neural systems, each consisting of several structures, support different kinds of memory. On the basis of animal and human studies, including many we have reviewed to this point, Herbert Petri and Mortimer Mishkin (1994) propose a largely temporal–frontal-lobe neural basis for explicit memory. This system comprises much of Mishkin's expanded ventral stream "what" pathway (see Figure 15.5).

Figure 18.6A illustrates the neural structures Petri and Mishkin assign to explicit memory. Most are in the temporal lobe or closely related to it, including the hippocampus, the rhinal cortices adjacent to the hippocampus in the temporal lobe, and the prefrontal cortex. Nuclei in the thalamus also participate, inasmuch as many connections between the prefrontal cortex and the temporal cortex are made through the thalamus. The regions that make up the explicit-memory circuit receive input from the neocortex and from the ascending systems in the brainstem, including the acetylcholine, serotonin, and noradrenaline activating systems (Figure 18.6B).

The following sections describe explicit-memory functions of different brain regions. We begin with medial-temporal-lobe structures—the hippocampus and perirhinal cortex—and move to the temporal and prefrontal cortices and other brain regions to which these structures connect.

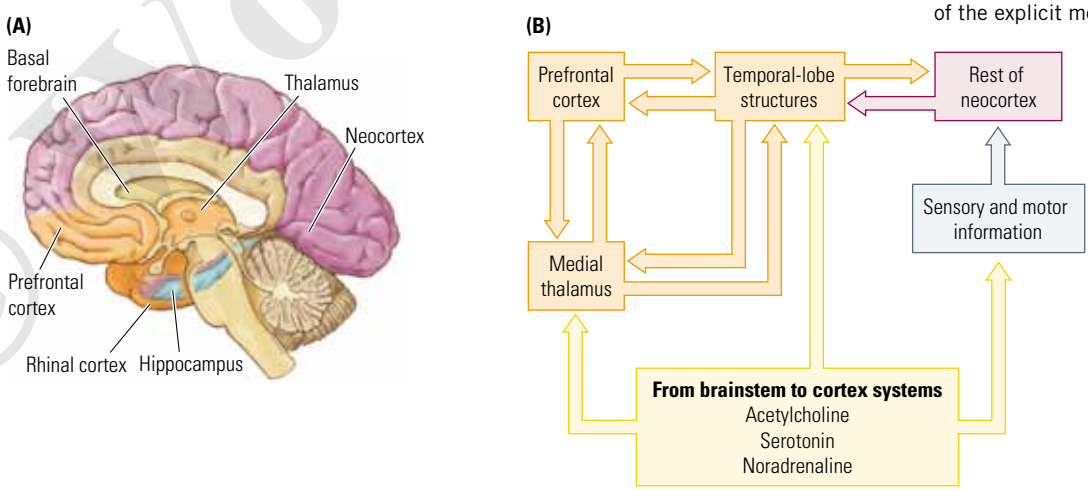


Figure 18.6 ▼

Neural Circuit Proposed for Explicit Memory

(A) General anatomical areas of explicit memory. (B) Flow of information, beginning with inputs from the sensory and motor systems that are not considered part of the explicit memory circuit.

Hippocampal Anatomy

Fifty years ago, neuroanatomist H. Chandler Elliott (1969) described the hippocampus as "quite archaic and vestigial, possibly concerned with primitive feeding reflexes no longer emergent in man." Quite to the contrary, this structure, small in comparison with the rest of the human forebrain, plays a dominant role in discussions of memory today. We describe hippocampal anatomy in some detail, both in reference to its position as a way station between the posterior sensory cortex and the frontal cortex and in reference to its intrinsic complexity. (It was named *hippocampus*—Greek for "seahorse"—in the sixteenth century, either for its resemblance to the half-horse–half-fish that pulled the sea god Poseidon's chariot or for the small, horselike fish itself.)

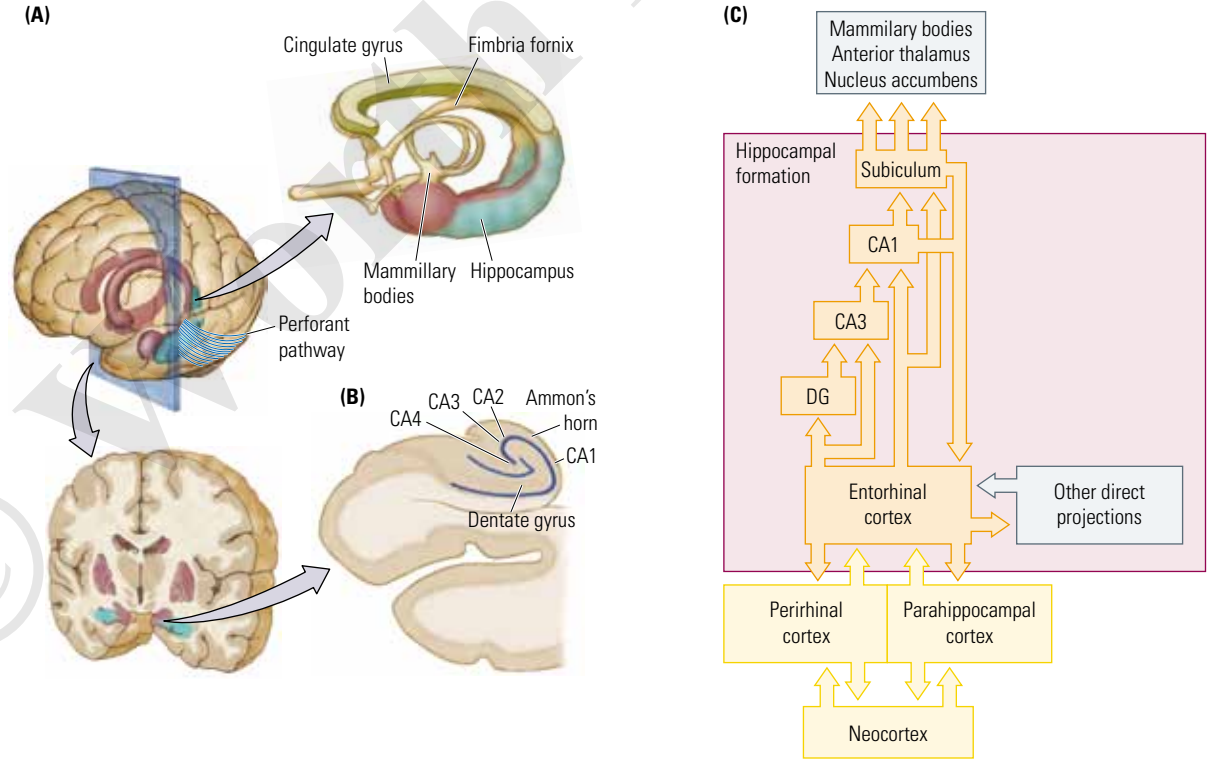
The hippocampus, a limbic structure that extends in a curve from the lateral neocortex of the medial temporal lobe toward the brain's midline, has a tubelike appearance (**Figure 18.7**A). It consists of two gyri, **Ammon's horn** (the horn of plenty, the mythological goat's horn from which fruits and vegetables flow endlessly), and the **dentate gyrus** (from the Latin *dentatus*, meaning "toothlike," because its main cell layer has a sharp bend like the edge of a tooth).

Each gyrus contains a distinctive type of cell (Figure 18.7B). Ammon's horn contains pyramidal cells, and the dentate gyrus cells are stellate (star-shaped) **granule cells**. The pyramidal cells of Ammon's horn are divided into four groups: CA1, CA2, CA3, and CA4 (CA standing for *cornu Ammonis*, the Latin name for Ammon's horn). For structural and functional reasons, the cells of the two gyri are differentially sensitive to *anoxia* (lack of oxygen) and to many toxins. With mild anoxia, CA1 cells are the most likely to die; with more-severe anoxia, other CA cells and finally the dentate gyrus cells will die.

Figure 18.7 ▾

Hippocampal Formation

(A) Lying medially within the temporal lobe, the hippocampus is connected to temporocortical structures by the perforant path and to the brainstem mammillary bodies and subcortical nucleus accumbens and anterior thalamus by the fimbria-fornix pathway. (B) Cross section through the hippocampus shows the locations of Ammon's horn, with its pyramidal cells (CA1 through CA4), and the dentate gyrus. (C) Neocortical structures project to the hippocampus through the entorhinal cortex, which receives feedback from the subiculum.



The hippocampus is reciprocally connected to the rest of the brain through two major pathways. The **perforant pathway** (because it perforates the hippocampus) connects the hippocampus to the posterior temporal cortex, as shown in Figure 18.7A. The other pathway, called the **fimbria fornix** ("arch fringe" because it arches along the edge of the hippocampus), connects the hippocampus to the thalamus, prefrontal cortex, basal ganglia, and hypothalamus.

It is through these two pathways that the hippocampus functions as a way station between the posterior neocortex and the frontal cortex, basal ganglia, and brainstem. Within the hippocampus, input from the neocortex goes to the dentate gyrus, which projects to Ammon's horn. Thus, granule cells are the sensory neurons of the hippocampus, and pyramidal neurons are its motor cells. CA1 cells project to another part of the temporal lobe called the subiculum, and the subicular cells project back to the temporal cortex and forward to the thalamus and brainstem (Figure 18.7C).

Case Histories of Hippocampal Function

Although evidence from the amnesic patient H.M. suggested a prominent role in memory for the hippocampus, H.M.'s hippocampal lesion was incomplete and included areas of the temporal lobe as well as the amygdala. Debate continues over what contribution the hippocampus makes to memory. It is a complex structure, and each patient with damage to the hippocampus whose case history we describe here has somewhat different lesions.

Larry Squire and Peter Bayley (2007) describe two patients, R.B. and D.G., whose lesions are limited to the CA1 region of the hippocampus and who have a limited retrograde amnesia covering perhaps 1 or 2 years. They also describe L.M. and W.H., who have more extensive but still incomplete hippocampal damage. Their retrograde amnesia covers 15 to 25 years. Patient E.P., with complete hippocampal damage plus some damage to surrounding structures, has retrograde amnesia covering 40 to 50 years.

These patients' amnesia suggests that the hippocampus itself is important in retaining memory after learning, and adjacent cortices are responsible for memory extending farther back in time. Squire and Bayley's consolidation theory, outlined in Section 18.1, proposes that the earliest memories can be accessed directly in the neocortex and so survive temporal-lobe lesions.

In contrast with the patients Squire and Bayley described, for whom some limit on retrograde amnesia exists, Lisa Cipolottie and her colleagues (2001) report that V.C., a patient whose hippocampus was entirely removed, though surrounding structures were undamaged, has retrograde amnesia that covers his entire life before the lesion was incurred. V.C.'s case suggests that the complete loss of the hippocampus results in complete retrograde and anterograde amnesia for explicit information from all age periods of life.

Cases of Early Hippocampal Damage The symptoms seen in adult cases of hippocampal damage led some researchers to hypothesize that if such damage occurred in infancy, the persons would be described not as amnesic but as severely mentally disabled. That is, they would be unable to speak, being unable to learn new words; unable to socialize, being unable to recognize other people; and unable to develop problem-solving abilities, being unable to remember solutions to problems.

Faraneh Vargha-Khadem and her colleagues (1997) report on three cases in which hippocampal damage was incurred early in life: for one subject, just after birth; for another, at 4 years of age; and for the third, at 9 years of age. None can reliably find his or her way in familiar surroundings, remember where objects and belongings are usually located, or remember where the objects were last placed. None is well oriented as to date and time, and all must frequently be reminded of regularly scheduled appointments and events, such as particular classes or extracurricular activities. None can reliably recount the day's activities or remember telephone conversations or messages, stories, television programs, visitors, holidays, and so on.

According to all three sets of parents, these everyday memory losses are so disabling that none of the affected persons can be left alone, much less lead lives commensurate with their ages or social environments. They are not mentally disabled, however. All have fared well in mainstream educational settings. They are competent in speech and language, have learned to read, and can write and spell. When tested for factual knowledge, they score in the average range. When tested on memory for faces and objects, they also score in the average range, although they are impaired on tasks requiring object–place associations and face–voice associations.

Cases of Damage to Neural Hippocampal Connections Taken together, the evidence suggests that the hippocampus is important for episodic memory, whereas semantic memory is the responsibility of adjacent structures. The complexity in the symptoms displayed by different patients relates to the fact that the lesions are seldom selective and vary widely from patient to patient. Not only is it difficult to establish that a lesion is restricted to the hippocampus but even if it is so restricted, the lesion nevertheless damages projections to and from other brain regions. Disconnecting the hippocampus can produce amnesia similar to that following hippocampal damage. David Gaffan and Elizabeth Gaffan (1991) describe a series of patients who sustained damage to the fimbria-fornix pathway, which connects the hippocampus to the frontal lobes and brainstem while sparing the hippocampus itself (see Figure 18.7A). These patients display retrograde and anterograde amnesia similar to that seen in patients with temporal-lobe damage, although perhaps not as extensive.

Hippocampal Function

What does the evidence we have reviewed tell us about the function of the hippocampus? Even though the specific hippocampal contribution to memory is debatable, studies of hippocampal patients allow us to draw four conclusions: (1) anterograde memory is more severely affected than retrograde memory, (2) episodic memories are more severely affected than semantic memories, (3) autobiographic memory is especially severely affected, and (4) "time travel" is diminished.

The hippocampus may also contribute to our ability to vary memory details when remembering—for example, recalling at one time only that an accident involved a bus and a car while recalling at another time extensive details related to the accident. Jordan Poppenk and colleagues (2013) review the many anatomical differences between the anterior hippocampus (area closer to the frontal

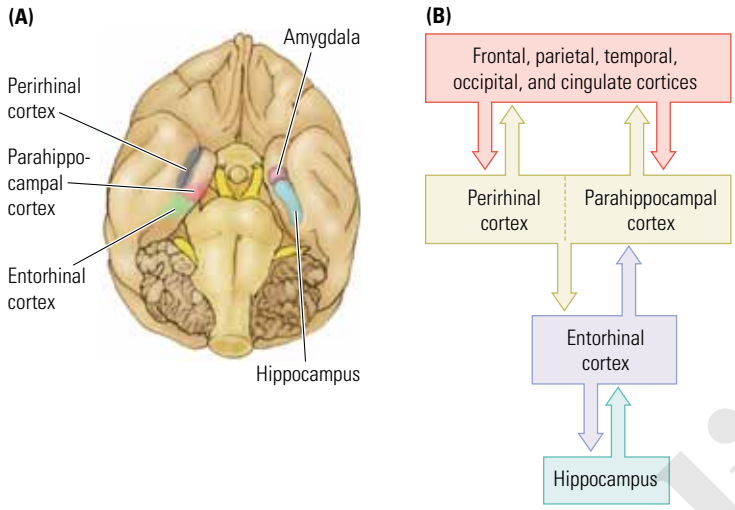


Figure 18.8 ◄

Medial Temporal Structures Participating in Memory (A) Rhesus monkey brain, ventral view, visualizing subcortical medial temporal regions. On the left are the perirhinal cortex, the parahippocampal cortex, and the entorhinal cortex. On the right, the amygdala and hippocampus are not directly visible because they lie beneath the medial temporal cortical regions illustrated on the left. (B) Input from the sensory areas in the cortex flows to the medial temporocortical, parahippocampal, and perirhinal regions, then to the entorhinal cortex, and finally to the hippocampus, which feeds information back to the medial temporal cortical regions.

lobes) and the posterior hippocampus (area closer to the temporal lobes). They suggest that the anterior hippocampus provides a coarse-grained representation of events, whereas the posterior area provides a fine-grained representation. Presumably, by accessing different memory subpathways through the hippocampus we can access and recount either abbreviated or elaborated versions of our life experiences.

The Temporal Cortex

When Suzanne Corkin and her colleagues (1997) used MRI to reexamine the extent of H.M.'s temporal-lobe removal, they found that the resection had removed portions of temporal cortex adjacent to the hippocampus (see Figure 18.3). Temporal-lobe areas bordering the rhinal fissure (called *rhinal cortex*) include the perirhinal cortex and the **entorhinal cortex**, which provides a major route for neocortical input to the hippocampal formation (**Figure 18.8**).

These regions, which project to the hippocampus, are often damaged in patients with medial-temporal-lobe lesions. Therefore, conventional surgeries and many forms of brain injury that affect the hippocampus may also damage the rhinal cortex or the pathways from it to the hippocampus. Discriminating between deficits that stem from rhinal cortex damage and deficits that result from disconnection or damage to the hippocampus is difficult.

Elizabeth Murray (2000) has used neurotoxic lesion techniques selectively to damage cells and spare fibers of either the hippocampus or the rhinal cortex in monkeys, then examine the specific contributions of each structure to amnesia. In Murray's studies, monkeys reach through the bars of their cages to displace objects under which a reward may be located (**Figure 18.9**A). To find the reward, the animals must use their abilities to (1) recognize objects or (2) recognize a given object in a given context.

A *matching-to-sample task* tests object recognition. A monkey sees a sample object that it displaces to retrieve a food reward hidden underneath. After a brief interval, the monkey is allowed to choose between the sample and a different object and is rewarded for choosing the familiar object. In an alternative *non-matching-to-sample* version, the monkey must choose the novel object

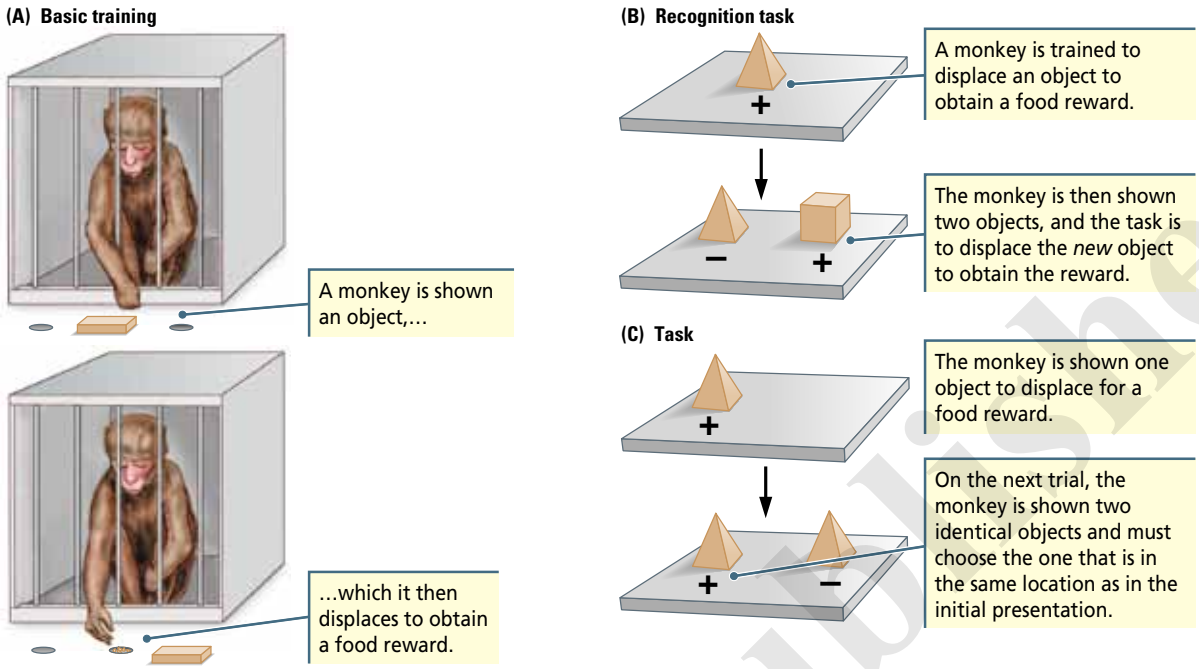


Figure 18.9 ▲

Two Memory Tasks for Monkeys

(Figure 18.9B). Delays can be introduced between the sample and the matching–nonmatching parts of both tests.

A contextual version of the task requires a monkey to choose an object by using cues based on the object's spatial location. The task may require choosing an object that remains in the same place, as shown in Figure 18.9C, or an object that appears in the same location in a visually presented scene in a picture.

In these studies of memory for objects and contexts, animals with selective hippocampal removal displayed no impairments on the object-recognition tests but were impaired when the test included context. In contrast, animals with rhinal lesions displayed severe anterograde and retrograde impairments on the object-recognition tests. The conclusion: object recognition (factual, or semantic, knowledge) depends on the rhinal cortices, whereas contextual knowledge (autobiographic, or episodic, knowledge) depends on the hippocampus.

Alex Clarke and Lorraine Tyler (2014) support this conclusion. They used fMRI to image participants' brains as they named a wide range of objects—animal, mineral, or vegetable, just like the guessing game. Activation in the ventral stream, from visual to perirhinal cortex, reflected object categories. General categories activated areas closer to primary visual cortex, and specific objects activated perirhinal cortex. If the object in the guessing game is to name a specific item, for example, the racehorse that won the 1973 Triple Crown, the category guessing (animal) would begin toward the visual cortex, and the identification of the winner, Secretariat, would occur in rhinal cortex. Personal knowledge—that you saw the races or have watched them on YouTube or got the right answer in this guessing game—is a function of the hippocampus.

Hemispheric Specialization for Explicit Memory

A variety of investigations reveal that asymmetries in explicit memory exist in all neocortical lobes.

Temporal Cortex

Because one treatment for epilepsy is removal of the affected temporal lobe, including both neocortical and limbic systems, many patients have undergone such surgery and have subsequently undergone neuropsychological study. The results of these studies suggest significant differences in the memory impairments stemming from damage to the left and right hemispheres. They also show that the temporal neocortex contributes significantly to these functional impairments.

After right-temporal-lobe removal, patients are impaired on face-recognition, spatial-position, and maze-learning tests (**Figure 18.10**). Impairments in memory for spatial position are illustrated by performance on the Corsi block-tapping test, illustrated in **Figure 18.11**A, in which a subject learns to tap out a sequence on a block board. Just as there is a memory span for digits (about seven), a similar memory span codes for locations in space. In the Corsi (1972) test, patients and controls are tested on sequences of block locations that contain one item more than the number their memory span can accommodate. One sequence, however, is repeated every third trial. Controls learn the repeated sequence in several trials, although they still have trouble with the novel

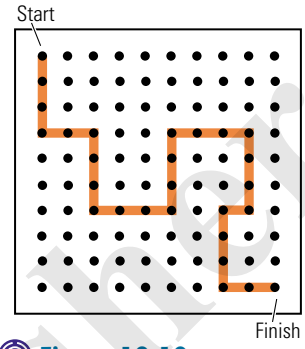


Figure 18.10 ▲

Visually Guided Stylus Maze The black circles represent metal bolt heads on a wooden base. The task is to discover and remember the correct route by trial and error, indicated here by the orange line. Deficits on this task are correlated with the amount of hippocampus damage in the right hemisphere.

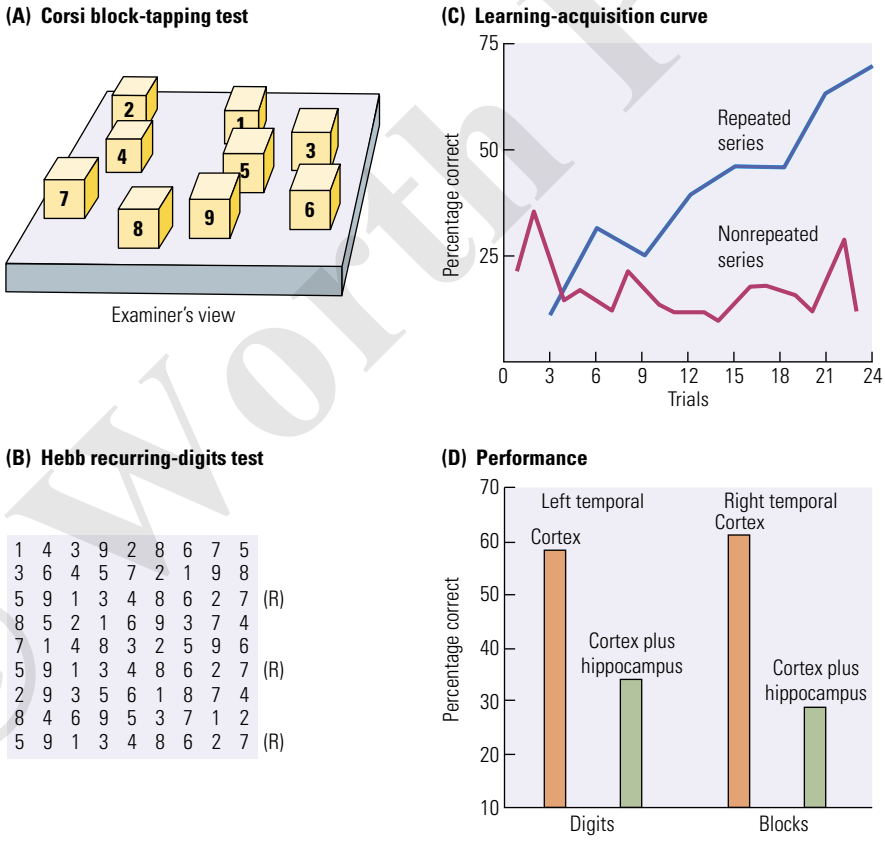


Figure 18.11 ◄

Assessing Temporal-Lobe Role in Memory (A) The Corsi block-tapping test requires a person to copy a sequence the examiner taps out. The blocks' numbers are visible on the examiner's side of the board only, and one numerical sequence repeats. (B) In the Hebb recurring-digits test, people are given multiple series of nine numbers, two digits longer than the usual digit-span memory. One series repeats (R) every third trial. (C) Performance on repeated series improves as the number of trials increases, but the nonrepeating series shows no improvement. (D) Patients with left-hemisphere medial temporal lesions are impaired on the Hebb recurring-digits test; subjects with right-hemisphere medial-temporal-lobe damage are impaired on the Corsi block-tapping test. (Research from Corsi, 1972.)

sequences. Subjects with damage to the right temporal lobe either do not learn the repeated sequence or learn it very slowly.

Left-temporal-lobe lesions result in functional impairments in recalling word lists, consonant trigrams, and nonspatial associations. Lesions may also cause impairments on the Hebb recurring-digits test illustrated in Figure 18.11B. This test is similar to the block-tapping test in that subjects are given lists of digits to repeat that exceed their digit spans. Among the lists is one digit sequence that repeats. Patients with left-temporal-lobe lesions do not display the typical learning-acquisition curve, illustrated in Figure 18.11C, but instead fail to learn the repeated digit sequence.

Brenda Milner (1965) doubly dissociated the effects on several memory tasks from damage to each hemisphere's temporal cortex. She concluded that lesions of the right temporal lobe result in impaired memory of nonverbal material. Lesions of the left temporal lobe, on the other hand, have little effect on the nonverbal tests but produce deficits on verbal tests such as the recall of previously presented stories and word pairs, as well as the recognition of words or numbers and recurring nonsense syllables. The results of these studies, graphed in Figure 18.11D, indicate that not only the medial temporal lobe but also the adjacent temporal neocortex are associated with severe memory deficits.

Parietal and Occipital Cortex

Cortical injuries in the parietal, posterior temporal, and occipital cortices sometimes produce specific long-term memory difficulties. Examples include color amnesia, prosopagnosia, object anomia (inability to recall the names of objects), and topographic amnesia (inability to recall the location of an object in the environment). Many of these deficits appear to develop in the presence of bilateral lesions only.

Frontal Cortex

The frontal cortex also participates in memory, including autobiographical memory, as described earlier. An interesting pattern of hemispheric asymmetry emerges in comparisons between memory encoding and retrieval. Usually referred to as *HERA*, for hemispheric encoding and retrieval asymmetry, this pattern predicts:

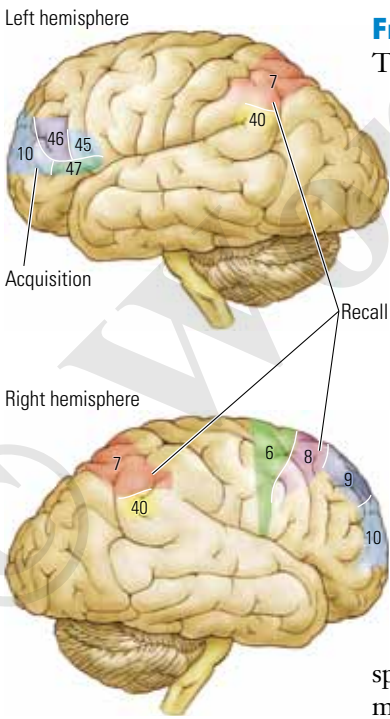
1. Left prefrontal cortex differentially more engaged in encoding semantic information than in retrieving it.
2. Left prefrontal cortex differentially more engaged in encoding episodic information than in retrieving it.
3. Right prefrontal cortex differentially more engaged in episodic memory retrieval than is the left prefrontal cortex.

For example, Tulving and coworkers (1994) showed that the left orbitofrontal cortex is preferentially active during memory encoding of words or series of words, but these regions do not retrieve this information. Rather, the right dorsolateral prefrontal cortex (DLPFC) and the posterior parietal cortex in both hemispheres are active during memory retrieval (**Figure 18.12**).

The asymmetry between encoding and retrieving may be related to hemispheric asymmetry in the use of language and spatial processes. Most information storage may include language use in some way, whereas retrieval may

Figure 18.12 ▼

Hemispheric Encoding and Retrieval Asymmetry (HERA) Active cortical areas, revealed by PET, during acquisition or recall of verbal information. During acquisition, activation appears in the left ventrolateral prefrontal cortex (areas 10, 46, 45, and 47). During recall of the same material, activation occurs in the right premotor cortex (areas 6 and 8), in prefrontal areas 9 and 10, and in the parietotemporal cortex bilaterally (areas 7 and 40). (Research from Tulving et al., 1994.)



additionally tap spatial processes to locate stored information. Thus, Roberto Cabeza and Lars Nyberg (2000), in a review of 275 PET and fMRI studies, note that brain activation during memory encoding and retrieval is likely due to general processes the brain employs to handle information as well as to local processes related to storing and retrieving specific kinds of information.

18.3 Long-Term Implicit Memory

The implicit–explicit memory distinction is especially vivid in H.M., whom you met in the chapter-opening Portrait. H.M. exhibited severe explicit-memory defects on many neuropsychological tests yet was surprisingly competent at some forms of implicit learning. **Implicit memory** of learned skills, conditioned reactions, and short-term events, is nonconscious and unintentional. Using language and performing motor skills, such as riding a bicycle or playing a sport, access implicit memory, which is encoded in much the same way as it is received. Processing is data driven, or bottom-up, and depends simply on sensory or motor information: it does not require manipulation by higher-level cortical processing. Implicit memory depends upon many of the neural structures that constitute the dorsal stream action pathway (see Figure 14.3C).

Milner trained H.M. on a mirror-drawing task that requires drawing a third outline between the double outline of a star while looking only at the reflection of the star and the pencil in a mirror (**Figure 18.13**A). This task is difficult at first even for controls, but they improve with practice. Patients with amnesia can also display a typical learning curve on this task, as did H.M., but like him, may not remember ever performing it (Figure 18.13B). When Suzanne Corkin (1968) trained H.M. on a variety of manual tracking and coordination tasks, his initial performance tended to be inferior to those of controls, but he showed nearly standard improvement from session to session. Yet again, he had no explicit memory of ever performing the tasks.

Sparing of Implicit Memory in Amnesia

Other forms of implicit memory also survive in amnesic patients. One entails the experimental technique of **priming**, in which a stimulus is used to sensitize the nervous system to a later presentation of the same or a similar stimulus. In

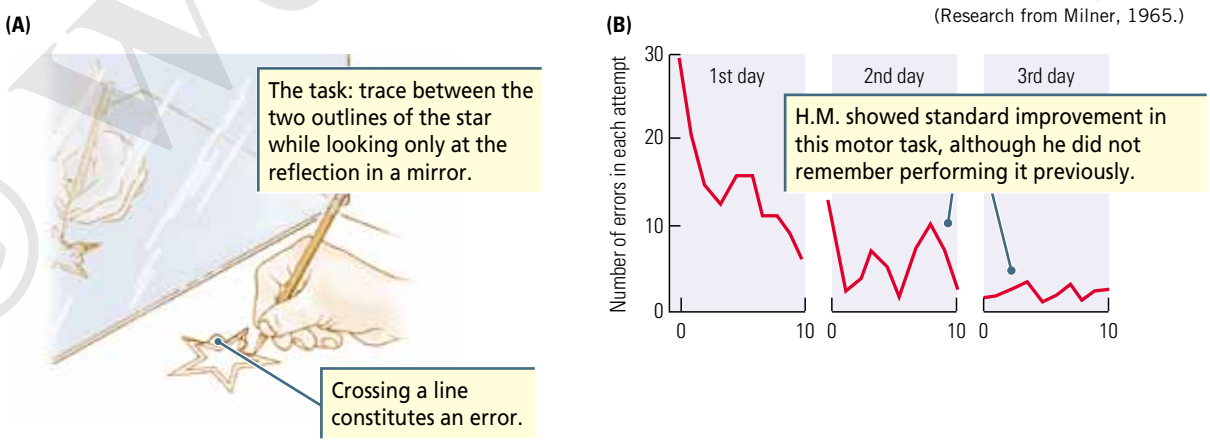


Figure 18.13 ▼
Test of Motor Memory
(A) The mirror-drawing task. (B) Patient H.M.'s performance over three training sessions. (Research from Milner, 1965.)

a typical priming task, a person is first given a list of words to read, then given a list containing only the beginnings of words. The task is to complete each incomplete item with the first word that comes to mind.

If one of the priming words is TAB, the person might complete it as *table*, *tablet*, *tabby*, *tabulation*, or something similar. If one of the words on the first list is *table*, however, a person is more likely to complete TAB as *table* than as any other possibility, showing that he or she remembers the word. The first list primed the person to give a certain response later on. Amnesic subjects perform as well on priming as controls do, indicating that they remember what was on the first study list even as they report no conscious recollection of ever having seen it.

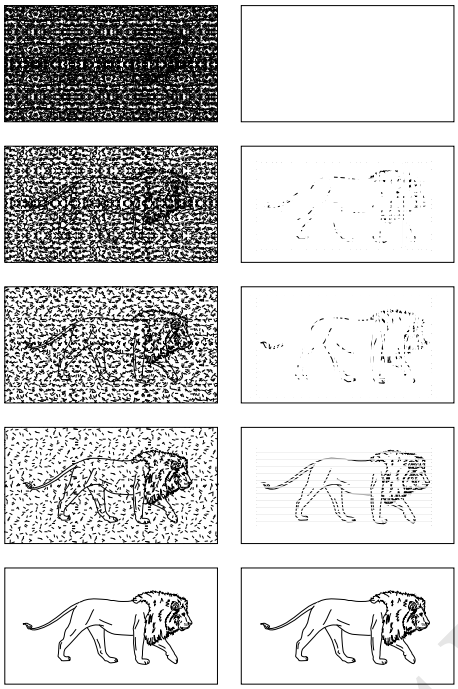


Figure 18.14 ▲

Gollin Incomplete-Figures Test Subjects and participants are shown a series of drawings in sequence, from least to most clear. Identifying the object from the first sketch is impossible; most people must see several panels to identify it correctly. On a retention test some time later, however, they identify the image sooner than they did on the first test, indicating memory for the image. Amnesic subjects also show improvement after priming, even though they forget taking the test before. (Republished with permission of AMMONS SCIENTIFIC LTD., from Perceptual and motor skills, Gollin, E. S., Developmental studies of visual recognition of incomplete objects, 11:289–298, 1960; permission conveyed through Copyright Clearance Center, Inc.)

In another priming demonstration, subjects and controls are shown an incomplete sketch and asked what it is. If they fail to identify the sketch, they are shown another slightly more complete sketch. This process continues until they eventually recognize the picture. When controls and amnesic patients are shown the same sketch at a later date, both groups will identify it at an earlier stage than was possible for them the first time. Thus, both groups indicate through their performance that they remember the previous experience of seeing the lion in **Figure 18.14** completed, even though the amnesic subjects cannot consciously recall ever seeing the sketches before.

The independence of implicit from explicit memory can be demonstrated in other ways. If asked to think about the meaning of a word or the word's shape, controls' explicit recall of the word is greatly improved. Yet their scores on word completion, which taps implicit memory, are not affected by this manipulation. This is the **depth-of-processing effect**. On the other hand, if controls are presented with a word in one modality (for example, hearing the word) and are tested for recall in another modality (say, writing the word or identifying by reading), their scores on a word-completion test are greatly reduced, but their explicit recall is little affected, a phenomenon called a **study–test modality shift**.

Neural Substrates of Implicit Memory

Herbert Petri and Mortimer Mishkin (1994) suggested a brain circuit for implicit memory that includes the entire neocortex and basal ganglia structures (the caudate nucleus and putamen). The basal ganglia receive projections from all regions of the neocortex as well as from dopamine cells in the substantia nigra and send projections through the globus pallidus and ventral thalamus to the premotor cortex (**Figure 18.15**). The motor cortex shares connections with the cerebellum, which also contributes to implicit memory. In a review of the literature on the neural basis of implicit memory, Paul Reber (2013) argues that, rather than being supported by a discrete neural circuit, implicit memory reflects instead plastic changes that take place in the brain regions processing the information.

Motor Cortex Plasticity

In the pursuit rotor task, a person attempts to keep a stylus in a particular location on a rotating turntable about the size of a vinyl record album. The task draws on skills similar to those needed in mirror drawing. When researchers

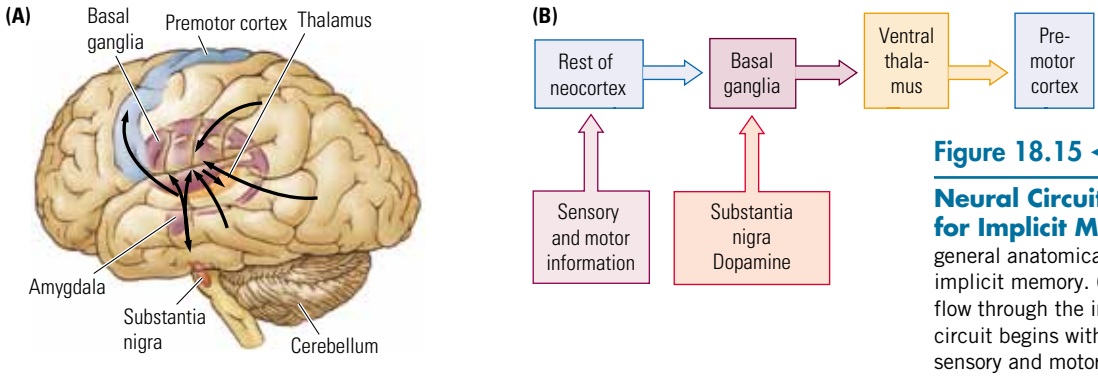
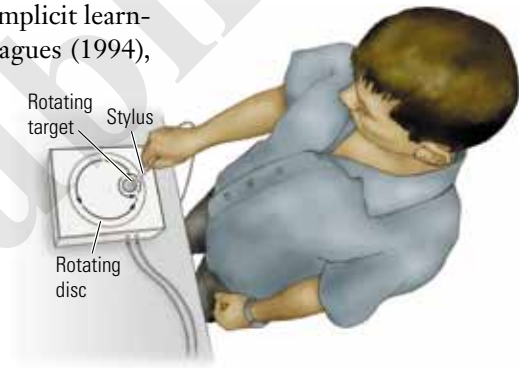


Figure 18.15 ◂

Neural Circuit Proposed for Implicit Memory (A) The general anatomical areas of implicit memory. (B) Information flow through the implicit memory circuit begins with inputs from the sensory and motor systems, which themselves are not considered part of the circuit.

used PET to record regional cerebral blood flow as controls learned to perform this task, they found that performance is associated with increased cerebral blood flow in the motor cortex, basal ganglia, and cerebellum (Grafton et al., 1992). Acquisition of the skill was associated with a subset of these structures, including the primary motor and supplementary motor cortices and the pulvinar nucleus of the thalamus.

A more dramatic demonstration of motor cortex plasticity in implicit learning comes from a study by Alvaro Pascual-Leone and his colleagues (1994), who found that acquiring implicit knowledge requires motor cortex reorganization not required for explicit-memory performance. Participants were required to press one of four numbered buttons, using a correspondingly numbered finger, in response to numbered cues provided on a video monitor. For example, when number 1 appears on the screen, push button 1 with finger 1. The measure of learning was the decrease in reaction time between the cue's appearance and the pushing of the button on successive trials.



▲ A person who attempts the pursuit rotor task must keep the stylus in contact with a metal disc that is moving in a circular pattern on a turntable, which also is moving in a circular pattern.

Two groups were tested with sequences of 12 cues. For the control group, there was no order to the sequences, but the sequence presented to the other group was repeated so that after they learned the pattern, they could anticipate the cue and so respond very quickly. The implicit-memory component of this task was improvement in reaction time with practice; the explicit-memory component was the participants' recognition of the sequence, which enabled them to generate responses without needing the cues.

Transcranial magnetic stimulation mapped the motor-cortex area representing the limb making the responses; muscle activity in the limb was recorded simultaneously. Researchers thus discovered which cortical areas send commands to the muscles at various times in the course of learning. Here, Pascual-Leone and colleagues found that the cortical area controlling the limb appeared to increase in size as implicit learning took place. When the participants knew the sequence of stimuli and thus had explicit knowledge of the task, however, the motor cortex area active during task performance returned to its baseline dimensions. Thus, acquiring implicit knowledge requires cortical plasticity not required for explicit-memory performance.

The Basal Ganglia

Evidence from other clinical and experimental studies supports a formative role for basal ganglia circuitry in implicit memory. In a study of patients with **Huntington's disease**, a hereditary disorder characterized by *choreas* (ceaseless,

involuntary movements) stemming from cellular degeneration in the basal ganglia, patients were impaired in the implicit mirror-drawing task illustrated in Figure 18.13. Patients with temporal-lobe lesions were unimpaired (Martone et al., 1984). Conversely, the patients with Huntington's disease were unimpaired on verbal recognition, an explicit-memory task.

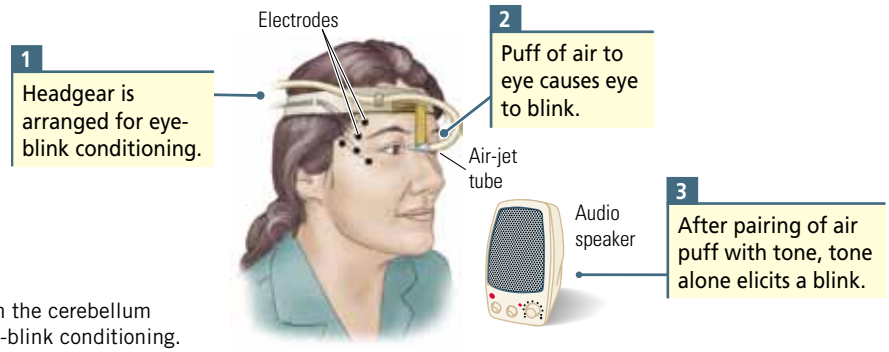
J.K.'s case is illustrative. He was above average in intelligence and worked as a petroleum engineer for 45 years. In his mid-70s, he began to show symptoms of *Parkinson's disease* (in which the projections from the dopaminergic cells of the brainstem to the basal ganglia die), and by about age 78, he started having memory difficulties. Curiously, J.K.'s memory disturbance primarily affected tasks he had done all his life. He once stood at the door of his bedroom, frustrated by his inability to recall how to turn on the lights. He remarked, "I must be crazy. I've done this all my life, and now I can't remember how to do it!" When he was seen trying to turn the radio off with the remote control for the television set, he explained, "I don't recall how to turn off the radio; so I thought I would try this thing!"

J.K. clearly displayed an implicit memory deficit. In studies of patients with Parkinson's disease, Elise Anderson and colleagues (2014) report improvements in implicit memory when Parkinsonian subjects are given L-dopa treatment. This dopamine precursor restores basal ganglia dopamine, with subsequent deterioration of performance when treatment is withheld.

The Cerebellum

Cortical motor regions also receive projections through the thalamus from the cerebellum. Kyu Lee and Richard Thompson (2006) demonstrated the cerebellum's important position relative to the brain circuits taking part in motor learning (see Figure 9.15). They also suggest that the cerebellum plays an important role in a form of nonconscious learning called **classical (Pavlovian) conditioning**, in which a neutral stimulus is paired with a stimulus that evokes behavior.

In the Lee–Thompson model, a puff of air paired with a stimulus, such as a tone, is administered to a rabbit's eyelid. Eventually, whenever the tone is sounded, the conditioned rabbit blinks even though the air puff does not occur. Lesions to pathways from the cerebellum abolish this *conditioned response* but do not stop the rabbit from blinking in response to an actual air puff, the *unconditioned response*. This evidence suggests that the cerebellum mediates learning discrete, adaptive, behavioral responses.



▶ Circuits in the cerebellum mediate eye-blink conditioning.

18.4 Long-Term Emotional Memory

Like implicit memory, **emotional memory** for the affective properties of stimuli or events relies on bottom-up processing. But emotional memory, which is arousing, vivid, and available on prompting, likewise has the intentional, top-down element of explicit memory. We use internal cues both in processing emotional events and in initiating their spontaneous recall.

Evoking Negative Emotions

In **fear conditioning**, a noxious stimulus is paired with a neutral stimulus to elicit an emotional response. A rat or other animal is placed in a box that has a grid floor through which a mild but noxious electrical current can pass. (This shock is roughly equivalent to the static-electrical shock we get when we rub our feet on a carpet, then touch a metal object or another person.) When the tone is later presented without the shock, the animal will act afraid. It may become motionless and may urinate in expectation of the shock. A novel stimulus, such as a light, presented in the same environment has little effect on the animal. Thus, the animal tells us that it has learned to associate the tone with the shock.

Although both eye-blink, a nonemotional form of conditioning, and fear conditioning are Pavlovian, different parts of the brain mediate learning in each case. Circuits of the amygdala mediate fear conditioning, and circuits of the cerebellum mediate eye-blink conditioning. Emotional memories contain both implicit (nonconscious) and explicit (conscious) aspects: people can react with fear to specific identifiable stimuli, and they can also fear situations for which they do not seem to have specific memories.

In a common pathology, **panic disorder**, people show marked anxiety but cannot identify a specific cause. Thus, emotional memory can be seen as separate from explicit and implicit memory. Perhaps the difficulty people have in coping with posttraumatic stress is that the emotional memory evoked by stress is dissociated from other stress-related memories.

Neural Substrates of Emotional Memory

Emotional memory has a unique anatomical component—the amygdala (**Figure 18.16**A). The amygdala consists of a number of nuclei, the basolateral complex, the cortical nucleus, the medial nucleus, and the central nucleus. The

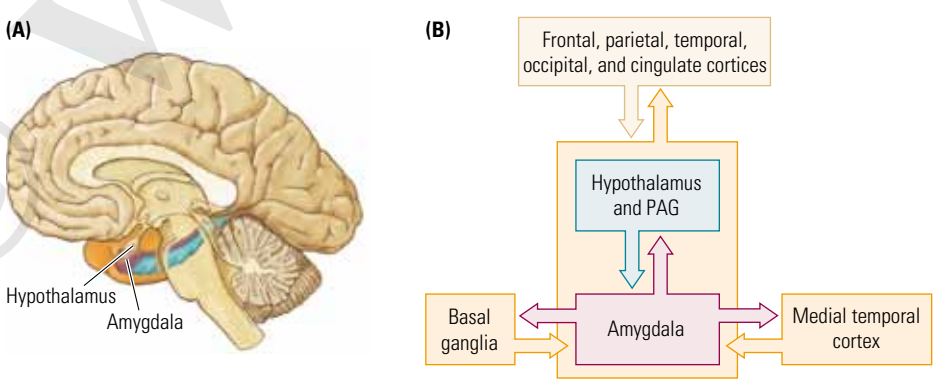


Figure 18.16 ◂

Neural Circuit Proposed for Emotional Memory

(A) The key structure in emotional memory is the amygdala. (B) Information flow in emotional memory.

basolateral complex can be further subdivided into the lateral, the basal, and the accessory basal nuclei. The amygdala connects to autonomic systems that control such functions as blood pressure and heart rate and to the hypothalamus, which controls hormonal systems. A number of early neuropsychological studies on monkeys that had received amygdala damage noted their tameness.

Damage to the amygdala abolishes emotional memory but has little effect on implicit or explicit memory. The amygdala has especially close connections with medial temporal cortical structures (Figure 18.16B). It projects to structures taking part in producing autonomic responses—namely, the hypothalamus and brainstem periaqueductal gray matter (PAG). In addition, the amygdala links to the implicit-memory system through its connections with the basal ganglia. Joseph LeDoux (2012) argues that these connections should be regarded as a survival circuit that prompts us to fight or flee, as the situation dictates.

Unique Aspects of Emotional Memory

Emotionally arousing experiences spark vivid memories, a fact confirmed both by animal and human studies and detailed in Chapter 20. Emotionally significant experiences, pleasant and unpleasant, reactivate hormonal and brain systems that act to stamp in these vivid memories by modulating memory circuits in the rest of the brain. Future experiences can reactivate these circuits, for example in circumstances that require a rapid fight-or-flight response.

A study of severely demented patients by Bob Sainsbury and Marjorie Coristine (1986) illustrates the nonconscious aspect of emotional remembering. The patients were believed to have severe cortical abnormalities but intact amygdalar functioning. The researchers first established that their ability to recognize photographs of close relatives was severely impaired.

The patients were then shown four photographs, one of which depicted a relative (either a sibling or a child) who had visited during the preceding 2 weeks. The task was to identify the person whom they liked better than the others. Although the subjects were unaware that they knew anyone in the photographs, they consistently preferred the photographs of their relatives. This result suggests that each patient, although demented, still had an emotional memory that guided his or her preference.

18.5 Short-Term Memory

In 1890, William James drew a distinction between memories that endure only briefly and longer-term memories. Not until 1958, however, did Donald Broadbent specifically postulate separate short- and long-term memory systems. **Short-term memory**, also called **working memory** or *temporal memory*, is a neural record of recent events and their order. We use the short-term system to hold sensory events, movements, and cognitive information, such as digits, words, names, or other items, for a brief period.

Because short-term information may be related to objects or to movements, short-term memory may be related to the ventral (object-recognition) or dorsal (motor) streams of sensory processing. Both streams project to the prefrontal cortex, although to different places (see Figure 16.3). Thus, short-term

memory for motor and for object information is mediated by locations defined by the dorsal and ventral streams, respectively, to two different regions of the frontal cortex.

Short-Term Memory and the Temporal and Parietal Lobes

Elizabeth Warrington and Larry Weiskrantz (1978) describe patient K.F., who had received a left posterior-temporal lesion that resulted in an almost total inability to repeat verbal stimuli such as digits, letters, words, and sentences. In contrast, his long-term recall of paired-associates words or short stories was nearly standard. K.F.'s condition contrasts starkly with that of H.M. and other medial-temporal-lobe subjects, who retain functional short-term memory (Allen et al., 2014).

Warrington and Weiskrantz also found that some patients apparently have defects in short-term recall of visually presented digits or letters but have standard short-term recall for the same stimuli presented aurally. Russian neuropsychologist Alexander Luria (1968) described patients with just the opposite difficulty: specific deficits for aurally presented but not visually presented verbal items. Short-term-memory deficits can also result from damage to the polymodal sensory areas of the posterior parietal and posterior temporal cortex. Warrington and Weiskrantz present several cases of specific short-term-memory deficits in patients with lesions at the junction of the parietal, temporal, and occipital cortices.

Short-Term Memory and the Frontal Lobes

Damage to the frontal cortex is the recognized cause of many short-term memory impairments for tasks in which subjects must temporarily remember the locations of stimuli. The tasks themselves may be rather simple: given this cue, make that response after a delay. But as one trial follows another, both animals and people with frontal-lobe lesions start to mix up previously presented stimuli.

Neuropsychological Testing for Short-Term Memory Function

L. Prisko (1963) devised a compound stimulus task in which two stimuli in the same sensory modality are presented in succession, separated by a short interval. A subject's task is to report whether the second stimulus is identical with the first. In half the trials, the paired stimuli were the same; in the other half, they were different. Thus, the task required that the subject remember the first stimulus to compare it with the second while suppressing the stimuli that had been presented in previous trials. The Snapshot on page 504 describes another compound-stimulus paradigm.

Similarly, two tasks, one verbal and one nonverbal, were used in another test (Corsi, 1972). Subjects were required to decide which of two stimuli had been seen more recently. In the verbal task, they were asked to read word pairs presented on a series of cards (for example, *cowboy–railroad*). From time to time, a card appeared bearing two words with a question mark between them. Subjects had to indicate which word they had read more recently.

SNAPSHOT Disrupting Memory Formation

Ladislas von Meduna developed **electroconvulsive therapy** (ECT), the first electrical brain-stimulation treatment, in 1933 because he thought that people with epilepsy could not be schizophrenic and therefore that seizures could cure insanity. At first, the therapeutic seizures were induced with a drug called Metrazol, but in 1937, Ugo Cerletti and Lucio Bini replaced Metrazol with electricity.

ECT does not cure schizophrenia, but a review by Max Fink (2014) finds that it can be effective in treating major depression. A drawback to ECT is that it can temporarily impair memory (Sackheim, 2014). This observation led to using ECT to study memory, but its use for severe depression has grown rare with the advent of noninvasive treatments such as transcranial magnetic stimulation (TMS).

According to *system consolidation theory*, described in Section 18.1, long-term memories are not formed instantaneously but require biochemical and structural changes that take some time. Neuroscientists reasoned that if an animal was given a learning experience, application of ECT at different times afterward could be used to map the duration of changes required for memory formation.

But the results of many experiments using ECT suggest that not many memory-forming changes take place after a single experience, each with its own time course for consolidation. Recent experiences are related to transitory, short-term memory storage, whereas longer-term experiences are related to long-term memory formation.

More-refined application of brain stimulation makes use of noninvasive TMS. A magnetic coil is placed over the skull to stimulate the underlying brain area (Section 7.2). TMS can be used either to induce behavior or to disrupt ongoing behavior. Justin Harris and colleagues (2002) presented two vibratory stimuli to participants' fingertips and asked them to state whether the stimuli were the same or different. TMS delivered within 600 ms of the first stimulus disrupted choice accuracy, but TMS after 900 ms did not.

Harris (2006) further demonstrates that the primary sensory cortex is the site for short-term memory of somatosensory stimulation and that a memory can be formed within 900 ms. Thus, short-term memories are encoded at low hierarchical levels of the nervous system.

Jacinta O'Shea and colleagues (2007) used a pop-out paradigm to study the specificity of short-term memory. (If the same stimulus is presented repeatedly in a number of pictures, participants identify its shape and location more quickly.) They found that TMS applied to the frontal eye fields, a premotor cortex site of visual short-term memory, disrupted memory for location but not for form. Thus, different neural locations encode different stimulus features, such as form and location, hence different short-term memories, separately.

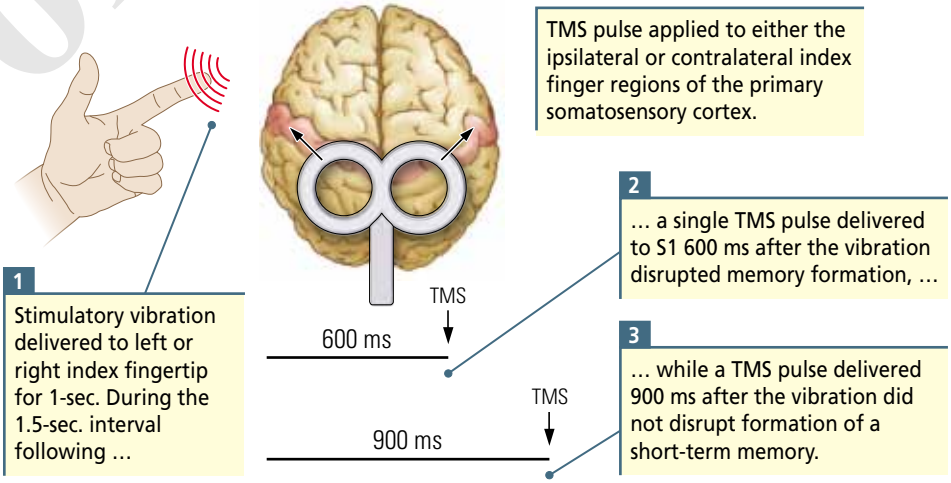
Fink, M. What was learned: Studies by the consortium for research in ECT (CORE) 1997–2011. *Acta Psychiatrica Scandinavica* 129(6):417–426, 2014.

Harris, J. A. Psychophysical investigations into cortical encoding of vibrotactile stimuli. *Novartis Foundation Symposium* 270:238–245, 2006.

Harris, J. A., C. Miniussi, I. M. Harris, and M. E. Diamond. Transient storage of a tactile memory trace in primary somatosensory cortex, *Journal of Neuroscience*, 22:8721, 2002.

O'Shea, J., N. G. Muggleton, A. Cowey, and V. Walsh. Human frontal eye fields and spatial priming of pop-out. *Journal of Cognitive Neuroscience* 19:1140–1151, 2007.

Sackeim, H. A. Autobiographical memory and electroconvulsive therapy: Do not throw out the baby. *Journal of ECT* April 21, 2014.



Testing for Tactile Memory in S1. (Research from Harris et al., 2002, and Harris, 2006.)

Sometimes, both words had been seen before; at other times, only one word had been seen. In the latter case, the task became a simple test of recognition, whereas in the former case, it was a test of *recency memory*. Patients with left temporal removals showed a mild deficit in recognition, in keeping with their verbal memory difficulty; frontal-lobe patients performed at normal. On the recency test, however, both frontal-lobe groups (left and right) were impaired, with the left-side group significantly worse.

The nonverbal task was identical to the verbal task except that the stimuli were photographs of paintings rather than words. Patients with right-temporal-lobe removals showed mild recognition deficits, consistent with their visual-memory deficit, whereas those with right-frontal-lobe lesions performed at normal. On the recency test, the frontal-lobe groups were impaired, but now the right-side group was significantly worse.

Interference Tasks

Morris Moscovitch (1982) devised a task in which patients were read five different lists of 12 words each and instructed to recall as much of each list as they could immediately after presentation. In the first four lists, all words were drawn from the same taxonomic category, such as sports; the words in the fifth list came from a different category, such as professions.

Controls showed a decline from list 1 to list 4 in the number of words recalled correctly; that is, they exhibited **proactive interference**: the earlier lists interfered with learning new information. But they also exhibited an additional phenomenon on list 5: they recalled as many words as they did for list 1, thus demonstrating *release from proactive interference*. Frontal-lobe patients also showed strong proactive interference, as would be expected from the Prisko experiments, but they failed to show release from proactive interference on list 5.

Another memory deficit in patients with frontal-lobe lesions has been demonstrated in a test of movement copying (shown in Figure 14.10). When patients with cortical lesions were asked to copy complex arm and facial movements, in addition to making errors of sequence, frontal-lobe patients made many errors of intrusion and omission (Kolb and Milner, 1981). That is, when asked to copy a series of three discrete facial movements, frontal-lobe patients left one movement out (error of omission) or added a movement seen in a previous sequence (error of intrusion).

Dorsal- and Ventral-Stream Participation in Short-Term Memory

The results of experiments with monkeys confirm that different prefrontal areas take part in different types of short-term memory. Joaquin Fuster (1989) demonstrated that if monkeys are shown objects they must remember for a short period before making a response, neurons in the frontal cortex fire during the delay. This finding suggests that these neurons are active in bridging the stimulus–response gap. Patricia Goldman-Rakic (1992) examined this phenomenon further in two tasks, one testing memory for the location of objects and the other memory for object identity.

For the first task, a monkey was required to fixate on a point in the center of a screen while a light was flashed in some part of its visual field. After a variable delay of a few seconds, the monkey was required to shift its eyes to look at the

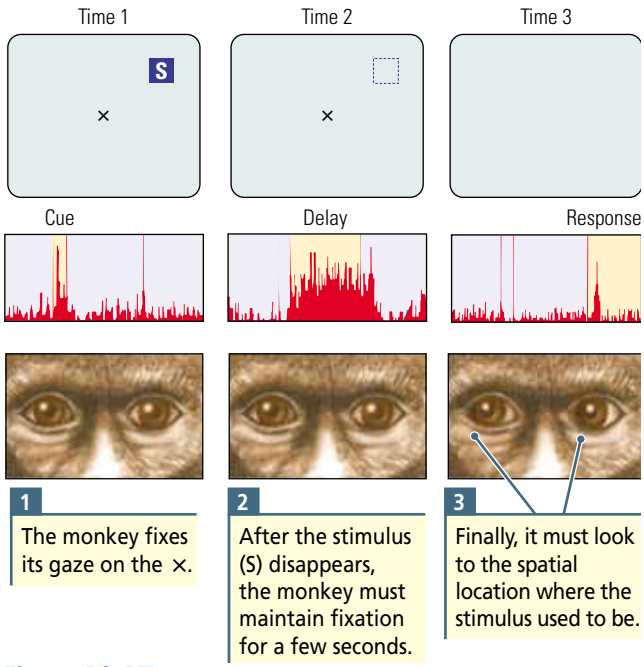


Figure 18.17 ▲

Testing Short-Term Memory Single cells can code spatial location of objects. During the delay in step 2, single cells in area 8 code the location of the second stimulus in memory. (Data from Goldman-Rakic, P.S. Working memory and the mind. *Scientific American* 267(3):111–117, 1992.)

point where the light had been. In the second task, as the monkey fixated on the center of the screen, one of two objects appeared on the screen. The monkey was required to look to the left in response to one stimulus and to the right in response to the other (**Figure 18.17**). Cells that code spatial vision are located in area 8 of the premotor cortex, whereas cells that code object recognition are located in areas 9 and 46 of the DLPFC (**Figure 18.18**A).

Michael Petrides and his coworkers (1993) used PET and MRI to demonstrate similar function–anatomy relations in humans. Their model posits two short-term-memory systems, for spatial and object memory (Figure 18.18B).

A spatial vision test required participants to point to one of eight patterns on each of eight cards in response to a colored bar at the top of the card. That is, in response to a cue, participants had to search for a specific pattern. Performance of this task was accompanied by increased activity in area 8 of the left hemisphere.

In contrast, an object task required participants to point to a different pattern in an array of eight patterns repeated on eight successive cards, which meant that they had to keep track of the patterns they had indicated already. During this task, the researchers found increased regional cerebral blood flow in the mid-dorsolateral prefrontal cortex (areas 9 and 46, mainly on the right).

Taken together, these studies confirm that the dorsal and ventral visual pathways from the parietal cortex and from the temporal lobes project to

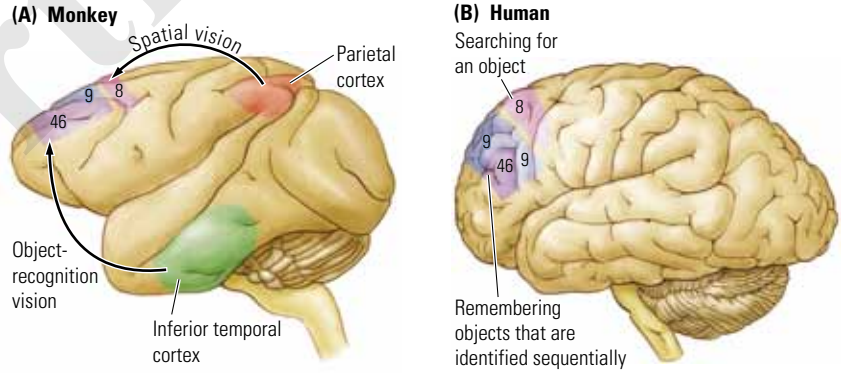


Figure 18.18 ▲

Two Short-Term Memory Systems in the Frontal Cortex (A) Results of single-cell-recording experiments show that premotor area 8, which receives projections from the parietal cortex, participates in short-term memory for object location in space (dorsal stream). DLPFC areas 9 and 46 participate in short-term memory for visual object recognition (ventral stream) and receive information from the inferior temporal cortex. (B) Results of PET-recording experiments show that area 8 searches for an object when a stimulus is presented, and areas 9 and 46 remember objects identified in sequence. (Part A information from Wilson et al., 1993; part B information from Petrides et al., 1993.)

different prefrontal cortical regions and support two kinds of short-term memory. The dorsal stream enables vision for action and the ventral stream, vision for perception.

18.6 Neurological Diseases and Long-Term Memory

Memory impairments result not only from diffuse brain damage but also from brain diseases such as transient global amnesia, herpes simplex encephalitis infections, Alzheimer's disease, and Korsakoff's syndrome.

Transient Global Amnesia

Concussion, migraine, hypoglycemia, and epilepsy, as well as interrupted blood flow from either a transient ischemic stroke or an embolism, are among the many possible causes of **transient global amnesia**. Described as loss of old memories and inability to form new ones, the condition is acute, with a sudden onset and usually a short course (Fisher and Adams, 1958). Transient global amnesia can be a one-time event, but Hans Markowitsch (1983) suggests, even so, that some memory loss can be permanent. Indeed, significant chronic memory loss is typical in transient global amnesia but usually overlooked because of the dramatic recovery and because careful memory testing after recovery is seldom done.

Herpes Simplex Encephalitis

Antonio Damasio and his coworkers (1991) describe several herpes simplex encephalitis cases in which temporal-lobe damage is accompanied by severe memory impairments. They describe one such patient, Boswell, in considerable detail. Boswell resembles many temporal-lobe-injury patients in having extensive anterograde amnesia while demonstrating typical intelligence and language abilities and performing at normal on implicit-memory tests.

Boswell is different, however, in that his retrograde amnesia is far more severe than that displayed by most temporal-lobe-injury patients: he is entirely unable to retrieve information from any part of his life history. The damage to the medial temporal cortex probably accounts for his anterograde amnesia, whereas additional damage in the lateral temporal cortex, the insula (diagrammed in Figure 18.5), and the ventromedial prefrontal cortex probably contributes to his retrograde amnesia.

Damasio suggests that in Boswell and other herpes simplex encephalitis patients, the insula may be especially implicated in retrograde amnesia. On the basis of study results using PET imaging, Michael and Marcus Raichle (1994) report that the insula is active when participants perform a well-practiced verbal task but inactive when they perform a novel verbal task. This finding seems consistent with Damasio's suggestion that the insula accesses previously acquired memories.

▼ Horizontal brain sections of two patients with selective retrograde amnesia for autobiographic information. (Left) An amnesic patient who contracted herpes simplex encephalitis. The right frontal and temporal lobes are dark, corresponding to a metabolic reduction in the right temporal frontal region (arrow). (Right) A patient with psychogenic amnesia. Again, a significant metabolic reduction is visible in the right temporal frontal area (arrow). (Markowitsch, H. J. Functional Neuroimaging Correlates of Functional Amnesia. *Memory*, Vol. 7, Issue 5-6, Plate 2. (1999): pp. 561–584.Reprinted by permission of Psychology Press Ltd., Hove.)

Alzheimer's Disease

Alzheimer's disease exhibits both a progressive loss of cells and the development of cortical abnormalities. It is characterized at first by anterograde amnesia and later by retrograde amnesia as well. Among the first areas of the brain to show histological change is the medial temporal cortex, but as the disease progresses, other cortical areas are affected.

Here, too, the pattern of brain change and the pattern of memory deficit suggest that damage to the medial temporal cortex is related to anterograde amnesia and that damage to other temporal association and frontal cortical areas is related to retrograde amnesia. Alzheimer's-related amnesia is displayed mainly on tests of explicit memory, but eventually, implicit memory also may suffer.

Korsakoff's Syndrome

Long-term alcoholism, especially when accompanied by malnutrition, has long been known to degrade memory. In the late 1800s, Russian physician Sergei Korsakoff called attention to a syndrome that he found to accompany chronic alcoholism, the most obvious symptom being a severe loss of memory. He wrote:

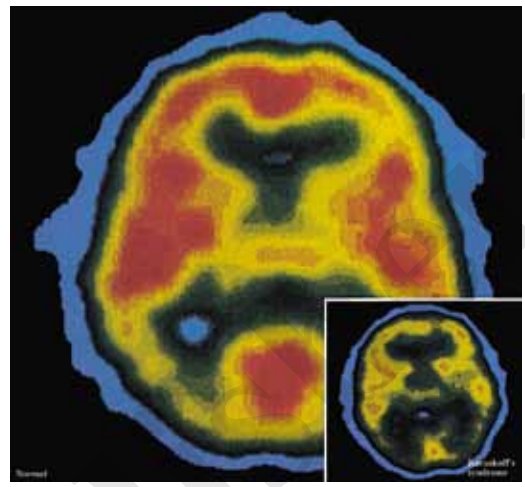
> The disorder of memory manifests itself in an extraordinarily peculiar amnesia, in which the memory of recent events, those that just happened, is chiefly disturbed, whereas the remote past is remembered fairly well. This reveals itself primarily in that the patient constantly asks the same questions and repeats the same stories. At first, during conversation with such a patient, it is difficult to note the presence of psychic disorder; the patient gives the impression of a person in complete possession of his faculties; he reasons about everything perfectly well, draws correct deductions from given premises, makes witty remarks, plays chess or a game of cards, in a word, comports himself as a mentally sound person. Only after a long conversation with the patient, one may note that at times he utterly confuses events and that he remembers absolutely nothing of what goes on around him: he does not remember whether he had his dinner, whether he was out of bed. On occasion the patient forgets what happened to him just an instant ago: you came in, conversed with him, and stepped out for one minute; then you come in again and the patient has absolutely no recollection that you had already been with him. . . . With all this, the remarkable fact is that, forgetting all events, which have just occurred, the patients usually remember quite accurately the past events, which occurred long before the illness. (Oscar-Berman, 1980, p. 410)

Korsakoff's syndrome has been studied intensively since a seminal article, published in 1971 by Helen Sanders and Elizabeth Warrington, because Korsakoff patients are far more readily available than are persons with other forms of global amnesia. Six major symptoms constitute the syndrome: (1) anterograde amnesia; (2) retrograde amnesia; (3) **confabulation**, in which patients glibly produce plausible stories about past events rather than admit memory loss (the stories are plausible because they tend to be based on past experiences; a man once told us, for example, that he had been at the Legion with his pals, which, though untrue, had been his practice in the past); (4) meager content

in conversation; (5) lack of insight; and (6) apathy (patients lose interest in things quickly and generally appear indifferent to change).

The symptoms of Korsakoff's syndrome may appear suddenly, within the space of a few days. The cause is a thiamine (vitamin B_1) deficiency resulting from prolonged intake of large quantities of alcohol. The syndrome, which is usually progressive, can be arrested by massive doses of vitamin B_1 but cannot be reversed. Prognosis is poor, with only about 20 percent of patients showing much recovery in a year on a B_1-enriched diet. Many patients demonstrate no recovery even after 10 to 20 years.

The vitamin deficiency kills cells in the medial part of the diencephalon—the "between brain" at the top of the brainstem—including the medial thalamus and the mammillary bodies of the hypothalamus. The frontal lobes of 80 percent of patients show atrophy.



▲ PET scans from a healthy patient (larger image) and a Korsakoff patient (inset) reveal reduced activity in the frontal lobes of the diseased brain. (The frontal lobes lie at the bottom center of each scan.) Red and yellow represent areas of higher metabolic activity; activity is lower in the darker areas. (Dr. Peter R. Martin, from *Alcohol Health & Research World*, Spring 1985, 9, cover.)

Neurotransmitter Activating Systems and Memory

At least three neurotransmitter systems—cholinergic, serotonergic, noradrenergic, mapped in Figure 5.18—ascending from the brainstem to the forebrain are implicated in memory. Other ascending transmitter systems, including the histamine and orexin systems, are less studied but may also contribute to memory.

Loss of cholinergic cells is related to, and may even be responsible for, the amnesia displayed by patients with Alzheimer's disease. Curiously, in animal experiments, selective lesions of an ascending system have not produced amnesia, but conjoint damage to at least two systems has produced memory impairments. Cholinergic cells project from the basal forebrain to the frontal lobes and the temporal lobes and help maintain a waking EEG pattern. Selective damage to these cells is not associated with memory impairment. Serotonergic cells in the midbrain that project to the limbic system and cortex also are active in maintaining a waking EEG. If this cell group only is removed in animals, no serious memory difficulty results.

Profound amnesia can be produced, however, if the serotonergic cells and the cholinergic cells are damaged together. Cornelius Vanderwolf (1988) demonstrated that animals receiving such treatment behave as if the entire neocortex has been removed in that they no longer display any intelligent behavior. Additionally, cortical EEG recordings from such animals show a pattern typical of sleep, even though the animals can be behaviorally active.

Another example of the ascending systems' conjoint activity occurs between the cholinergic and the noradrenergic systems. Pharmacological blocking of either system has little effect on learning, but if both systems are blocked together, experimental rats are extremely impaired on learning tasks (Decker et al., 1990). Because many diseases of aging are associated with the loss of neurons from the ascending projections of the cholinergic, serotonergic, or noradrenergic systems, cell loss in more than one of these systems could be a cause of amnesia even when cortical or limbic structures are intact.

18.7 Special Memory Abilities

We began our discussion by noting that a primary purpose of explicit memory is to allow us to make good decisions and that our memories thus need not be perfectly detailed. The gist is sufficient. Some people—among them musicians, dancers, and athletes—may display exceptional implicit memory, but in practice every experience leaves an implicit memory trace in everyone. Those who do possess extraordinarily detailed memory display exemplary episodic, or autobiographical, recall.

Some people with **Asperger's syndrome**, a form of autism spectrum disorder in which intellectual function is high, can display excellent memory abilities. Others' special memory abilities are restricted, for example, to superior autobiographical memory. Here we describe, first, a case of special semantic memory ability described by Luria and second, people who display almost complete autobiographical memory.

Savant Syndrome

S. was a newspaper reporter with an extraordinary ability to form explicit memories that he could not forget. The fact that, unlike other reporters, he never took notes at briefings brought him to his employer's attention. When questioned on the matter, S. responded by repeating verbatim the transcript of the briefing they had just attended.

At his employer's urging, S. went to see a psychologist and met Alexander Luria, who began studying S.'s remarkable memory ability, a case study that endured for the following 30 years. Luria (1968) published an account of his investigation, and to this day *The Mind of a Mnemonist* is one of the most readable case studies in the literature of memory.

To sample these abilities, consider **Table 18.1**. S. could look at a table like this for 2 or 3 minutes and then repeat it from memory: by columns, by rows, by diagonals, in reverse, or in sums. Tested unexpectedly 16 or more years later, S. could still reproduce the table, reciting the columns in any order or combination, without error.

Table 18.1 Type of table S. memorized

6	6	8	0
5	9	3	2
1	6	8	4
7	9	3	5
4	2	3	7
3	8	9	1
1	0	0	2
3	4	2	1
2	7	6	8
1	9	2	6
2	4	6	7
5	5	2	0
x	0	1	x

Note: With only 2 to 3 minutes of study of such a table, S. was able to reproduce it in reverse order, horizontally, or vertically, and to reproduce the diagonals.

For a good part of his life, S. supported himself as an mnemonist—an entertainer who specializes in feats of memory. In the course of his career, he memorized hundreds of such lists or lists of names, letters, nonsense syllables, and so on; after memorizing any of them, he was able to recall it at any later date.

S.'s ability to commit information to memory hinged on three processes. First, he visualized stimuli mentally, recalling them simply by reading from this internal image. Second, he experienced **synesthesia**, or *sensory mixing*, which usually entails perceiving a stimulus of one sense as the sensation of a different sense, as when sound produces a sensation of color (see Section 8.3). But for S., a word invoked multisensory impressions of sound, splashes of color, odor, taste, texture, and even temperature! Finally, S. employed the pegboard technique many mnemonists use: he kept a collection of standard images in his mind and associated them with new material he wanted to remember. This trick and others employed by mnemonists offer insight into how explicit memories are usually formed and how such understanding can

improve memory in typical people as well as in people with memory impairments. Here are some examples from S.:

> Even numbers remind me of images. Take the number 1. This is a proud, well-built man; 2 is a high-spirited woman; 3 a gloomy person (shy, I don't know); 6 a man with a swollen foot; 7 a man with a mustache; 8 a very stout woman—a sack within a sack. As for the number 87, what I see is a fat woman and a man twirling his mustache. (Luria, 1968)

Did S. pay a price for his memory abilities? Luria's position clearly is that he did. He characterizes S. as a person with little aim in life, seemingly dull and superficial, and suggests that S. was unable to reason, to categorize, and to see order in things as ordinary people can. He also had little ability to use or understand metaphors (for example, the phrase "to weigh one's words"); he visualized and interpreted them literally and so was puzzled by what they meant. S. often had difficulty understanding simple statements and had even more difficulty understanding the sense of poetry.

Superior Autobiographical Memory

A research group headed by James McGaugh has collected several cases of individuals who display *highly superior autobiographical memory*, or *HSAM* (LePort et al., 2012). They display virtually complete recall for events in their lives, usually beginning around age 10, and can often describe any episode, including the day of the week that it occurred and the date. Their recall can include the weather and social and public events.

They use no memory strategy as aids and are, as a group, otherwise quite ordinary; that is, their performance on formal memory tests is not unusual. Brain imaging of those who display HSAM reveals increased gray matter in the temporal and parietal lobes and increased size of fiber projections between the temporal lobe and the frontal cortex. These brain regions, when damaged, have been associated with impairments in autobiographical memory.

Unlike S., people with HSAM generally cope well with life, although some display obsessive-compulsive behaviors. Some also report that they ruminate on past memories and experience enjoyable memories again and again. One individual with HSAM, known to us, elaborates his conversation by recounting details, including the date, the weather, and coincident activities of family members. This takes some patience on the part of the listener.

SUMMARY

Our multiple memory systems operate independently of one another (review Figure 18.1).

18.1 Learning, Memory, and Amnesia

Research results find differences in the processes of acquiring and storing memory. For example, anterograde amnesia, the inability to form new memories, is often more severe than retrograde amnesia, the inability to retrieve old memories.

The medial temporal and inferior frontal lobes and the circuits within and between them mediate long-term learning and explicit memory, including episodic memory, related to personal experiences, and semantic memory, related to facts. Explicit memories are often lost after medial temporal damage, while long-term implicit memory, such as motor skills, and the ability to form new memories are usually spared. Opposing theories of amnesia argue for memory-system consolidation, multiple-trace memory, or reconsolidated memory.

18.2 Long-Term Explicit Memory

A neural system consisting of the prefrontal cortex, medial temporal lobe, and subcortical temporal-lobe structures, including the hippocampus, rhinal cortex, and connections with the ventral prefrontal cortex, is the likely location of conscious explicit memory. Episodic memory is especially dependent on the hippocampus and ventral prefrontal cortex, where damage can be associated with the loss of all retrograde autobiographic memory and an inability to imagine a personal role in future events.

18.3 Long-Term Implicit Memory

Motor memory, priming, and conditioning constitute implicit memory, a nonconscious neural system consisting of pathways connecting the basal ganglia, motor cortex, and cerebellum. Deficits in learned motor skills and habits are associated with damage to the basal ganglia; and the loss of conditioned responses, with damage to the cerebellum.

18.4 Long-Term Emotional Memory

Neural systems centered in the amygdala of the limbic system, subcortical to the temporal lobes, encode our emotional recollections of affective experiences. These recollections share aspects of explicit and implicit memory.

18.5 Short-Term Memory

Sensory regions of the neocortex mediate short-term (working, temporal, or recency) memory for items held in mind for seconds to minutes. The dorsal stream traversing the parietal and frontal cortex participates in short-term memory for locations, whereas the ventral stream from the sensory regions forward into the inferior temporal–dorsolateral prefrontal cortex mediates short-term memory for objects.

18.6 Neurological Diseases and Long-Term Memory

Memory impairments can result from diffuse brain damage and from brain disease, as occurs in transient global amnesia, herpes simplex encephalitis infections, Alzheimer's disease, and Korsakoff's syndrome. Neurotransmitter activating systems also contribute to neurological diseases that affect memory.

18.7 Special Memory Abilities

People can display extraordinary semantic or autobiographical memory. The very neural circuits that produce memory deficits when damaged may be enhanced in those who possess savant syndrome or superior autobiographic memory. Thus, special abilities may coexist alongside islands of intellectual weakness.

References

Akers, K. G., A. Martinez-Canabal, L. Restivo, A. P. Yiu, A. De Cristofaro, H. L. Hsiang, A. L. Wheeler, A. Guskjolen, Y. Niibori, H. Shoji, K. Ohira, B. A. Richards, T. Miyakawa, S. A. Josselyn, and P. W. Frankland. Hippocampal neurogenesis regulates forgetting during adulthood and infancy. *Science* 618:598–602, 2014.

Allen, R. J., F. Vargha-Khadem, and A. D. Baddeley. Item-location binding in working memory: Is it hippocampus-dependent? *Neuropsychologia* 59:74–84, 2014.

Anderson, E. D., F. B. Horak, M. R. Lasarev, and J. G. Nutt. Performance of a motor task learned on levodopa deteriorates when subsequently practiced off. *Movement Disorders* 29:54–60, 2014.

Annese, J., N. M. Schenker-Ahmed, H. Bartsch, P. Maechler, C. Sheh, N. Thomas, J. Kayano, A. Ghatan, N. Bresler, M. P. Frosch, R. Klaming, and S. Corkin. Postmortem examination of patient H.M.'s brain based on histological sectioning and digital 3D reconstruction. *Nature Communications* 5:3122, 2014.

Bartlett, F. C. *Remembering*. Cambridge, U.K.: Cambridge University Press, 1932.

Bekhterev, V. M. Demonstration eines Gehirns mit Zerstörung der vorderen und inneren Theile der Hirnrinde beider Schlafenlappen. *Neurologisches Zentralb* 19:990–991, 1900.

Broadbent, D. E. *Perception and Communication*. London: Pergamon, 1958.

Cabeza, R., and L. Nyberg. Imaging Cognition II: An empirical review of 275 PET and fMRI studies. *Journal of Cognitive Neuroscience* 12:1–47, 2000.

Cabeza, R., and M. Moscovitch. Memory systems, processing modes, and components: Functional neuroimaging evidence. *Perspectives on Psychological Science* 8:49–55, 2013.

Cipolotti, L., T. Shallice, D. Chan, N. Fox, R. Scahill, G. Harrison, J. Stevens, and P. Rudge. Long-term retrograde amnesia: The crucial role of the hippocampus. *Neuropsychologia* 39:151–172, 2001.

Clarke A., and L. K. Tyler. Object-specific semantic coding in human perirhinal cortex. *Journal of Neuroscience* 34:4766–4775, 2014.

Corkin, S. Acquisition of motor skill after bilateral medial temporal-lobe excision. *Neuropsychologia* 6:255–265, 1968.

Corkin, S., D. G. Amaral, R. G. Gonzalez, K. A. Johnson, and B. T. Hyman. H.M.'s medial temporal lobe lesion: Findings from magnetic resonance imaging. *Journal of Neuroscience* 17:3964–3979, 1997.

Corsi, P. M. *Human Memory and the Medial Temporal Region of the Brain*. Ph.D. dissertation. Montreal: McGill University, 1972.

Damasio, A. R., D. Tranel, and H. Damasio. Amnesia caused by herpes simplex encephalitis, infarctions in basal forebrain, Alzheimer's disease and anoxia/ischemia. In L. Squire and G. Gainotti, Eds., *Handbook of Neuropsychology*, vol 3. Amsterdam: Elsevier, 1991.

Decker, M. W., M. T. Gill, and J. L. McGaugh. Concurrent muscarenic and beta-adrenergic blockade in rats impairs place learning in a water maze and retention of inhibitory avoidance. *Brain Research* 513:81–85, 1990.

Elliott, H. C. *Textbook of Neuroanatomy*. Philadelphia: Lippincott, 1969.

Fisher, C. M., and R. D. Adams. Transient global amnesia. *Transactions of the American Neurological Association* 83:143, 1958.

Fuster, J. M. *The Prefrontal Cortex*. New York: Raven, 1989.

Gaffan, D., and E. Gaffan. Amnesia in man following transection of the fornix: A review. *Brain* 114:2611–2618, 1991.

Goldman-Rakic, P. S. Working memory and the mind. *Scientific American* 267(3):111–117, 1992.

Gollin, E. S. Developmental studies of visual recognition of incomplete objects. *Perceptual and Motor Skills* 11:289–298, 1960.

Grafton, S. T., J. C. Mazziotta, S. Presty, K. J. Friston, S. J. Frackowiak, and M. E. Phelps. Functional anatomy of human procedural learning determined with regional cerebral blood flow and PET. *Journal of Neuroscience* 12:2542–2548, 1992.

James, W. *The Principles of Psychology*. New York: Holt, 1890.

Josselyn S. A., and P. W. Frankland. Infantile amnesia: A neurogenic hypothesis. *Learning and Memory* 16:423–433, 2012.

Kolb, B., and B. Milner. Performance of complex arm and facial movements after focal brain lesions. *Neuropsychologia* 19:491–503, 1981.

LeDoux, J. Rethinking the emotional brain. *Neuron* 73:653–676, 2012.

Lee, K. H., and R. F. Thompson. Multiple memory mechanisms in the cerebellum? *Neuron* 51:680–682, 2006.

LePort, A. K., A. T. Mattfeld, H. Dickinson-Anson, J. H. Fallon, C. E. Stark, F. Kruggel, L. Cahill, and J. L. McGaugh. Behavioral and neuroanatomical investigation of Highly Superior Autobiographical Memory (HSAM). *Neurobiology of Learning and Memory* 98:78–92, 2012.

Levine, B. Autonoetic consciousness and self-regulation in patients with brain injury. *International Journal of Psychology* 35:223, 2000.

Levine, B., S. E. Black, R. Cabeza, M. Sinden, A. R. Mcintosh, J. P. Toth, and E. Tulving. Episodic memory and the self in a case of isolated retrograde amnesia. *Brain* 121:1951–1973, 1998.

Luria, A. R. *The mind of a mnemonist*. New York: Basic Books, 1968.

Markowitsch, H. J. Transient global amnesia. *Neuroscience and Biobehavioral Reviews* 7:35–43, 1983.

Martone, M., N. Butlers, M. Payne, J. T. Baker, and D. S. Sax. Dissociations between skill learning and verbal recognition in amnesia and dementia. *Archives of Neurology* 41:965–970, 1984.

Mazzucchi, A., G. Moretti, P. Caffara, and M. Parma. Neuropsychological functions in the follow-up of transient global amnesia. *Brain* 103:161–178, 1980.

Milner, B. Visually-guided maze learning in man: Effects of bilateral hippocampal, bilateral frontal, and unilateral cerebral lesions. *Neuropsychologia* 3:317–338, 1965.

Milner, B. Memory and the medial temporal regions of the brain. In K. H. Pribram and D. E. Broadbent, Eds., *Biology of Memory*. New York: Academic Press, 1970.

Milner, B., S. Corkin, and H.-L. Teuber. Further analysis of the hippocampal amnesic syndrome: 14-year follow up study of H.M. *Neuropsychologia* 6:215–234, 1968.

Moscovitch, M. Multiple dissociations of function in amnesia. In L. S. Cermak, Ed., *Human Memory and Amnesia*. Hillsdale, N.J.: Lawrence Erlbaum, 1982.

Murray, E. Memory for objects in nonhuman primates. In M. S. Gazzaniga, Ed., *The New Cognitive Neurosciences*, 2nd ed., pp. 753–763. London: MIT Press, 2000.

Nadel, L., and M. Moscovitch. Memory consolidation, retrograde amnesia and the hippocampal complex. *Current Opinion in Neurobiology* 7:212–227, 1997.

Oscar-Berman, M. Neuropsychological consequences of long-term chronic alcoholism. *American Scientist* 68:410–419, 1980.

Pascual-Leone, A., J. Grafman, and M. Hallett. Modulation of cortical motor output maps during development of implicit and explicit knowledge. *Science* 263:1287–1289, 1994.

Petri, H. L., and M. Mishkin. Behaviorism, cognitivism, and the neuropsychology of memory. *American Scientist* 82:30–37, 1994.

Petrides, M., B. Alivisatos, A. C. Evans, and E. Meyer. Dissociation of human mid-dorsolateral from posterior dorsolateral frontal cortex in memory processing. *Proceedings of the National Academy of Sciences U.S.A.* 90:873–877, 1993.

Poppenk, J., H. R. Evensmoen, M. Moscovitch, and L. Nadel. Long-axis specialization of the human hippocampus. *Trends in Cognitive Science* 17:230–240, 2013.

Posner, M. I., and M. E. Raichle. *Images of Mind*. New York: Scientific American Library, 1994.

Prisko, L. *Short-Term Memory in Focal Cerebral Damage*. Ph.D. dissertation. Montreal: McGill University, 1963.

Reber, P. J. The neural basis of implicit learning and memory: A review of neuropsychological and neuroimaging research. *Neuropsychologia* 51:2026–2042, 2013.

Sainsbury, R., and M. Coristine. Affective discrimination in moderately to severely demented patients. *Canadian Journal on Aging* 5:99–104, 1986.

Sanders, H. I., and E. K. Warrington. Memory for remote events in amnesic patients. *Brain* 94:661–668, 1971.

Schacter, D. L., and D. L. Addis. The cognitive neuroscience of constructive memory: Remembering the past and imagining the future. *Philosophical Transactions of the Royal Society of London B* 362:773–786, 2007.

Schwabe, L., K. Nader, and J. C. Pruessner. Reconsolidation of human memory: Brain mechanisms and clinical relevance. *Biological Psychiatry* 76:274–280, 2014.

Scoville, W. B., and B. Milner. Loss of recent memory after bilateral hippocampal lesions. *Journal of Neurology, Neurosurgery & Psychiatry* 20:11–21, 1957.

Siri, S., E. A. Kensinger, S. F. Cappa, and S. Corkin. Questioning the living/nonliving dichotomy: Evidence from a

patient with an unusual semantic dissociation. *Neuropsychology* 17:630–645, 2003.

Smith, C. N., J. C. Frascino, R. O. Hopkins, and L. R. Squire. The nature of anterograde and retrograde memory impairment after damage to the medial temporal lobe. *Neuropsychologia* 51:2709–2714, 2013.

Squire, L. R., and P. J. Bayley. The neuroscience of remote memory. *Current Opinion in Neurobiology* 17:185–196, 2007.

Tronson, N. C., and J. R. Taylor. Molecular mechanisms of memory reconsolidation. *Nature Reviews Neuroscience* 8:262–275, 2007.

Tulving, E. Episodic memory: From mind to brain. *Annual Review of Psychology* 53:1–25, 2002.

Tulving, E., S. Kapur, F. I. M. Craik, M. Moscovitch, and S. Houle. Hemispheric encoding/retrieval asymmetry in episodic memory: Positron emission tomography finding. *Proceedings of the National Academy of Sciences U.S.A.* 91:2016–2020, 1994.

Vanderwolf, C. H. Cerebral activity and behavior: Control by central cholinergic and serotonergic systems. *International Review of Neurobiology* 30:255–340, 1988.

Vargha-Khadem, F., D. G. Gadian, K. A. Watkins, W. Connelly, W. Van Paesschen, and M. Mishkin. Differential effects of early hippocampal pathology on episodic and semantic memory. *Science* 277:376–380, 1997.

Wang, Q., and C. Peterson. Your earliest memory may be earlier than you think: Prospective studies of children's dating of earliest childhood memories. *Developmental Psychology* 50, 1680–1686, 2014.

Warrington, E. K., and L. Weiskrantz. Further analysis of the prior learning effect in amnesic patients. *Neuropsychologia* 16:169–177, 1978.

Whitty, C. W. M., and O. L. Zangwill. Traumatic amnesia. In C. W. M. Whitty and O. L. Zangwill, Eds., *Amnesia*. London: Butterworth, 1966.

Wilson, F. A. W., S. P. O. Scalaidhe, and P. S. Goldman-Rakic. Dissociation of object and spatial processing domains in primate prefrontal cortex. *Science* 260:1955–1958, 1993.