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Richard F. Thompson & Stephen A. Madigan:Memory

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What Is Memory?

Memory is the most extraordinary phenomenon in the natural world. Our brains are modified and reorganized by our experiences. Our interactions with the physical world—our sensory experiences, our perceptions, our actions—change us continuously and determine what we are later able to perceive, remember, understand, and become.

Every person has perhaps billions of bytes of information stored in long-term memory. This “memory store” is the vast store of information you possess as a result of learning and are not aware of unless you call it up. It includes all vocabulary and knowledge of language, all the facts that have been learned, the personal experiences of a lifetime, and much more—all the skills learned, from walking and talking to musical and athletic performance, many of the emotions felt and in fact ongoing experience, and the continuous sensations, feelings, and understandings of the world we term *consciousness*. Indeed, without memory there can be no mind.

Most animal species display some behaviors, such as reflexes and instincts, that do not greatly depend on learning from experience. They are instead part of a species' evolved biological makeup and appear in individuals as a result of genetics and fetal development. You might think of this as being like your computer's read-only memory that has built-in instructions and data. In some species this kind of "hard-wired" behavior seems to constitute most of the species' repertoire of behaviors. But many other species have another kind of memory that has functions similar to the random access memory of your computer—a kind of memory that allows the recording, maintenance, and utilization of new information. The evolution of this kind of memory and capacity for learning was a major step in the development of complex forms of life. Why this capacity evolved isn't hard to understand: An animal with a such a memory system can process information that is no longer directly available in the environment, as, for example, when a squirrel is able to remember in the winter where it stored nuts the previous fall.

Memory: Four Portraits

This book examines some of the basics of current scientific understanding of memory, starting with descriptions of the memories of four individuals to illustrate some of the remarkable properties of the human memory system.

A Life Without Memory

The most famous case history of a memory disorder is that of HM (initials are used to protect the patient's privacy). HM was a young man with severe epilepsy that could not be controlled with drugs. As a result of neurosurgery to treat the epilepsy, HM lost the ability to form new long-term memories, a condition called anterograde amnesia. His memory is only moment to moment. He can no longer remember his own experiences for more than a few minutes. As he once expressed it:

Right now, I'm wondering, have I done or said anything amiss? You see, at this moment everything looks clear to me, but what happened just before? That's what worries me. It's like waking from a dream. I just don't remember.

If you were introduced to HM and talked with him for a while, you would get the impression of a normal man with an above-average IQ. If you left and then returned a few minutes later, he would have no memory of having met and talked with you earlier. His immediate "working memory," however, is intact. If you ask him to remember a phone number you've just read to him, he can repeat it to you, but he cannot easily memorize it so as to recall it later. He has learned to use trick associations to remember things, but this works only as long as he can keep repeating the association to himself. Distract him and the memory is completely gone. Readers may recall the popular film *Memento*, whose hero suffered from the same disorder as HM.

Although HM cannot store his own experiences in long-term memory, he can learn and store motor skills relatively normally. Suppose you were his tennis instructor. As you teach him various skills over a series of lessons he improves as well as anyone else would. But each time he is brought to the lesson he has to be introduced to you again and you have to remind him that he is learning tennis.

HM provides a dramatic illustration of the distinction between short-term and long-term memories and the fact that they involve different brain systems, as do motor skill memories. His long-term memories of things learned and experienced before his surgery, incidentally, are relatively intact. (We will have much more to say later about HM and other examples of amnesia.)

A Mnemonist

Rajan Mahadevan was the son of a prominent surgeon in Mangalore, India. Rajan liked to astound his school friends by reciting the complete railway timetable for the Calcutta railway system. Later he contacted Guinness World Records Limited in

London for suggestions on how to establish a memory record. He was told to focus on π , the Greek letter pronounced "pie." π is the number 3.14. . . (the ratio of the diameter and circumference of a circle), and it is an endless and apparently irregular sequence of digits with no patterns or predictability (3.14159265. . .). Rajan set to work. On July 14, 1981, he stood before a packed meeting hall in Mangalore and started reciting π from memory. He recited numbers for 3 hours and 49 minutes, reaching 31,811 digits of π without a single error, winning him a place in the Guinness book. He later became a graduate student in psychology at Kansas State University, where he studied and was studied. His extraordinary memory was for numbers, not words, and he used strategies to help him remember (more about this later). Later, in 1987, a Japanese "memorist," Hideaki Tomoyoni, recited the first 40,000 digits of π and replaced Rajan in the Guinness book.

Life with Too Much Memory

The most famous case history of a person with what is often referred to as "photographic" memory was recorded by the distinguished Russian psychologist Alexander Luria, who named his subject "S."

I gave S. a series of words, then numbers, then letters, reading to him slowly or presenting them in written form. He read or listened attentively and then repeated the material exactly as it had been presented. I increased the number of elements in each series, giving him as many as thirty, fifty or even seventy words or numbers, but this, too, presented no problem for him. He did not need to commit any of the material to memory; if I gave him a series of words or numbers, which I read slowly and distinctly, he would listen attentively, sometimes ask me to stop and enunciate a word more clearly, or, if in doubt whether he heard a word correctly, would ask me to repeat it. Usually during an experiment he would close his eyes or stare into space, fixing his gaze on one point; when the experiment was over, he would ask that we pause while he went over the material in his mind to see if he had retained it. Thereupon, without another moment's pause, he would reproduce the material that had been read to him.

It was of no consequence to him whether the series I gave him contained meaningful words or nonsense syllables, numbers or sounds; whether they were presented orally or in writing. All he required was that there be a 3–4 second pause between each element in the series, and he had no trouble reproducing whatever I gave him.

As the experimenter, I soon found myself in a state verging on utter confusion. An increase in the length of a series led to no noticeable increase in difficulty for S., and I simply had to admit that the capacity of his memory *had no distinct limits*; that I had been unable to perform what one would think was the simplest task a psychologist can do: measure the capacity of an individual's memory. I arranged a second and third session with S.; these were followed by a series of sessions, some of them days and weeks apart, others separated by a period of several years.

But these later sessions only further complicated my position as experimenter, for it appeared that there was no limit either to the *capacity* of S.'s memory or to the *durability of the traces he retained*. Experiments indicated that he had no difficulty reproducing any lengthy series of words whatever, even though these had originally been presented to him a week, a month, a year or even many years earlier.

Such feats of memory seem to be beyond most of us. Indeed such individuals are extremely rare; only a handful have been identified in the past 100 years or so. At the same time, actors routinely memorize entire plays, musicians memorize long musical scores, and adherents of some religions commit vast amounts of sacred text to memory. With appropriate strategies and training, we can all do much better at memorizing, as we will see later.

Musical memory can be quite extraordinary, and very little is known about it. A classic example concerns the eminent conductor Arturo Toscanini. At one point he wished to conduct his NBC orchestra in a rather obscure piece, the slow movement of Joachim Raff's Quartet no. 5. The libraries and music stores in New York were searched for the score, but none could be found. Toscanini, who had not seen the music for decades, wrote down all the orchestral parts for the entire movement. Much later, a copy of the score was discovered and compared to Toscanini's manuscript.

He had made exactly one error! But is Toscanini like the rest of us?

False Memories

The preceding case histories and our own common experiences have led many of us to assume that memory is much like a tape recorder or video recorder, holding a perfectly accurate record of what has been experienced. Nothing could be further from the truth. Memory is extraordinary, but it is far from perfect. A classic case in point is John Dean's testimony to a congressional committee about his conversations with President Richard Nixon and others concerning the Watergate cover-up. The first meeting he held with the president was on September 15, 1972. Dean described this and other meetings in astonishing detail in written testimony prepared later for a congressional committee. There was no way to check the accuracy of Dean's memory at the time. But in 1974 the president released transcripts of the tape recordings he had made of these meetings.

Ulrich Neisser, a leading authority on human memory, compared Dean's testimony of the September 15 meeting with the tape transcript of the meeting:

Comparison with the transcript shows that hardly a word of Dean's account is true. Nixon did not say *any* of the things attributed to him here: He didn't ask Dean to sit down, he didn't say Halderman had kept him posted, he didn't say Dean had done a good job (at least not in that part of the conversation), he didn't say anything about Liddy or the indictments. Nor had Dean himself said the things he later describes himself as saying: that he couldn't take credit, that the matter might unravel some day, etc. (Indeed, he said just the opposite later on: "Nothing is going to come crashing down.") His account is plausible, but entirely incorrect. In this early part of the conversation Nixon did not offer him any praise at all, unless "You had quite a day, didn't you?" was intended as a compliment. (It is hard to tell from a written transcript.) Dean cannot be said to have reported the "gist" of the opening remarks; no count of idea units or comparison of structure would produce a score much above zero.

But despite all the inaccuracies, the basic message of Dean's testimony, that President Nixon knew about the break-in and the cover-up, was true. So his memories did at least reflect reality.

A more serious issue is whether people can be made to remember things that did not really happen. Can false memories actually be implanted? Elizabeth Loftus, a leader in the study of human memory and its foibles, has explored this issue in depth, as we will see later. Here we give one rather charming example that occurred recently. This involved Alan Alda, who is known best as Hawkeye Pierce from the TV show *M*A*S*H*. What people may not know is that Alda is a lifelong science buff and host of *Scientific American Frontiers*, a television program dedicated to communicating scientific theories to the public.

Alan Alda visited Loftus at the University of California, Irvine, to work on a show about memory. A week before Alda arrived, Loftus sent him some questionnaires, ostensibly designed to learn about his personality, in particular food preferences. When Alda met Loftus, she explained to him that she and her colleagues had analyzed the data he sent back and discovered that Alda had once gotten very sick after eating too many hard-boiled eggs as a child. (So far as Loftus knew, this had actually never happened.) Later, Loftus and her researchers had a picnic lunch with Alda. There was a smorgasbord of delicious food, most importantly some hard-boiled and deviled eggs. When offered some of these eggs, Alda refused to eat them. Was this because Loftus had induced in him a false memory about his childhood and eggs? In any event, Alda's avoidance of eggs on that occasion was filmed and is a part of the *Scientific American Frontiers* program on memory.

The Many Varieties of Memory

One of the major achievements of modern memory research is the discovery that there are several different kinds of memory systems with different properties and different brain mechanisms. A convenient classification of these forms of memory is shown in

Figure 1-1. The rest of this chapter describes the main features and properties of these different memory systems and uses them to introduce the major phenomena of memory that this book will discuss.

Explicit Declarative Memory: Episodic and Semantic

Larry Squire, of the University of California, San Diego, has argued eloquently for the basic distinction between declarative and nondeclarative forms of memory (Figure 1-1). Declarative or explicit memory is what most people mean by memory. The words “explicit” and “declarative” here signify the ability of individuals to consciously and deliberately access and describe the contents of their memory. Even here there are two different aspects to explicit memory. The first is autobiographical or *episodic* memory, the memories of your own experiences. The second is *semantic* memory, the sum total of knowledge you have—your vocabulary, understanding of mathematics, and all the facts you know. The distinction between these two is easy enough to see in Table 1-1.

Endel Tulving, of the University of Toronto, has made the difference between semantic memory and episodic memory into something more than a matter of definition. His conception of episodic memory puts it at the center of the highest human mental capacities: It is the ability to consciously and deliberately perform “mental time travel.” This ability can be seen in any example of ordinary, everyday recollection. One day we asked a colleague to write a narrative description of everything he could remember about his trip from home to campus that morning. What he produced appears in Box 1-1. In one sense this act of recollection is not extraordinary because any mentally normal person is capable of it. In another sense it is extraordinary: A very large amount of information was stored and maintained in memory, without any intent on the part of the subject to memorize or retain it. Note also that what he remembered did not consist of striking, unusual, emotional, or important events. Most of it really has to be called mundane. Yet there it is in memory. Try

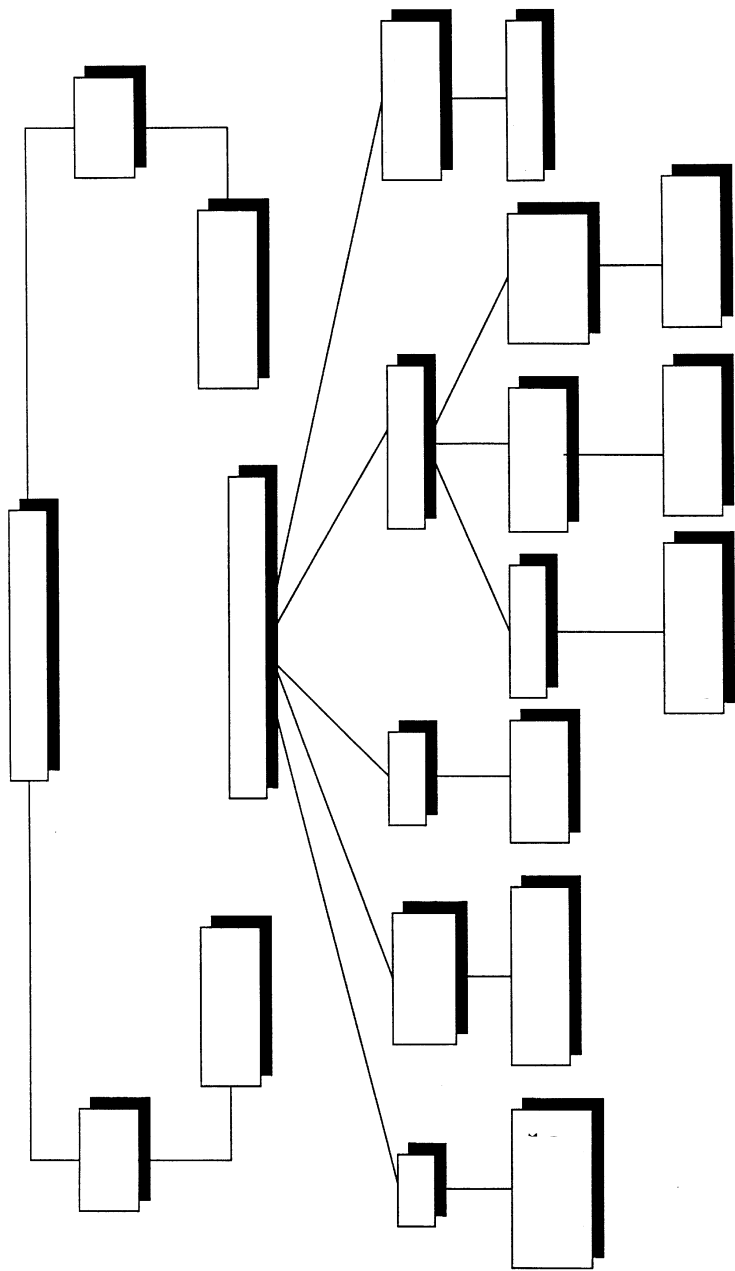


FIGURE 1-1 A schematic of the different types or forms of memory and the brain structures involved.

TABLE 1-1 Two Kinds of Declarative Memory

Semantic Memory	Episodic Memory
Where is the Eiffel Tower?	What did you have for breakfast?
What does “adumbrate” mean?	What was the last movie you saw?
Name the Seven Dwarfs	How much did you pay for that CD?

this kind of recollection yourself and you will find that you also have the strong subjective sense that what you are recalling is accurate. Try this kind of recollection for *yesterday* morning’s events, and you will quickly discover another characteristic of the ordinary workings of episodic memory: swift forgetting!

Do you think our memories of our own experiences are really different from our memories of facts? Some authorities think that the only real difference is how well things have been learned. Each of us can remember dramatic experiences in our own lives and when they occurred. Memories of our own experiences are often learned in one “trial,” although we may rehearse memories important to us. On the other hand, memories for specific items like words in a foreign language may take many trials to learn. When was the first time you learned the meaning of the word “tomato”? You have heard “tomato” so many times you can’t possibly remember when you first heard it. Actually you were probably so young when you learned the word that it is buried in “infantile amnesia.” People can’t remember anything that happened to them before about age 3 or 4. Chapter 3 treats the developmental aspects of memory.

We are consciously aware of both these aspects of explicit memory. The hippocampus and surrounding cerebral cortex of the medial temporal lobe (see Figure 1-2) are the brain structures critical for declarative memory. On the other hand, there is some evidence that the brain systems in the cerebral cortex that store autobiographical or episodic memory and fact or semantic memories may differ.

There is another important kind of explicit memory not mentioned in Figure 1-1: short-term memory. Short-term memory

BOX 1-1 Ordinary Recollection and Episodic Memory

I backed the car out and turned around to get on the street, but I had to wait as three cars passed by. I was talking to Nancy about how she was going to get home as I had the car for Monday. This caused me to miss the turn on to Olympic and continue on to Overland as we normally do; this morning I was supposed to drop Nancy off at a co-worker of hers, so I turned on Pico instead. I was just barely able to make the green light to turn across the traffic and head east on Pico; a red 280ZX turned with me from the opposite direction on to Pico. The traffic was intermediately heavy on Pico; the road surface was rough. Nancy was telling me as we drove by Rancho Park where she jogged the other day that she did not recommend running along Pico because of the traffic. There were a few joggers warming up in the parking lot next to the golf course. As I drove by the 20th Century Fox studios I saw a sign for the movie *The Verdict*, saying it was nominated for five Oscars, but I thought it actually didn't win any last night. Several Honda Accords seemed to hover around me at this point. I was driving in the left-most lane, looking for Cardiff. I had to ask Nancy for the street name and where exactly it was. She said it was just past the bagel shop with a green and yellow sign, in the same block as the synagogue we visited a couple of weeks ago. I thought briefly about the circumcision we witnessed and veered into a sort of turning lane. A car screeched and I realized the cross-traffic had stopped to let a pedestrian cross. I tried to cross over, but I was in third gear so I didn't move. A red and white Cadillac came past me real close to get in its left-turning lane and turned right behind me. I watched it briefly in the mirror. The traffic cleared and we crossed over. Cars were parked on both sides, making it tight. I looked at the left side for a white house where Cheryl lives but had to ask Nancy to make sure; I interrupted her as I did so. I found an opening and stopped to let her out. We agreed she'd come at 5 p.m. by bus; she said she'd leave at 4:30. I said that I would get her to USC (University of Southern California) at 5:15, but she disagreed. We kissed goodbye. I looked in the mirror and saw a new silver BMW and thought it was Erin, who was going to meet with them—it was. He pulled up alongside as I released the trunk with the switch on the floor. He leaned over in his car; I pulled down the window and said, "So you all are going to work this morning." He said something back. The sun roof was open in his car. He backed away as we said goodbye so I could pull out. A car was coming from the other direction as I pulled out. There was a woman in it. (I have written 25 minutes now and can go on, but I have to go to a meeting. This is only about one-fifth of the drive in, however.)

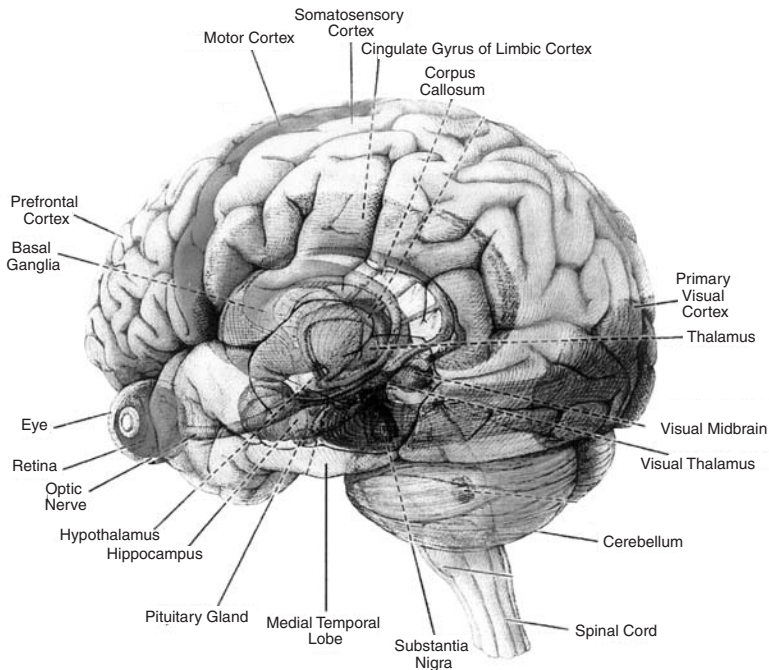


FIGURE 1-2 The human brain with major structures and regions labeled. The entire surface of the brain is covered by a several millimeter thick layer of neurons that forms the cerebral cortex. Key structures for memory include the cerebral cortex, the hippocampus, the basal ganglia and the cerebellum.

generally refers to retention and retrieval of very recently presented information, such as a new telephone number you just looked up. It may last no more than a few seconds. Research on short-term memory has led to the idea of “working memory,” which includes retaining new information but also involves transformation and use of that information, retrieval of knowledge from long-term memory to integrate with the new information, and awareness of your surroundings. The concept of working memory is closely related to what is commonly referred to as consciousness or awareness. As you will see in Chapter 2, working memory also seems to be closely related to general intelligence.

Implicit-Procedural Memory

As Figure 1-1 indicates, there is a major distinction between explicit episodic memory and another form of memory called implicit procedural. To a first approximation, explicit episodic memory deals with *knowing that*; implicit-procedural memory deals with *knowing how*. We've already seen an example of the implicit-procedural memory system in the form of patient HM's ability to learn new motor skills. One of the main reasons that memory theorists originally postulated the existence of these two different systems was the fact that certain kinds of brain damage seemed to impair explicit-declarative memory but not implicit-procedural memory. In general, implicit memory does not necessarily involve being aware of the memory.

Can people learn while they are under general anesthesia for surgery? Seem unlikely? There is actually some evidence for this extreme example of implicit memory! In one study patients were played a tape of the story of Robinson Crusoe during cardiac surgery. When they had recovered from the anesthesia, they were asked if they remembered anything that happened during surgery and they all stated that they remembered nothing. They were then asked to free associate to the word "Friday," and five of the 10 responded with "Robinson Crusoe." A group of 15 control patients were not played the tape, and when asked to free associate to "Friday," none of them responded with "Robinson Crusoe"!

Much of this little book on memory is about declarative memory. The other major category—implicit memory—is something of a grab bag. It is defined more or less as memory without awareness and involves several different kinds of memories. But even if we are not aware of these types of memories they are still very important, as they are involved in learning to walk and talk. These aspects of implicit memory will be treated briefly here and expanded on in later chapters. The various brain systems involved are indicated in the drawing of the human brain in Figure 1-2. Don't be concerned if this looks complicated now; the key forms of memory and their brain systems will be made clearer in later chapters.

Habituation

If a drop of water falls on the surface of the sea just over the flower-like disc of a sea anemone, the whole animal contracts vigorously. If, then, a second drop falls within a few minutes of the first, there is less contraction, and finally, on the third or fourth drop, the response disappears altogether. Here in this marine polyp with the primitive nerve net is clearly exhibited one of the most pervasive phenomena of the animal kingdom—decrement of response with repeated stimulation (habituation). Almost every species studied, from amoeba to man, exhibits some form of habituation when the stimulus is frequently repeated or constantly applied. The ubiquity of the phenomenon plus its obvious survival value suggests that this kind of plasticity must be one of the most fundamental properties of animal behavior.

You can verify this the next time you are at the seashore. Touch a sea anemone repeatedly and it will cease to contract. If you encounter a caterpillar, touch it lightly and it will curl up. Touch it repeatedly and it will cease curling up.

There are many examples of habituation in humans. City dwellers become habituated to the many noises of the city environment. A city dweller camping out in the forest will find the silence “deafening.” We are constantly exposed to many different kinds of stimuli, sights, sounds, touches. If we were to respond to each stimulus we wouldn’t have time to do anything else. We constantly habituate to most stimuli, particularly if they have no consequences for us.

Habituation has been widely used to study the learning ability and mental capabilities of human infants. It is easy to record the heart rate of a newborn infant or even a fetus. If a loud sound is presented the infant’s heart rate will increase briefly. If the sound is repeated several times, the heart rate will cease increasing to the sound; it habituates. We can use measures like this to ask the infant what she knows long before she can talk.

The occurrence of habituation has a number of characteristics or properties. For example, the more rapidly a stimulus is presented the more rapid is habituation, weaker stimuli lead to more rapid habituation, and so on. These same properties occur

in all animals that have been studied, from simple creatures like the sea anemone to humans. This led scientists to think that the basic neuronal mechanism of habituation is common to all these creatures, which in turn suggests that the mechanism must be very simple. Indeed, the “memory trace” (the actual neural process underlying habituation) is rather well understood.

Basic Associative Learning

Basic associative learning includes the kind of learning first discovered by Ivan Pavlov, the great Russian physiologist. Pavlov received a Nobel Prize in 1904 for his pioneering research on digestion. He discovered the conditioned response later. Incidentally, Pavlov was a frugal man. He deposited his Nobel Prize money in a bank in St. Petersburg. After the Russian revolution in 1917, he went to withdraw his money, only to be told that the communist government had confiscated it. Pavlov was completely nonpolitical and simply worked at his research. However, his discoveries were so important that the Soviet government supported him amply, building a major institute for him in Leningrad (formerly and now again St. Petersburg).

Pavlovian conditioning has had some bad press over the years, in part because communist theory embraced it to show that everything is learned—hence they could teach everyone to be good communists. Actually, Pavlov believed that there are marked individual differences among people that are not due to learning. He based this belief on his studies of the different temperaments of different individual dogs that he studied.

Pavlov’s earlier work on digestion led him naturally to his work with the conditioned salivary response. A dog was presented with the ringing of a bell followed by the placement of meat powder in its mouth. Initially, the bell produced no effect, but the meat powder of course elicited copious salivation. After a few pairings of bell and meat powder, the bell came to elicit salivation without meat powder. Surprisingly, we still have not identified the critical brain systems for salivary conditioning. In part be-

cause of the difficulties in accurately measuring salivation, particularly in people, other forms of Pavlovian conditioning have been more widely used.

Eye-Blink Conditioning

One of the most widely studied forms of Pavlovian conditioning is very simple: conditioning of the eye-blink response. A tone or light serves as the conditioned stimulus. It is followed in less than a second by a puff of air to the eye, which elicits a blink. After a number of pairings of tone and air puff, the tone alone elicits closure of the eyelid. This conditioned response is very precisely timed so that the eye blink is maximally closed at the exact moment in time when the air puff is delivered. If the interval between tone onset and air puff is a quarter of a second, the lid will be maximally closed at a quarter of a second after the tone onset; if the interval is a half second, the lid will be maximally closed at a half second; and so on. In animal studies the same is true for the learning of any discrete movement (e.g., the limb flexing of a response to an electrical shock to an animal's paw). Most studies of this form of learning in people have used the eye-blink response.

Eye-blink conditioning is an elementary example of a skilled movement. Work by one of the present authors (RFT) and his associates has shown that the memory traces for this form of learning are formed and stored in localized regions of the cerebellum (see Figure 1-2), but the hippocampus is also involved in this kind of learning. The term *memory trace* refers to the physical storage of the memory in the brain. In this case it appears to be in a very localized place in the brain where the neurons have actually undergone physical changes that code and store memory. It may also be the case that memory traces for complex skilled movements are stored in the cerebellum (Figure 1-2). We will have more to say about memory storage in the cerebellum.

When you are learning a new motor skill, such as a golf swing, you concentrate your efforts on the precise movements. This effort engages the highest area of the brain, the cerebral cortex, par-

ticularly the motor areas of the cortex. However, once the swing is thoroughly mastered and highly skilled, the best thing to do is not think about it at all and just let it happen. Evidence suggests that the memories for such complex skills are stored in the cerebellum. We are consciously aware of engagement of the cerebral cortex, as in learning the swing, but are not aware of engagement of the cerebellum. We think it stores the memories for the automatic performance of skilled movements. This type of learning, from eye blink to a golf swing, requires many trials, that is, many repetitions of the behavior before it becomes “natural.”

Emotional Learning

Another widely studied form of Pavlovian conditioning is *conditioned fear*. In brief, a neutral stimulus like a tone is followed by a strong electric shock to the paws of a rat. Even one experience is enough to train the rat to fear the tone. The next time the rat hears that tone, it will experience fear, typically expressed by changes in its heart rate, freezing (becoming motionless), or other behaviors. Fear can also easily be conditioned in humans by pairing a neutral stimulus or situation with an unpleasant event, for example, a very loud sound. Learned fear can develop in one trial. Part of Chapter 7 is devoted to this very important form of Pavlovian conditioning. It accounts for most of our fears, even our likes and dislikes, and phobias. Some people have developed intense “irrational” fears, perhaps for crowds, or snakes, or even running water. The critical brain region for learned fear is the amygdala, but the hippocampus is also involved.

Instrumental Learning

A third category of basic associative learning is called *instrumental or operant conditioning*, where the person or animal is able to control the outcome of a situation. In Pavlovian conditioning the person is unable to control the situation. She is given the stimulus, perhaps a picture of a snake followed by a very loud sound,

regardless of what she does. But in instrumental learning she could press a lever when she sees the snake to prevent the loud sound from occurring. In some common examples in animal studies, a rat is trained to press a lever to obtain a food reward or avoid a paw shock, or a pigeon is trained to peck a key for food. B. F. Skinner, a pioneering scientist in the study of learning, termed this type of situation operant conditioning. The animal or person learns to operate on the situation to obtain the desired outcome.

Much of the elementary learning people do is of this sort, although after early childhood the rewards and punishments are more complex. Approval of others, especially peers, is a powerful reward, just as disapproval is a powerful punishment, particularly in the teenage years but also throughout our lives. Instrumental learning may occur in one trial or may require many trials.

The amygdala is a major brain structure involved in learning to avoid an unpleasant or dangerous event, although other brain structures also are involved. On the other hand, learning to obtain rewards involves yet another brain system, the brain "pleasure system," which is also critical for drug addiction. The striatum also seems to be involved in some aspects of reward learning, as in well-learned habits.

Priming

Priming is the kind of memory shown by the surgical patients mentioned earlier who had been anesthetized. They had no awareness or explicit memory of having heard the story of Robinson Crusoe during surgery. But half of them free-associated the name Robinson Crusoe to the word "Friday." Free association is the common method for measuring priming memory.

In a standard priming test, people first read a list of common words (*office, trouble, hillside, . . .*) and have to rate the pleasantness of each word. This rating of pleasantness, incidentally, is irrelevant. It is simply a way to get the person to pay attention to the words. What you are doing here is "priming" or activating the words in the person's long-term memory (their "mental dictio-

nary"). Then at some later time they are given a test such as completing word fragments (for example, *t _ o _ b _ e*). The test does not ask them to explicitly remember anything (nor were they asked to learn or memorize anything originally). Nevertheless, it is easy to show that they will complete the word fragment as *t r o u b l e* much more often than someone who saw a list that did not have this word in it. Once again, it has been studies of brain-damaged subjects that have led memory theorists to conclude that the kind of memory measured by these implicit procedures is basically different than the memory assessed by explicit memory tests. Many investigators have reported that amnestics such as HM can perform at normal or near-normal levels in implicit tests—even though their memory for the word list is nonexistent when they are asked to use their explicit memory ("Try to recall as many of the words in the list as you can").

In a brain imaging experiment performed by Larry Squire, Marcus Raichle, and other colleagues, normal people studied a list of words. (See Box 1-2 for a description of brain imaging procedures.) Some subjects had to remember and state the words they had studied (explicit memory). In this case a brain structure critical for explicit memory, the hippocampus, became more active. Other subjects were given the priming test, where they said the first words that came to mind upon seeing the first two letters of each word. In this case a region of the right visual areas of the cerebral cortex became active. Indeed, damage to this region of the cortex in a patient markedly impaired priming memory, but the patient *was* able to remember the actual words in an explicit memory test as well as normal people. Explicit memory involves awareness, but priming memory does not, and the two forms of memory seem to involve different areas of the brain.

The existence of priming memory has interesting implications. It would seem that we have some kind of memory storage for experiences we are not very aware of. Some fragments of these memories are there in the brain but cannot be consciously retrieved. This kind of learning had also been described as incidental learning. We learn bits and pieces of experiences, particularly

BOX 1-2 Human Brain Imaging—A Window on the Mind

Brain imaging has provided a quantum leap in our ability to study the workings of the human brain. For the first time we can actually watch increases and decreases in the activity of brain regions as they occur without having to do surgery or insert electrodes. In this way brain structures and areas that are critically involved in various forms and aspects of learning and memory can be identified. These methods were, of course, first developed for medicine and have revolutionized medical diagnosis.

Current methods most widely employed for behavioral brain imaging make use of the remarkable fact that increases in the activity of any local group of neurons in the brain result in a rapid increase in blood flow to that particular area. By measuring these local increases in blood flow we can determine which brain areas are most active in a particular learning situation.

One commonly used brain imaging procedure is positron emission tomography (PET). In essence, radioactive biological probes are administered to the subject, usually injected into the bloodstream, and the radiation emitted from the brain (or other target tissue) measured with an array of radiation detectors. This method uses positrons, elementary particles with the mass of an electron but a positive charge. Isotopes of several common elements—for example, carbon or oxygen—emit high levels of positrons. When a positron encounters an electron, the two annihilate each other and are converted to two gamma rays, which can easily be detected and localized in the brain. These “radio-labeled” substances have to be injected into a person, which does not seem like a very good idea. Luckily, they have very short half-lives, decaying quickly (in about 2 minutes for oxygen 15), so there is no harm to the person.

unimportant experiences, without being particularly aware of doing so. Incidentally, the importance of implicit memory and priming was identified over 100 years ago by Hermann Ebbinghaus, a German philosopher, educator, and pioneer in the study of memory who spoke of how the accumulated experiences of a lifetime “remain concealed from consciousness and yet produce an effect which authenticates their previous existence.”

The radioactive isotopes must be made in a cyclotron, and because of the short half-lives, the cyclotron must be located at the imaging facility site. Since carbon is common to all organic compounds and nitrogen to many, the PET method can be used to study a wide variety of biological functions, including protein synthesis and neurotransmitter-receptor actions.

A more recently developed imaging method is magnetic resonance imaging (MRI), which involves placing the patient or research subject in a very strong magnetic field. Changes in a property of hydrogen protons known as “spin” are then produced when the MRI machine sends in a radio signal at a frequency that causes some proportion of protons to enter an “excited” state. This in turn generates a signal that MRI detectors pick up and later convert to an image of the tissue in the scanned brain areas.

In brain studies the primary research method is called functional MRI (fMRI) and makes use of the same general biological phenomenon as PET—namely regional changes in blood flow. If the amount of oxygen carried by the hemoglobin changes, the degree to which hemoglobin disturbs a magnetic field also changes. Thus, fMRI measures changes in blood oxygenation due to changes in local regional blood flow, which in turn occur when neural activity in a given region of the brain changes.

The fMRI method has a number of advantages over the PET procedure. One is that it is noninvasive, does not require an injection, and does not involve any radioactive substance. fMRI also has much better spatial resolution than PET (it can localize neural activity in relatively small regions) and also better temporal resolution (it can detect changes in neural activity in a much smaller time frame than that required by PET).

Probability and Category Learning

If you were a gambler, imagine what you would do in the following situation. You are presented with two levers (as in a two-armed “one-armed bandit”) and must pull one of them every five seconds. Some of the time you win a reward from each lever. Although you are not aware of it, the “house” (i.e., the experimenter) has rigged the situation so that the right lever pays off 57 percent of the time and the left lever 43 percent of the time. If you play for

a long time, what do you think you will end up doing? Believe it or not you will reach a steady state where you pull the right lever 57 percent of the time and the left lever 43 percent of the time. Your behavior will come to match the exact probabilities of pay-off, even though you are unaware of this and even though you would have done better by pulling the right lever all the time.

This surprising result was found in a series of studies by the brilliant Harvard psychologist Richard Herrnstein, who characterized this behavior as the “matching law.” Even more remarkable, exactly the same result occurs if a rat has to press levers or a pigeon peck keys, with differing probabilities of reward. Mammals, including humans, and birds respond in exact proportion to the probability that reward will occur. In general, people are unaware of the fact that they are matching reward probabilities. Probability learning requires *many* trials.

Mark Gluck, of Rutgers University, developed an important elaboration of this type of probability or category learning in a game he termed *weather forecasting*. Four different cards are used, and one, two, or three of the cards are presented on each trial. The person playing the game has to guess from each presentation whether it will rain or be sunny. Sounds simple, right? But Mark rigged the situation so that the probability that a given card or combination of cards might mean rain was less than one. For example, one card predicted sunshine 57 percent of the time and rain 43 percent of the time. The player is not told this, only “right” or “wrong” on each trial. The player can’t simply memorize the relations between cards and weather because the relationships are considerably less than perfect.

At the beginning of the game, people more or less guess rain or shine at random on each trial. With much practice they actually improve substantially in their predictions of the weather. But they are unaware of why they are improving; that is, they cannot state what is governing their successful behavior.

In a series of studies, Larry Squire, Barbara Knowlton, Mark Gluck, and associates, working at the University of California, San Diego (Barbara is now at the University of California, Los

Angeles), tested amnestics, like HM, with damage to the hippocampus and medial temporal lobe. They actually showed improvement with practice, just as normal people do, but they could not remember the game afterward. On the other hand, patients with Parkinson's disease, with damage to the striatum, were unable to improve with practice, even though they could remember the game afterward. The striatum appears to play a key role in this type of unconscious category or probability learning.

Skills

Parkinson's patients also have difficulty starting or initiating voluntary movements, clearly indicating that the striatum is involved in motor control and presumably in motor skill learning as well. We noted earlier that the well-learned memories for motor skills appear to be stored in the cerebellum. But we also noted the important role of the motor areas of the cerebral cortex in the initial learning of motor skills. The striatum is also somehow involved in motor skill learning, although little more is known.

Overview

This book focuses on those aspects of memory we think are most important to you, the reader. The ability to store new information and experience into long-term or permanent memory is the hallmark of memory. But people also forget. How accurate are our memories? Believe it or not, it is relatively easy to establish false memories, to convince people they have certain memories that in fact they do not have.

Normal aging is accompanied by minor impairments in long-term memory ability, what has been termed "benign" forgetting. This is completely different from Alzheimer's disease, in which most memories, new and old, eventually disappear.

Amnesia is typically an inability to form long-term memories that can result from brain injury, but here the memories for some period prior to injury may still be present.

Emotional memories, fear and anxiety, are compelling. Intense anxiety when remembering and reliving traumatic events can exert disruptive effects on people for years. The problem is not so much being able to remember such traumas but instead being able to forget them.

Perhaps the most important learning people do is the acquisition of their native language. Indeed, language sets us apart from all other species. It allows us to describe anything, even things that do not exist. Nothing defines humanity so much as our ability to communicate abstract thoughts to others.

These are all aspects of long-term memory. We also distinguish between short-term or “working” memory and long-term memory. Short-term memory, often termed immediate memory, is how long you can remember a new telephone number you just looked up—a few seconds. Working memory includes new information but also retrieval of knowledge from long-term memory and awareness of one’s surroundings, what is commonly referred to as consciousness or awareness. Long-term memory is the vast store of information you possess and are not aware of unless you call it up. How the three pounds of tissue that are the brain accomplish these extraordinary functions of memory is one of the greatest mysteries and one of the most exciting fields of science today.