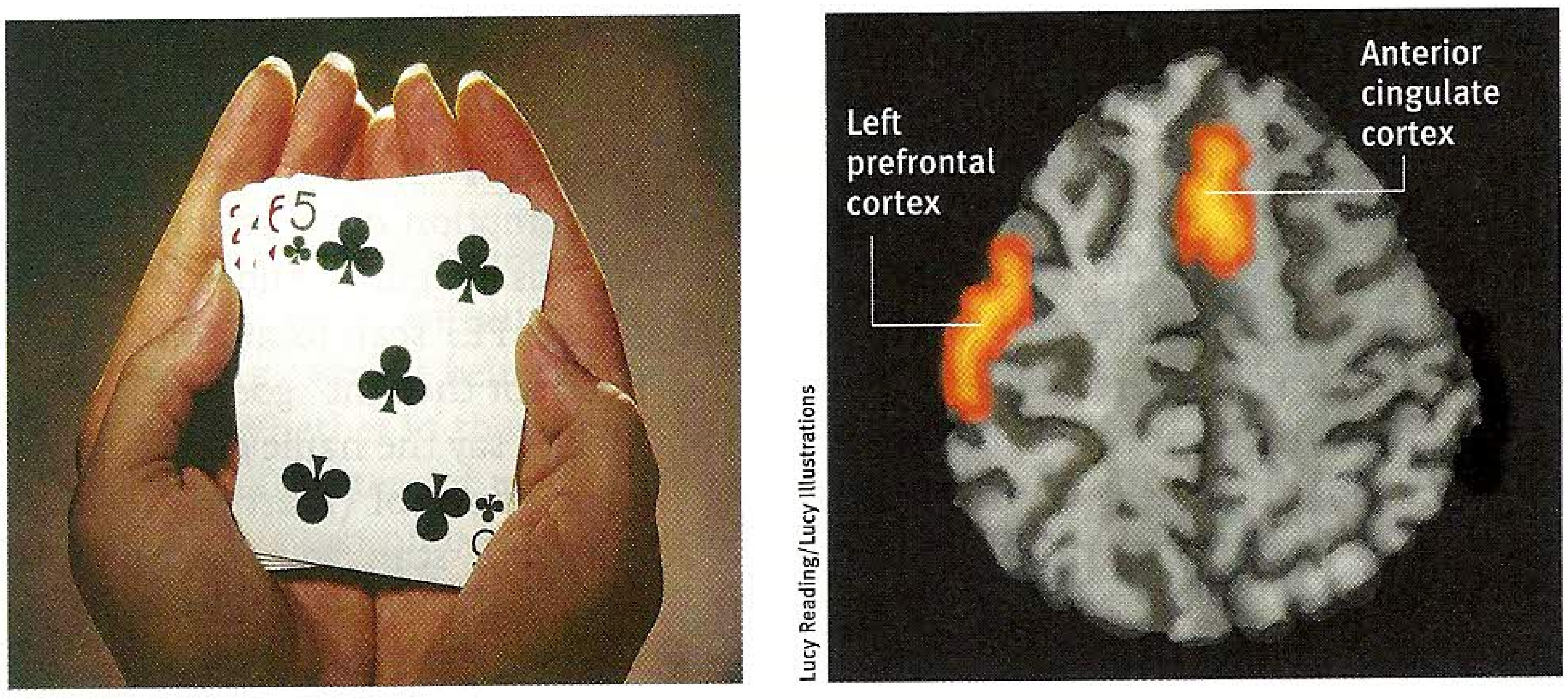
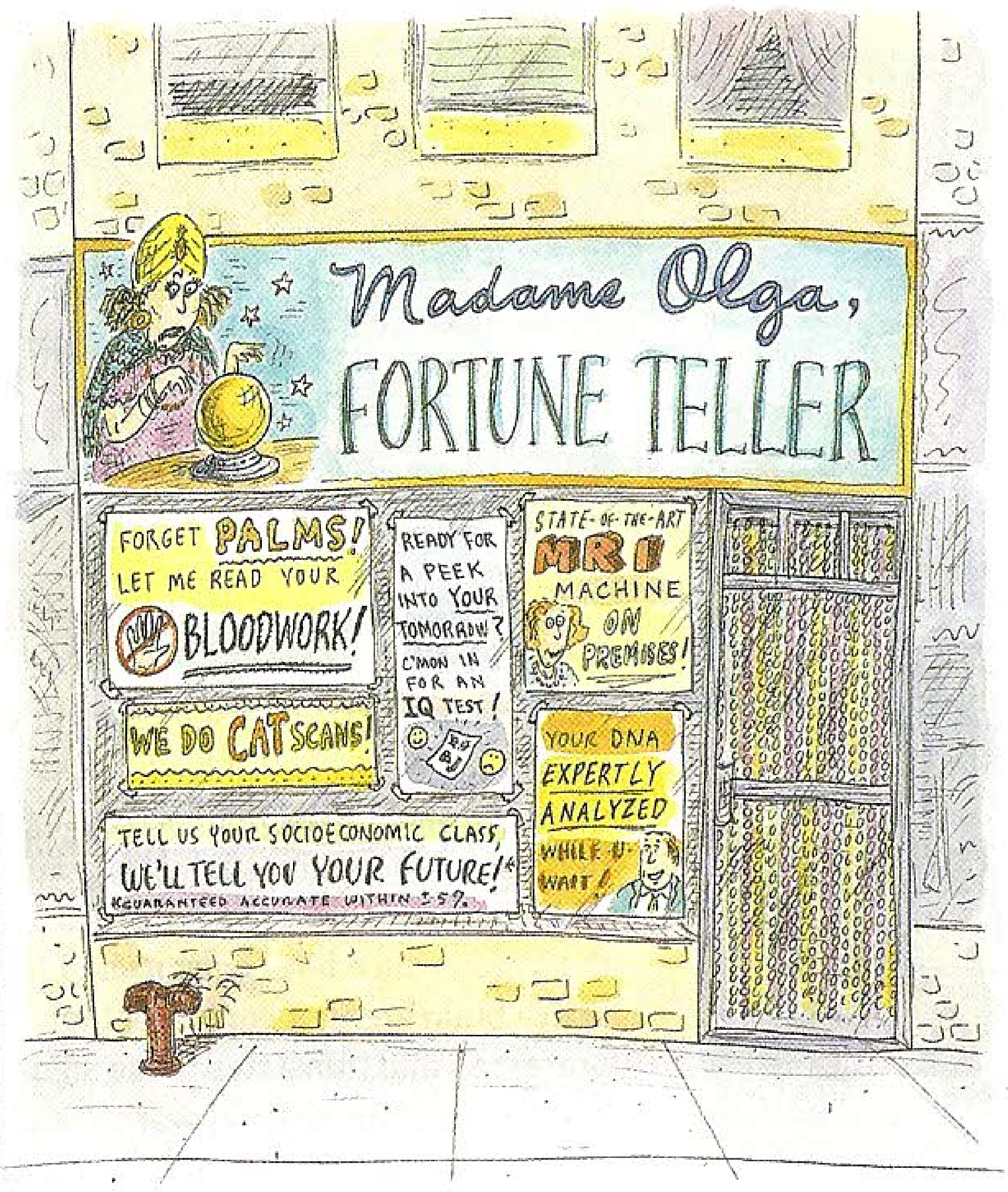
FIGURE 2.15
Brain reading
An fMRI scan identified two brain areas that became especially active when a participant lied about holding a five of clubs.



James Salzano/Salzano Photo

Lucy Reading/Lucy Illustrations



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In one intriguing study, neuroscientist Daniel Langleben and his colleagues (2002) discovered that fMRI scans located increased brain activity associated with lying. When participants lied about a playing card they held in their hand, the telltale fMRI revealed increased activity in two brain regions (**FIGURE 2.15**). One was the anterior cingulate cortex, an area typically active when we experience conflicting urges. Some researchers speculate that more portable methods of measuring brain activity might someday detect lies in real-life situations.

To be learning about the neurosciences now is like studying world geography while Magellan was exploring the seas. The number of explorers grows: The growing membership of the interdisciplinary Society for Neuroscience, founded in 1969, surpassed 36,000 in 2004. Every year the explorers announce new discoveries, which also generate new interpretations of old discoveries.

Researchers are assembling this wealth of new information in computer databases. This brain cartography will give all researchers instant access through electronic networks to PET or MRI studies that reveal activity in a particular brain area while a person, for example, solves math problems. Clearly, this is the golden age of brain science.

Older Brain Structures

OBJECTIVE 12 | Describe the components of the brainstem, and summarize the functions of the brainstem, thalamus, and cerebellum.

If you could open the skull and look inside, the first thing you might note is the brain's size. In dinosaurs, the brain represents 1/100,000th of the body's weight, in whales 1/10,000th, in elephants 1/600th, in humans 1/45th. It looks as though a principle is emerging. But keep on. In mice the brain is 1/40th the body's weight, and in marmosets 1/25th. So there are exceptions to the rule that the ratio of brain to body weight provides a clue to a species' intelligence.

More useful indicators about an animal's capacities come from its brain structures. In primitive vertebrate (backboned) animals, such as sharks, the brain primarily regulates basic survival functions: breathing, resting, and feeding. In lower mammals, such as rodents, a more complex brain enables emotion and greater memory. In advanced mammals, such as humans, the brain processes more information, so we are able to act with foresight.

To enable this increasing complexity, species have elaborated new brain systems on top of the old, much as the Earth's landscape covers the old with the new. Digging down, one discovers the fossil remnants of the past—brainstem components still performing much as they did for our distant ancestors. Starting with the brainstem and working up to the newer systems, let's now explore the brain.

The Brainstem

The brain's basement—its oldest and innermost region—is the **brainstem.** It begins where the spinal cord enters the skull and swells slightly, forming the **medulla.** Here lie the controls for your heartbeat and breathing. If the top of a cat's brainstem is severed from the rest of the brain above it, the animal will still breathe and live—and even run, climb, and groom (Klemm, 1990). But cut off from the brain's higher region, it won't purposefully run or climb to get food. Just above the medulla sits the *pons,* which helps coordinate movements.

The brainstem is also the crossover point, where most nerves to and from each side of the brain connect with the body's opposite side. This peculiar cross-wiring is but one of many surprises the brain has to offer.

Inside the brainstem, between your ears, lies the **reticular** ("netlike") **formation,** a finger-shaped network of neurons that extends from the spinal cord right up to the thalamus (**FIGURE 2.16**). As the spinal cord's sensory input travels up to the thalamus, some of it travels through the reticular formation, which filters incoming stimuli and relays important information to other areas of the brain.

In 1949, Giuseppe Moruzzi and Horace Magoun discovered that electrically stimulating the reticular formation of a sleeping cat almost instantly produced an awake, alert animal. When Magoun *severed* a cat's reticular formation from higher brain regions, without damaging the nearby sensory pathways, the effect was equally dramatic: The cat lapsed into a coma from which it never awakened. Magoun could clap his hands by the cat's ear, even pinch it; still, no response. The conclusion? The reticular formation is involved in arousal. Later researchers discovered that elsewhere in the brainstem are neurons whose activity is needed for sleep. (As you will see in Chapter 7, our brains are not idle while we sleep.)

- **brainstem** the oldest part and central core of the brain, beginning where the spinal cord swells as it enters the skull; the brainstem is responsible for automatic survival functions.
- **medulla** [muh-DUL-uh] the base of the brainstem; controls heartbeat and breathing.
- **reticular formation** a nerve network in the brainstem that plays an important role in controlling arousal.

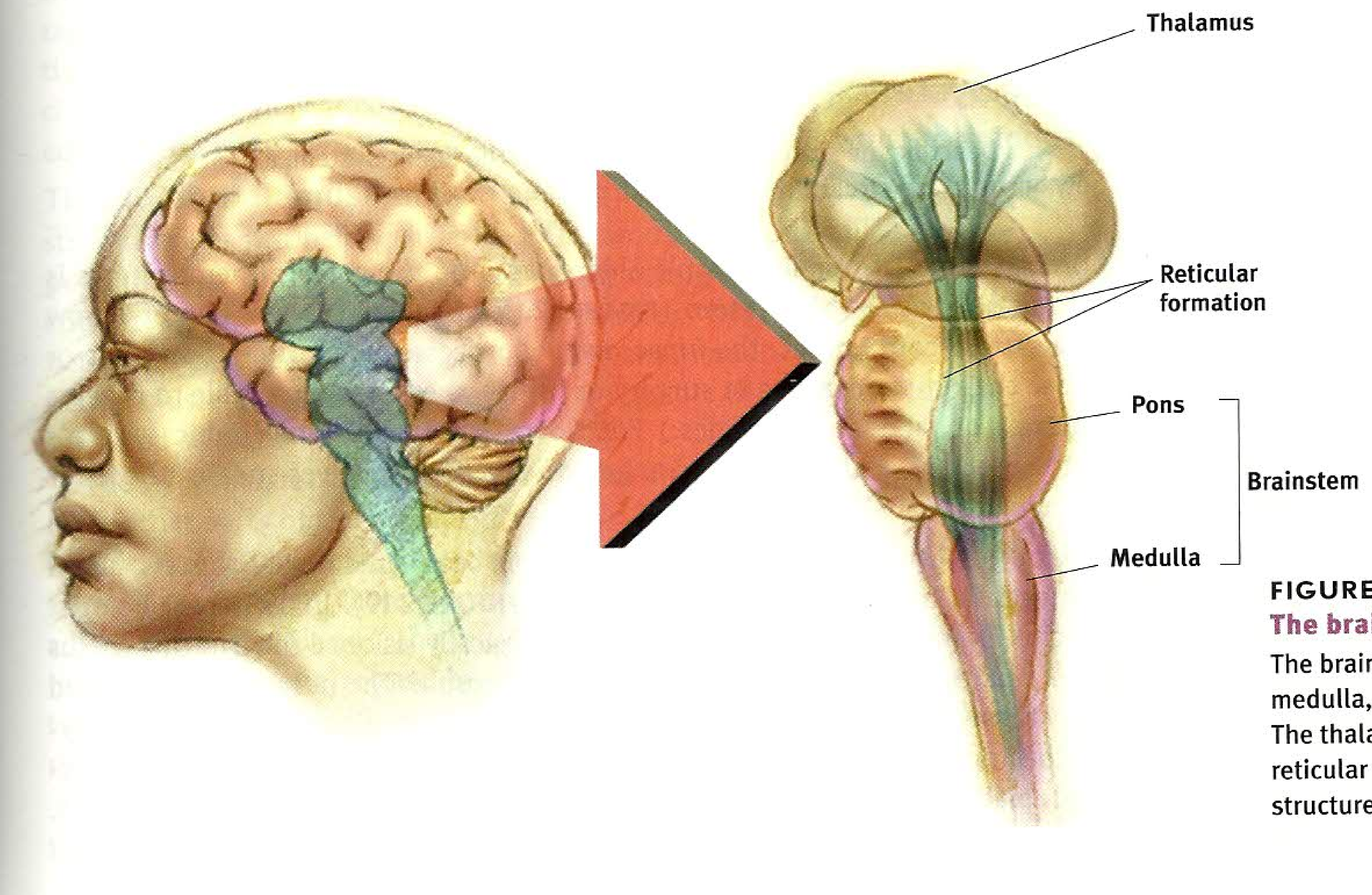


FIGURE 2.16
The brainstem and thalamus
The brainstem, including the pons and medulla, is an extension of the spinal cord. The thalamus is attached to its top. The reticular formation passes through both structures.

thalamus [THAL-uh-muss] the brain's sensory switchboard, located on top of the brainstem; it directs messages to the sensory receiving areas in the cortex and transmits replies to the cerebellum and medulla.

cerebellum [sehr-uh-BELL-um] the "little brain" attached to the rear of the brainstem; its functions include processing sensory input and coordinating movement output and balance.

The Thalamus

Atop the brainstem sits the brain's sensory switchboard, a joined pair of egg-shaped structures called the **thalamus** (Figure 2.16). It receives information from all the senses except smell and routes it to the brain regions that deal with seeing, hearing, tasting, and touching. Think of the thalamus as being to sensory input what London is to England's trains: a hub through which traffic passes en route to various destinations. The thalamus also receives some of the higher brain's replies, which it then directs to the medulla and to the cerebellum.

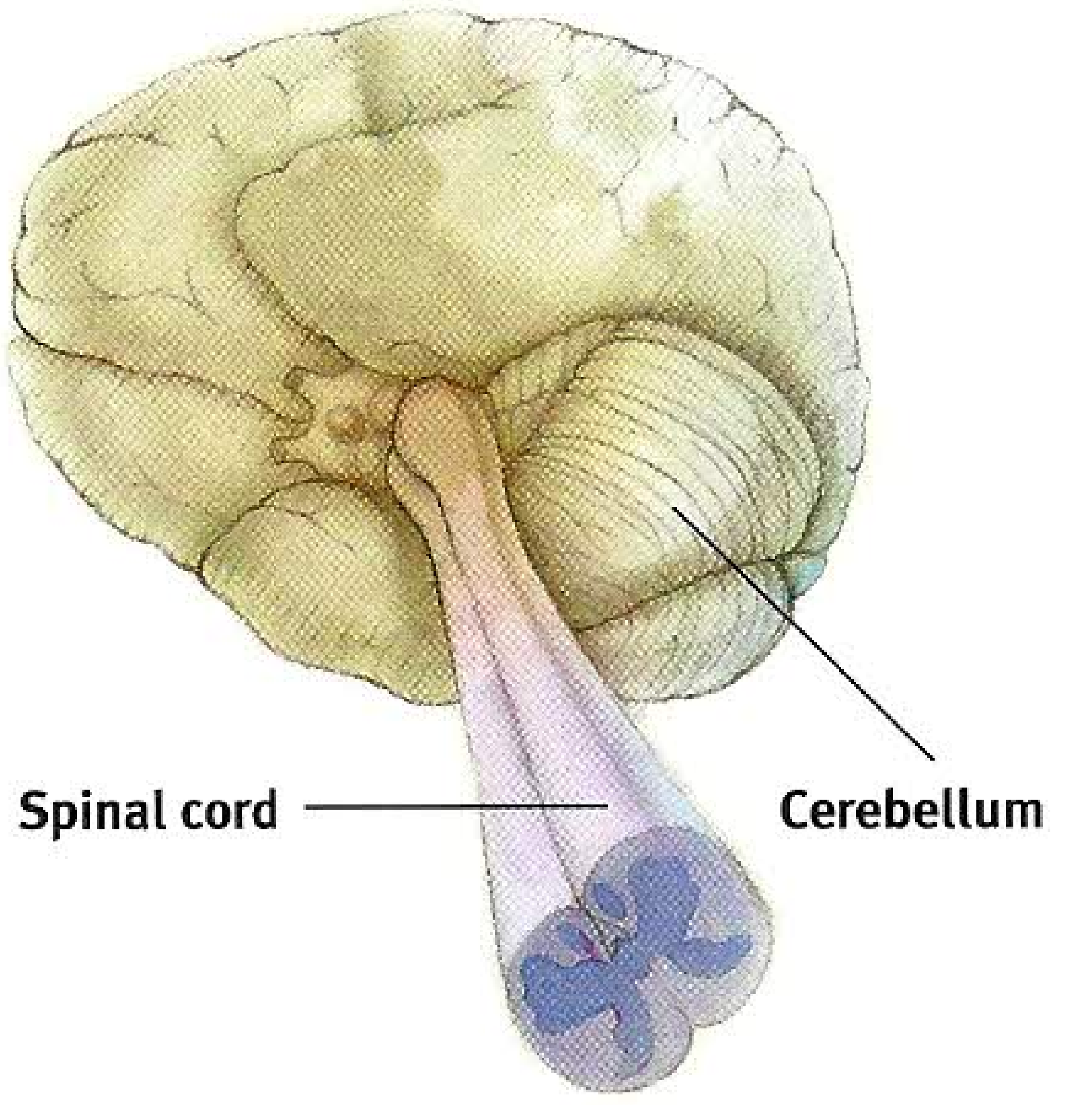


FIGURE 2.17
The brain's organ of agility
Hanging at the back of the brain, the cerebellum coordinates our movements, as when David Beckham directs the ball precisely.


Lluis Gene/AFP/Getty Images

The Cerebellum

Extending from the rear of the brainstem is the baseball-sized **cerebellum,** meaning "little brain," which is what its two wrinkled halves resemble (**FIGURE 2.17**). As you will see in Chapter 9, the cerebellum enables one type of nonverbal learning and memory. New studies reveal that it also helps us judge time, modulate our emotions, and discriminate sounds and textures (Bower & Parsons, 2003). In addition to processing sensory information, the cerebellum coordinates voluntary movement. When soccer great David Beckham fires the ball into the net with a perfectly timed kick, give his cerebellum some credit. If you injured your cerebellum, you would have difficulty walking, keeping your balance, or shaking hands. Your movements would be jerky and exaggerated.

Note: These older brain functions all occur without any conscious effort. This illustrates another of our recurring themes: *Our brain processes most information outside of our awareness*. We are aware of the *results* of our brain's labor (say, our current visual experience) but not of *how* we construct the visual image. Likewise, whether we are asleep or awake, our brainstem manages its life-sustaining functions, freeing our newer brain regions to dream, think, talk, or savor a memory.

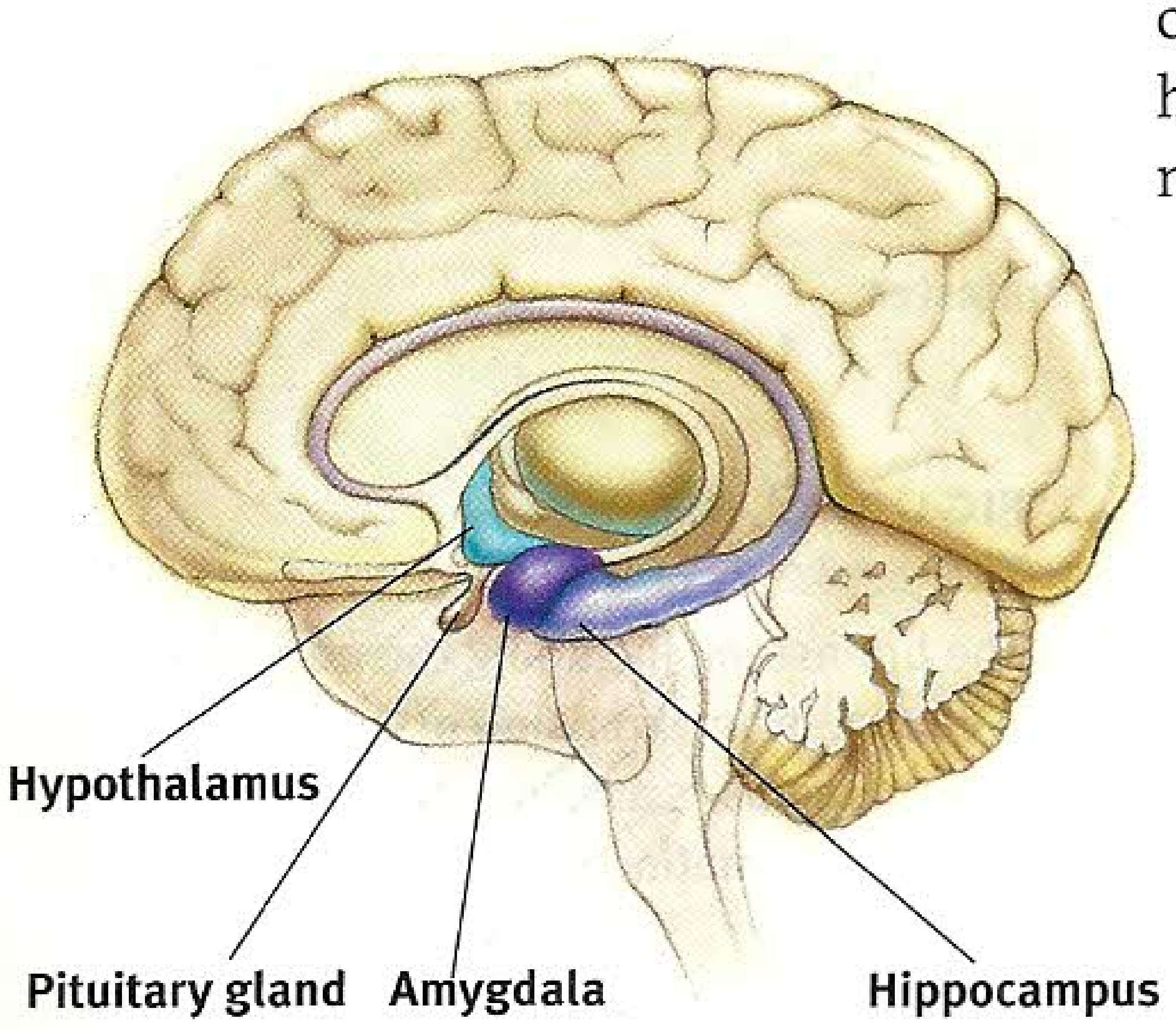
The Limbic System

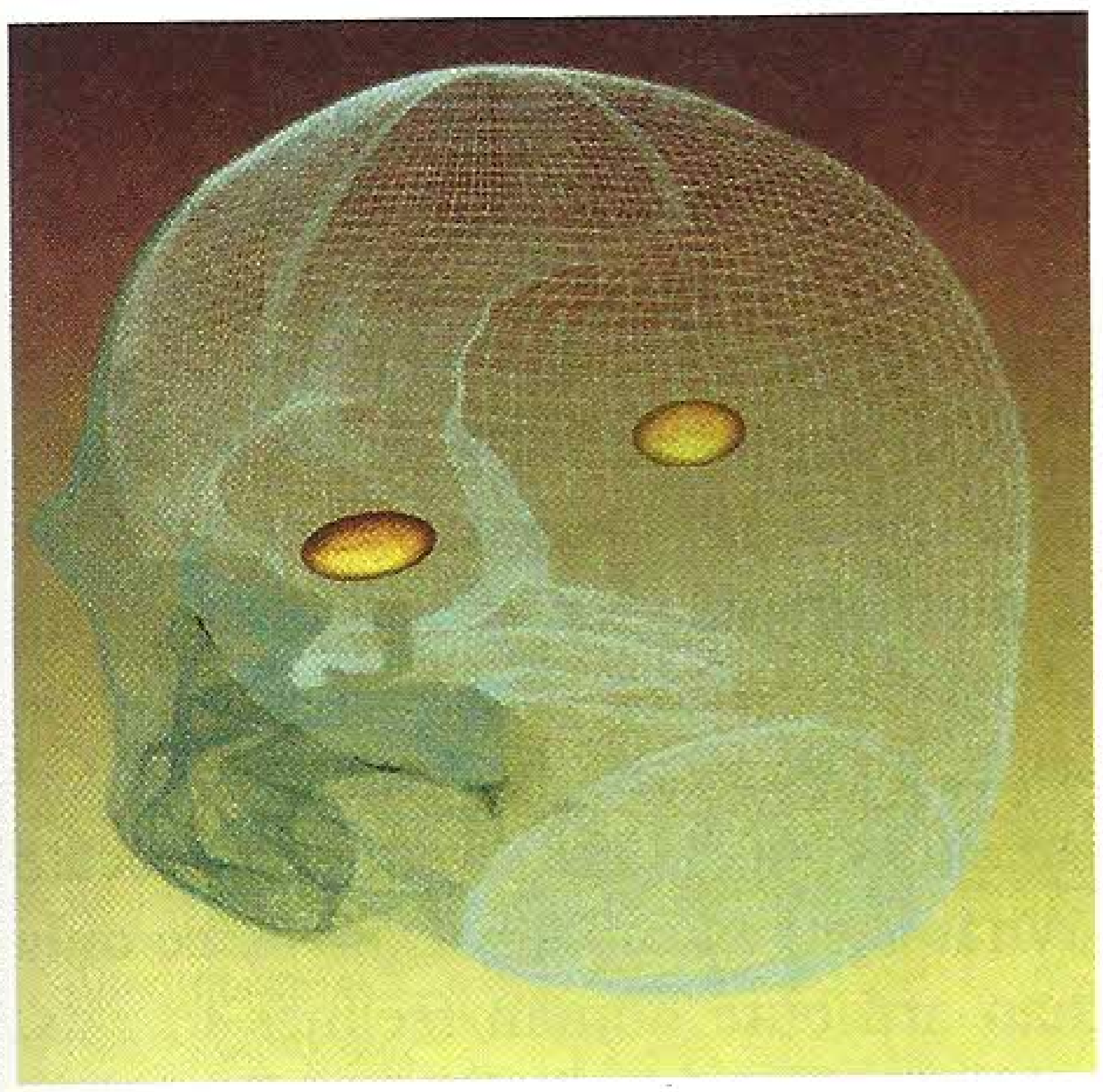
OBJECTIVE 13 | Describe the structures and functions of the limbic system, and explain how one of these structures controls the pituitary gland.

At the border ("limbus") of the brain's older parts and the cerebral hemispheres is the doughnut-shaped **limbic system** (**FIGURE 2.18**). We will see in Chapter 9 how one limbic system component, the *hippocampus,* processes memory. (If animals or humans lose their hippocampus to surgery or injury, they become unable to process new memories of facts and episodes.) For now, let's look at the limbic system's links to emotions such as fear and anger, and to basic motives such as those for food and sex.

The Amygdala In the limbic system, two lima bean-sized neural clusters, called the **amygdala,** influence aggression and fear (**FIGURE 2.19**). In 1939, psychologist Heinrich Klüver and neurosurgeon Paul Bucy surgically lesioned the part of a rhesus monkey's brain that included the amygdala. The result? The normally ill-tempered monkey turned into the most mellow of creatures. Poke it, pinch it, do virtually anything that normally would trigger a ferocious response, and still the animal remained placid. In later studies with other wild animals, including the lynx, wolverine, and wild rat, researchers noted the same effect. What then might happen

FIGURE 2.18
The limbic system
Limbic structures form a doughnut-shaped neural system between the brain's older parts and its cerebral hemispheres. Although part of the hormonal (endocrine) system, not the brain, the pituitary gland is controlled by the limbic system's hypothalamus, just above it.





Moonrunner Design Ltd., UK

FIGURE 2.19
The amygdala

Frank Siteman/Stock, Boston

Aggression as a brain state
Back arched and fur fluffed, this fierce cat is ready to attack. Electrical stimulation of a cat's amygdala provokes reactions such as the one shown here, suggesting its role in emotions like rage. Which division of the autonomic nervous system is activated by such stimulation? (See page 74.)

if we electrically stimulated the amygdala in a normally placid domestic animal, such as a cat? Do so in one spot and the cat prepares to attack, hissing with its back arched, its pupils dilated, its hair on end. Move the electrode only slightly within the amygdala, cage the cat with a small mouse, and now it cowers in terror.

These experiments confirm the amygdala's role in rage and fear, not to mention the perception of such emotions and the processing of emotional memories (Anderson & Phelps, 2000; Poremba & Gabriel, 2001). Still, we must be careful. The brain is *not* neatly organized into structures that correspond to our categories of behavior. Actually, both aggressive and fearful behavior involve neural activity in all levels of the brain, not solely in the amygdala. Even within the limbic system, stimulating neural structures other than the amygdala can evoke such behavior. If you put a charge to your car's dead battery, you can activate the engine. Yet the battery is merely one link in an integrated system.

Given that amygdala lesions can transform violent monkeys into mellow ones, might such lesions do the same in violent humans? You might think so. But such "psychosurgery" has produced varied results (Mark & Ervin, 1970; Valenstein, 1986). In a few cases involving patients who suffered brain abnormalities, it reduced fits of rage, though sometimes with devastating side effects on the patient's everyday functioning. For ethical reasons, and because of the uncertainties involved, drastic psychosurgery is rarely used. Perhaps, though, as we learn more about how the brain controls behavior, we will learn to alleviate brain disorders without creating new ones.

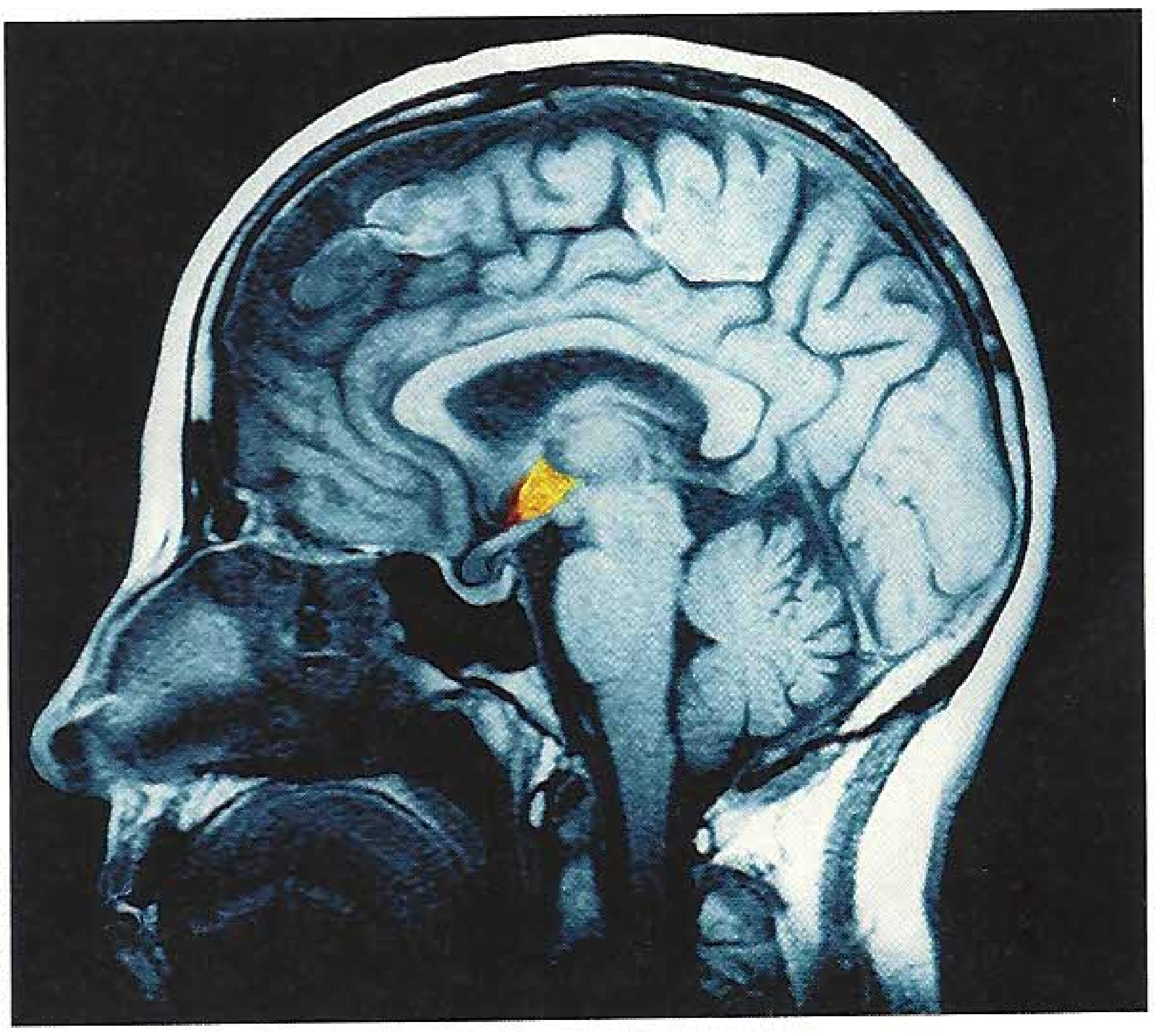
- **limbic system** a doughnut-shaped system of neural structures at the border of the brainstem and cerebral hemispheres; associated with emotions such as fear and aggression and drives such as those for food and sex. Includes the hippocampus, amygdala, and hypothalamus.
- **amygdala** [uh-MIG-duh-la] two lima bean-sized neural clusters that are components of the limbic system and are linked to emotion.
- **hypothalamus** [hi-po-THAL-uh-muss] a neural structure lying below (*hypo*) the thalamus; it directs several maintenance activities (eating, drinking, body temperature), helps govern the endocrine system via the pituitary gland, and is linked to emotion.

The Hypothalamus Another of the limbic system's fascinating structures lies just below (*hypo*) the thalamus, and so is called the **hypothalamus** (**FIGURE 2.20**). By either lesioning or stimulating different areas, neuroscientists have identified hypothalamic neural networks that perform specific bodily maintenance duties. Some neural clusters influence hunger; others regulate thirst, body temperature, and sexual behavior.

The hypothalamus both monitors blood chemistry and takes orders from other parts of the brain. For example, thinking about sex (in your brain's cerebral cortex) can stimulate your hypothalamus to secrete hormones. Through these hormones, the hypothalamus controls the adjacent "master gland," the pituitary (see Figure 2.18), which in turn influences hormone release by other glands. (Note the interplay between the nervous and hormone systems: The brain influences the hormone system, which in turn influences the brain.)

The story of a remarkable discovery about the hypothalamus illustrates how progress in scientific research often occurs—when curious,

FIGURE 2.20
The hypothalamus
This small but important structure, colored yellow/orange in this MRI scan photograph, helps keep the body's internal environment in a steady state by regulating thirst, hunger, and body temperature. Its activity also influences experiences of pleasurable reward.



ISM/Phototake

open-minded investigators make an unexpected observation. Two young McGill University neuropsychologists, James Olds and Peter Milner (1954), were trying to implant electrodes in the reticular formations of white rats when they made a magnificent mistake. In one rat, they incorrectly placed an electrode in what was later discovered to be a region of the hypothalamus (Olds, 1975). Curiously, the rat kept returning to the place on its tabletop enclosure where it had been stimulated by this misplaced electrode, as if seeking more stimulation. Upon discovering their mistake, Olds and Milner alertly recognized that they had stumbled upon a brain center that provides a pleasurable reward.

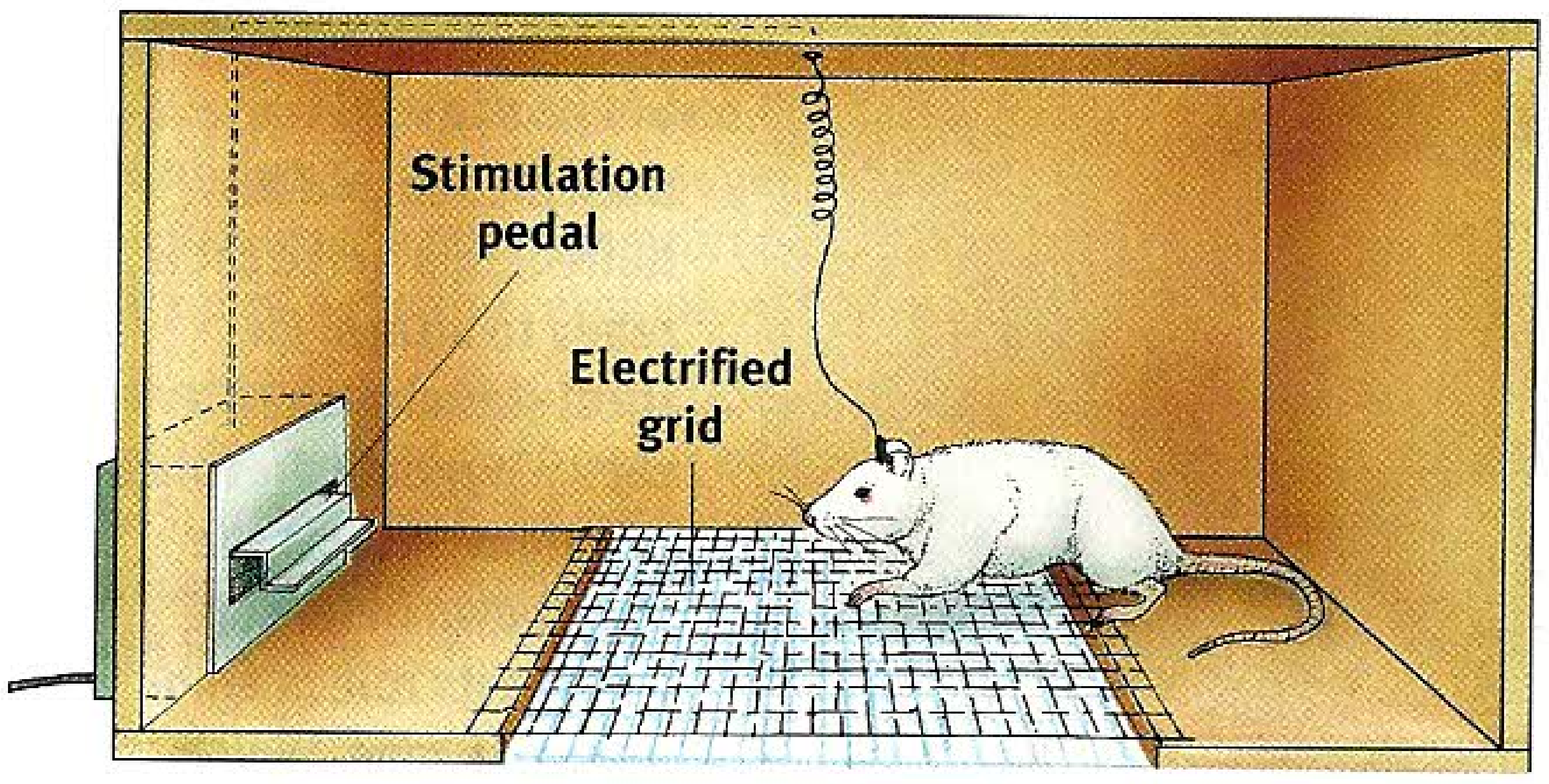


FIGURE 2.21
Rat with an implanted electrode
With an electrode implanted in a reward center of its hypothalamus, the rat readily crosses an electrified grid, accepting the painful shocks, to press a lever that sends electrical impulses to its "pleasure centers."

In a meticulous series of experiments, Olds (1958) went on to locate other "pleasure centers," as he called them. (What the rats actually experience only they know, and they aren't telling. Rather than attribute human feelings to rats, today's scientists refer to *reward centers,* not "pleasure centers.") When allowed to trigger their own stimulation in these areas by pressing a pedal, rats would sometimes do so at a feverish pace—up to 7000 times per hour—until they dropped from exhaustion. Moreover, they would do anything to get this stimulation, even cross an electrified floor that a starving rat would not cross even to reach food (**FIGURE 2.21**).

> "If you were designing a robot vehicle to walk into the future and survive, . . . you'd wire it up so that behavior that ensured the survival of the self or the species—like sex and eating—would be naturally reinforcing."
>
> Candace Pert (1986)

Similar reward centers in or near the hypothalamus were later discovered in many other species, including goldfish, dolphins, and monkeys. In fact, animal research has revealed both a general reward system that triggers the release of the neurotransmitter dopamine and specific centers associated with the pleasures of eating, drinking, and sex. Animals, it seems, come equipped with built-in systems that reward activities essential to survival.

More recent experiments have found new ways of using limbic stimulation to control animals' actions. By using brain stimulation to reward rats for turning left or right, Sanjiv Talwar and his colleagues (2002) trained rats that had never been outdoors to navigate natural environments (**FIGURE 2.22**). By pressing buttons on a laptop, the researchers can direct a rat—which carries a receiver, power source, and video camera on a backpack—to turn on cue, climb trees, scurry along branches, and turn around and come back down. Their work suggests future applications in search-and-rescue operations.

The cat on page 73 is aroused via its sympathetic nervous system.

Dramatic findings like these have led people to wonder whether humans, too, might have limbic centers for pleasure. Indeed we do. One neurosurgeon used electrodes to calm violent patients. Stimulated patients reported mild pleasure; however, unlike Olds' rats, they were not driven to a frenzy (Deutsch, 1972; Hooper & Teresi, 1986). Some researchers believe that addictive disorders, such as alcoholism, drug abuse, and binge eating, may stem from a *reward deficiency syndrome*—a genetically disposed deficiency in the natural brain systems for pleasure and well-being that leads people to crave whatever provides that missing pleasure or relieves negative feelings (Blum & others, 1996).

FIGURE 2.22
Ratbot on a pleasure cruise
When stimulated by remote control, this rat could be guided to navigate across a field and even up a tree.

Sanjiv Talwar, SUNY Downstate

The Cerebral Cortex

OBJECTIVE 14 | Define *cerebral cortex,* and explain its importance for the human brain.

Older brain networks sustain basic life functions and enable memory, emotions, and basic drives. Newer neural networks within the cerebral hemispheres form specialized work teams that enable our perceiving, thinking, and speaking. Your **cerebral cortex** is an intricate covering of interconnected neural cells that, like bark on a tree, forms a thin surface layer on your cerebral hemispheres. It is

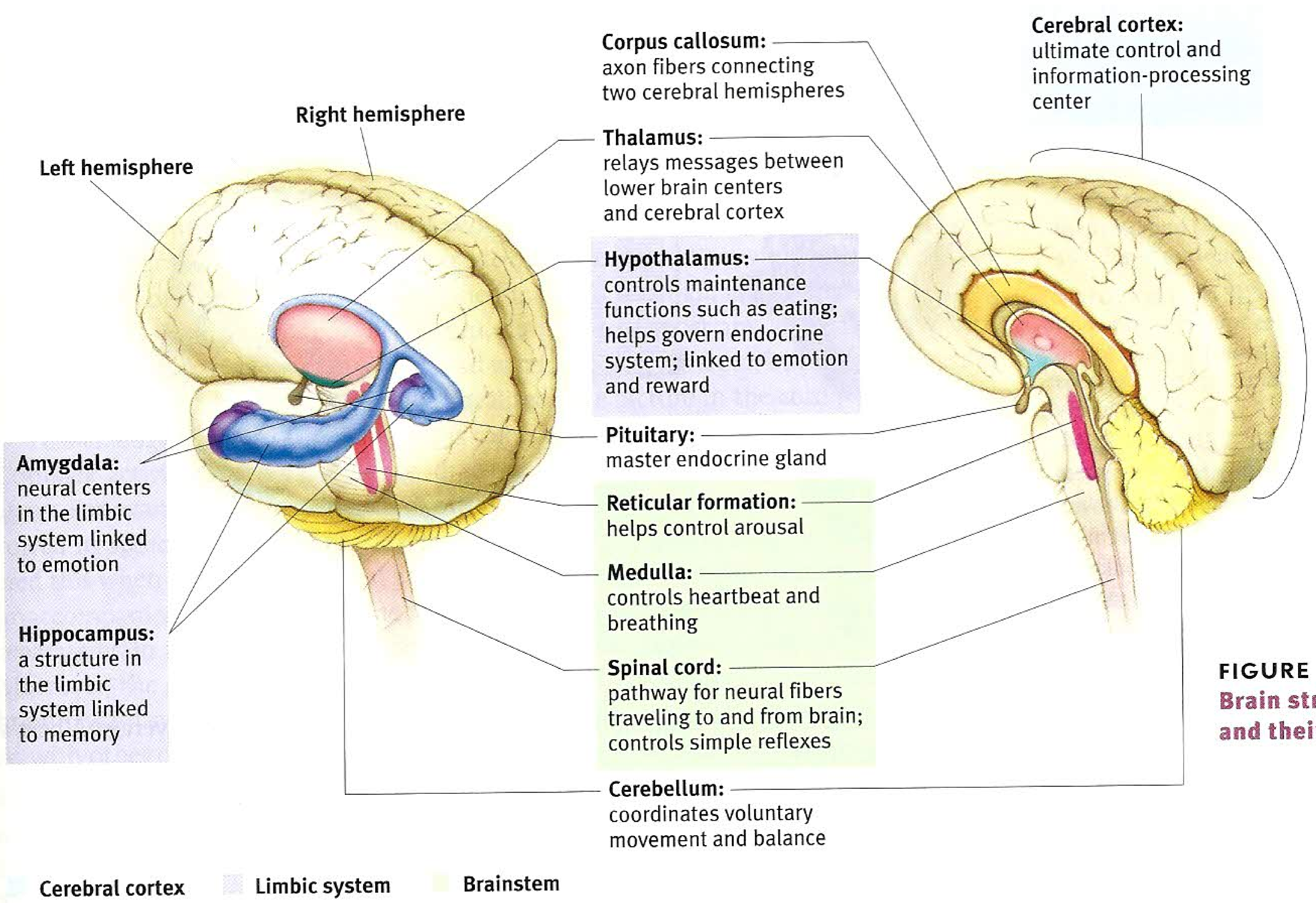


FIGURE 2.23
Brain structures and their functions

your body's ultimate control and information-processing center. (**FIGURE 2.23** locates the cerebral cortex as well as other brain areas discussed in this chapter.)

With the expansion of the cerebral cortex, tight genetic controls relax and the organism's adaptability increases. Frogs and other amphibians have a small cortex and operate extensively on preprogrammed genetic instructions. The larger cortex of mammals offers increased capacities for learning and thinking, enabling them to be more adaptable. What makes us distinctively human mostly arises from the complex functions of our brain's thinking crown, its cerebral cortex.

The people who first dissected and labeled the brain used the language of scholars—Latin and Greek. Their words are actually attempts at graphic description: For example, *cortex* means "bark," *cerebellum* is "little brain," and *thalamus* is "inner chamber."

Structure of the Cortex

OBJECTIVE 15 | Identify the four lobes of the cerebral cortex.

If you opened a human skull, exposing the brain, you would see a wrinkled organ, shaped somewhat like the meat of an oversized walnut. Eighty percent of the brain's weight lies in the ballooning left and right cerebral hemispheres, which are mostly filled with axon connections between the brain's surface and its other regions. The cerebral cortex—the brain hemispheres' thin surface layer—contains some 20 to 23 billion nerve cells (an estimate projected by sampling square-millimeter columns of cortical tissue [de Courten-Myers, 2002]).

Supporting these billions of nerve cells are nine times as many spidery **glial cells**—"glue cells" that guide neural connections, provide nutrients and insulating myelin, and mop up ions and neurotransmitters. Neurons are like queen bees; on their own they cannot feed or sheathe themselves. Glial cells are neural nannies. New evidence suggests they may also play a role in learning and thinking. By "chatting" with neurons they may participate in information transmission and memory (Travis, 1994). Moving up the ladder of animal life, the proportion of glia to neurons increases. A recent post-mortem analysis of Einstein's brain did not find more or larger-than-usual neurons,

- **cerebral** [seh-REE-bruhl] **cortex** the intricate fabric of interconnected neural cells that covers the cerebral hemispheres; the body's ultimate control and information-processing center.
- **glial cells (glia)** cells in the nervous system that support, nourish, and protect neurons.

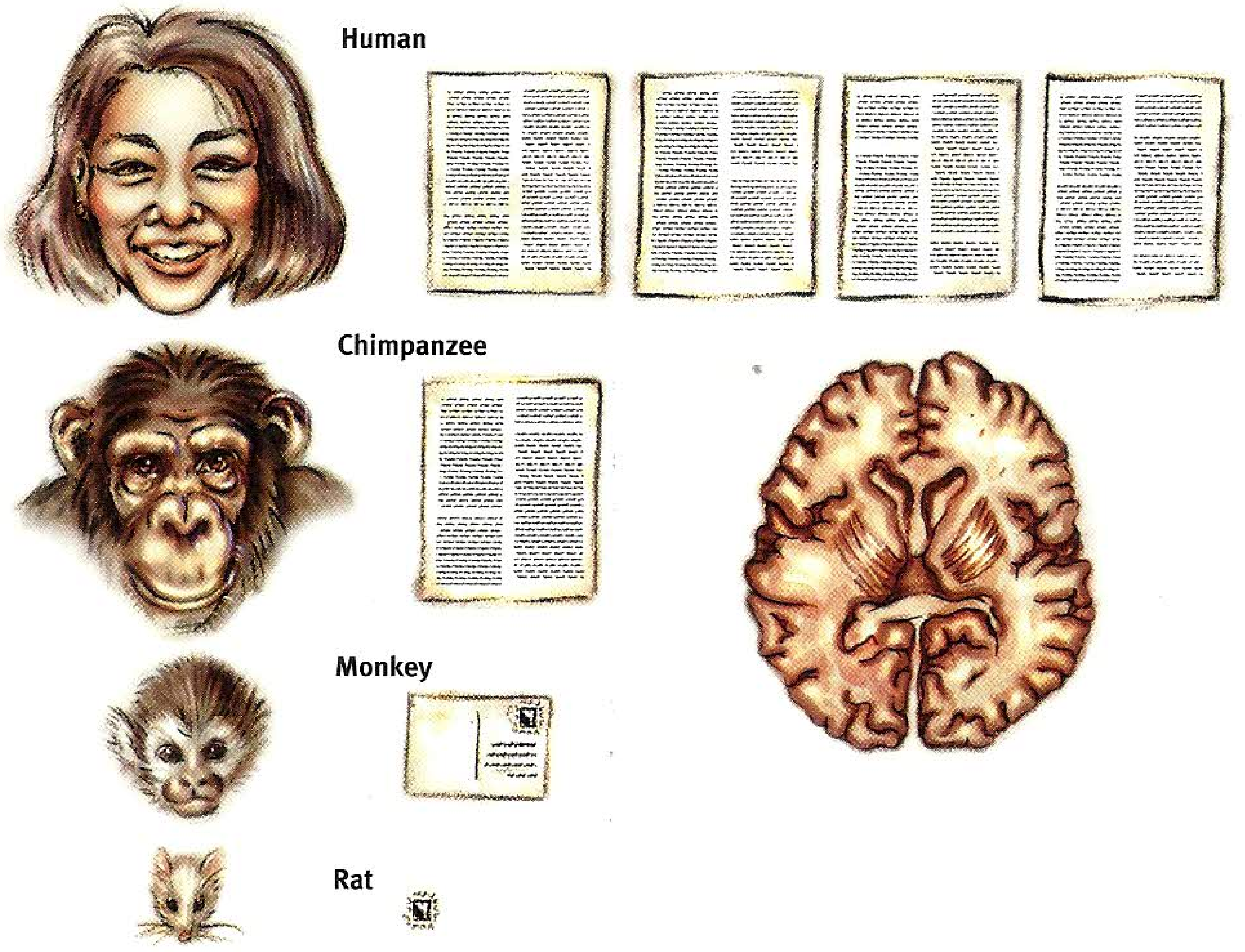


FIGURE 2.24
The cerebral cortex
If flattened, a human cortex would cover about four pages of this book. A chimpanzee's would cover one page, a monkey's a postcard, and a rat's a postage stamp (Calvin, 1996).

but it did reveal a much greater concentration of glia than found in an average Albert's head (Fields, 2004).

Looking at a human brain, the first thing you would notice about the cerebral cortex is its wrinkled surface, only about one-third of which would be visible. These folds greatly increase the brain's surface area. If flattened, the brain's surface would be roughly the size of a large pizza. (To fit a thin pizza crust inside a skull, we would need to crumple it up.) In rats and other lower mammals, the cortex surface is smoother, with less neural fabric (**FIGURE 2.24**).

Each brain hemisphere is divided into four *lobes,* geographic subdivisions separated by prominent *fissures,* or folds (**FIGURE 2.25**). Starting at the front of your brain and going around over the top, there are the **frontal lobes** (behind your forehead), the **parietal lobes** (at the top and to the rear), the **occipital lobes** (at the back of your head), and the **temporal lobes** (on the sides of your head, just above your ears). Each lobe carries out many functions, and many functions require the interplay of several lobes.

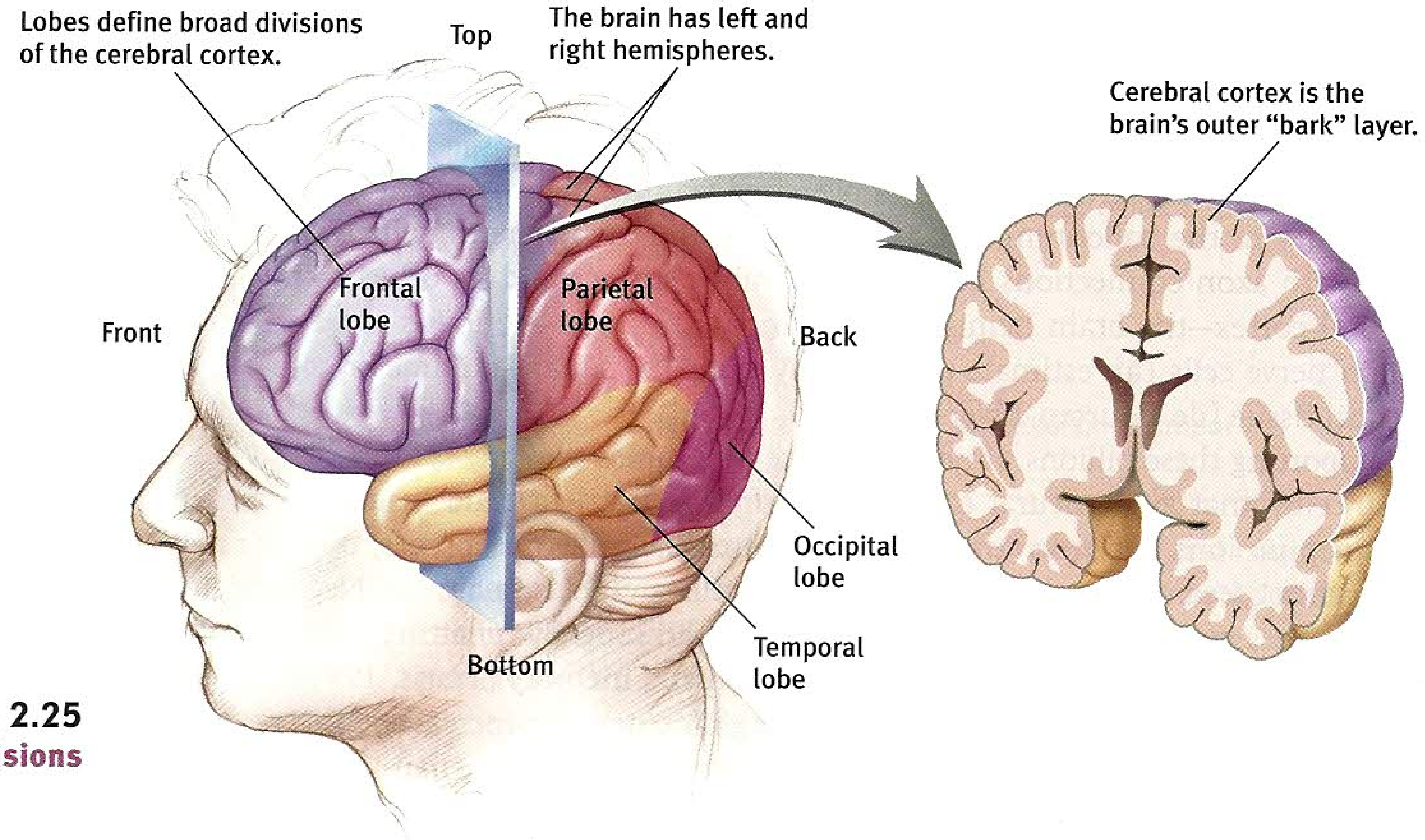


FIGURE 2.25
The cortex and its basic subdivisions

Functions of the Cortex

OBJECTIVE 16 | Summarize some of the findings on the functions of the motor cortex and the sensory cortex, and discuss the importance of the association areas.

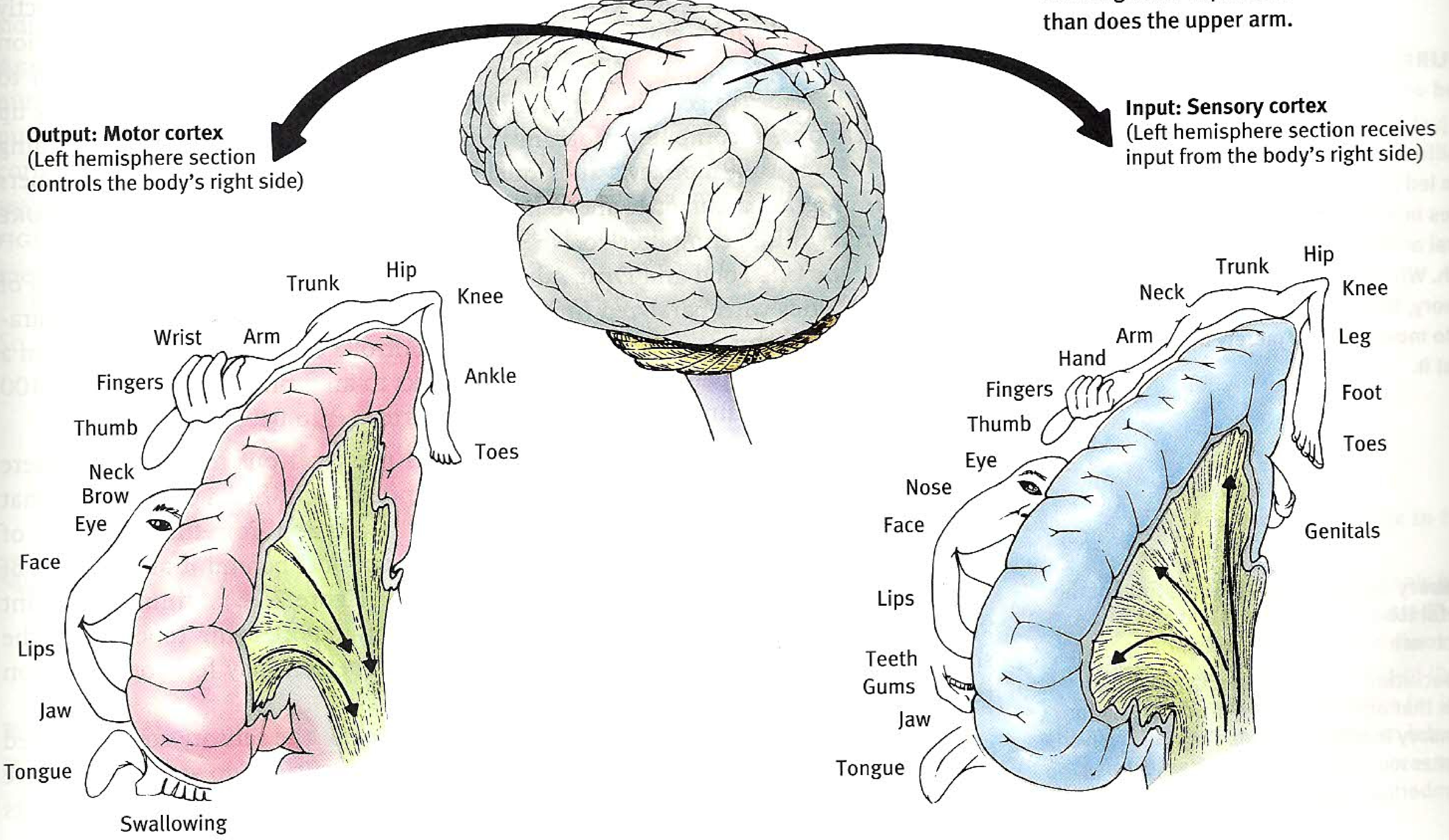
More than a century ago, autopsies of people partially paralyzed or speechless revealed damaged cortical areas. But this rather crude evidence did not convince researchers that specific parts of the cortex perform specific functions. After all, if control of speech and movement were diffused across the cortex, damage to almost any area might produce the same effect. A television would go dead with its power cord cut, but we would be deluding ourselves if we thought we had "localized" the picture in the cord.

This analogy reminds us how easy it is to err when trying to localize brain functions. Complex activities such as speaking, drawing, and shooting pool involve many brain areas. For example, our experience of vocal music integrates brain activity in areas involved in speech and music processing. Mereille Besson and colleagues (1998) discovered this when recording electrical activity in the brains of French musicians listening to unaccompanied operatic solos. The musicians' brains processed the lyrics and tunes in separate brain areas en route to their experiencing "the exquisite unity of vocal music." Moreover, the spine-tingling thrills that music lovers enjoy appear to activate the same brain reward systems that are stimulated by sex and pleasing foods (Weinberger, 2004). As with other complex activities and experiences, music engages multiple brain areas.

Motor Functions Scientists have, however, localized simpler brain functions. For example, in 1870, when German physicians Gustav Fritsch and Eduard Hitzig applied mild electrical stimulation to the cortexes of dogs, they made an important discovery: They could make different body parts move. The effects were selective: Stimulation caused movement only when applied to an arch-shaped region at the back of the frontal lobe, running roughly from ear to ear across the top of the brain. This arch we now call the **motor cortex** (**FIGURE 2.26**). Moreover, when the researchers stimulated specific parts of this region in the left or right hemisphere, specific body parts moved on the *opposite* side of the body.

- **frontal lobes** the portion of the cerebral cortex lying just behind the forehead; involved in speaking and muscle movements and in making plans and judgments.
- **parietal** [puh-RYE-uh-tuhl] **lobes** the portion of the cerebral cortex lying at the top of the head and toward the rear; receives sensory input for touch and body position.
- **occipital** [ahk-SIP-uh-tuhl] **lobes** the portion of the cerebral cortex lying at the back of the head; includes the visual areas, which receive visual information from the opposite visual field.
- **temporal lobes** the portion of the cerebral cortex lying roughly above the ears; includes the auditory areas, each of which receives auditory information primarily from the opposite ear.
- **motor cortex** an area at the rear of the frontal lobes that controls voluntary movements.

FIGURE 2.26
Left hemisphere tissue devoted to each body part in the motor cortex and the sensory cortex
As you can see from this classic though inexact representation, the amount of cortex devoted to a body part is not proportional to that part's size. Rather, the brain devotes more tissue to sensitive areas and to areas requiring precise control. Thus, the fingers have a greater representation in the cortex than does the upper arm.



Demonstration: Try moving your right hand in a circular motion, as if polishing a table. Now start your right foot doing the same motion synchronized with the hand. Now reverse the foot motion (but not the hand). Tough, huh? But easier if you try moving the *left* foot opposite to the right hand. The left and right limbs are controlled by opposite sides of the brain. So their opposed activities interfere less with one another.

Mapping the Motor Cortex A half-century ago, neurosurgeons Otfrid Foerster in Germany and Wilder Penfield in Montreal mapped the motor cortex in hundreds of wide-awake patients. Before putting the knife to the brain, the surgeons needed to know the possible side effects of removing different parts of the cortex. They painlessly (the brain has no sensory receptors) stimulated different cortical areas and noted the body responses. Like Fritsch and Hitzig, they found that when they stimulated different areas of the motor cortex at the back of the frontal lobe, different body parts moved. (Kids, don't try this without parental supervision.) They were now able to map the motor cortex according to the body parts it controlled (Figure 2.26). Interestingly, those areas of the body requiring precise control, such as the fingers and mouth, occupied the greatest amount of cortical space.

Neuroscientist José Delgado repeatedly demonstrated the mechanics of motor behavior. In one human patient, he stimulated a spot on the left motor cortex that triggered the right hand to make a fist. Asked to keep the fingers open during the next stimulation, the patient, whose fingers closed despite his best efforts, remarked, "I guess, Doctor, that your electricity is stronger than my will" (Delgado, 1969, p. 114). Scientists have also been able to predict a monkey's arm motion a tenth of a second before it moves—by repeatedly measuring motor cortex activity preceding specific arm movements (Gibbs, 1996).

Neural Prosthetics By similarly eavesdropping on the brain, could we enable someone—perhaps a paralyzed person—to move a robotic limb or command a cursor to write e-mail or surf the Web? To find out, Brown University brain researchers implanted 100 tiny recording electrodes in the motor cortexes of three monkeys (Nicolelis & Chapin, 2002; Serruya & others, 2002). As the monkeys used a joystick to move a cursor to follow a moving red target (to gain rewards), the researchers matched the brain signals with the arm movements. Then they let their computer operate the joystick. When a monkey merely thought about a move, the mind-reading computer moved the cursor with nearly the same proficiency as the monkey.

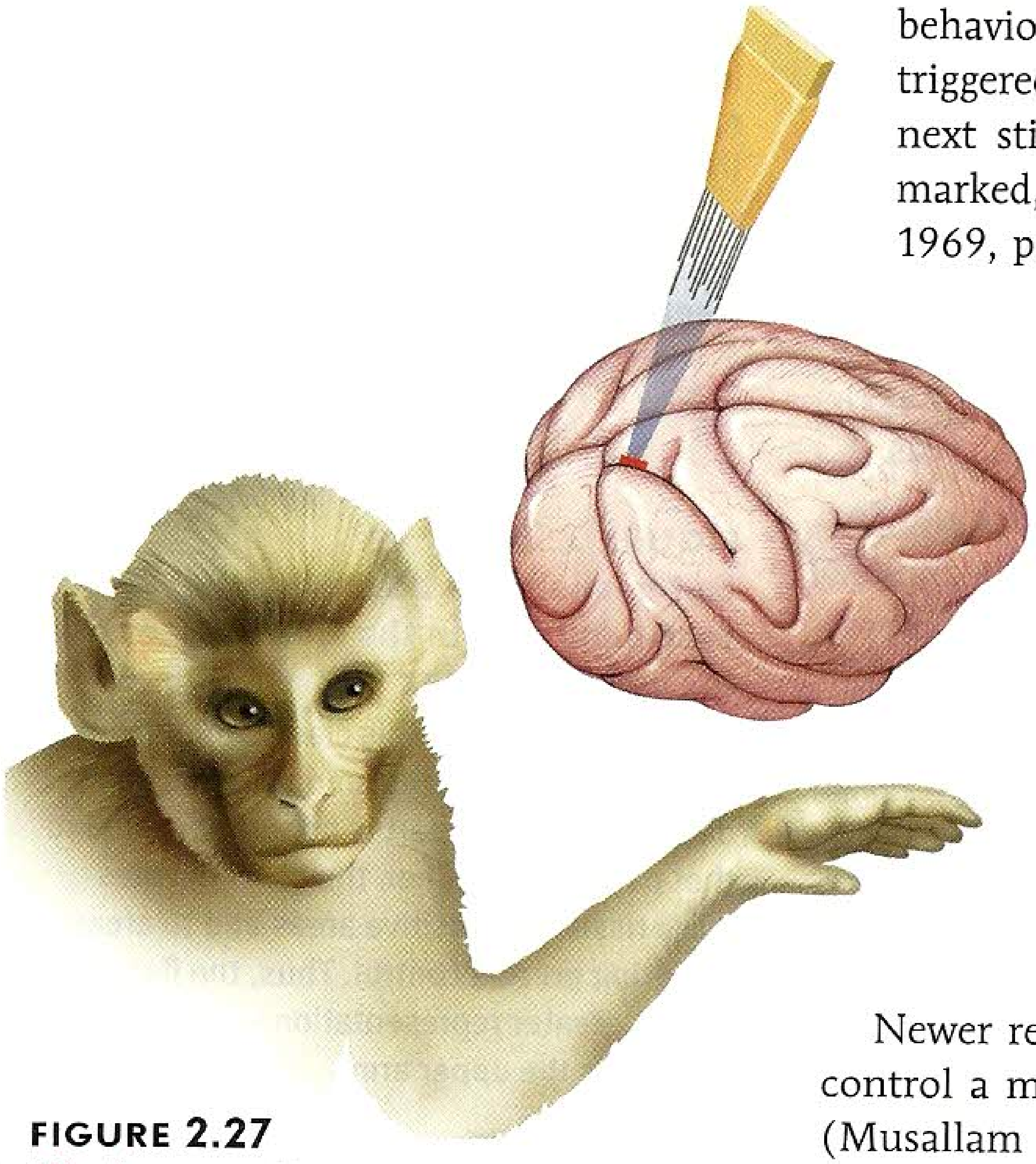


FIGURE 2.27
Mind over matter
Can just thinking make something happen? A California Institute of Technology research team led by Sam Musallam implanted electrodes in a parietal lobe region and recorded neural activity as a monkey planned to reach. When programmed into a computer's memory, this activity then enabled the monkey to move a cursor merely by thinking about it.

Newer research has recorded messages not from the motor neurons that directly control a monkey's arm, but from a brain area involved in planning and intention (Musallam & others, 2004). While the monkeys awaited a cue that told them to reach toward a spot (to get a juice reward) that had flashed on a screen in one of up to eight locations, a computer program recorded their neural activity. By matching the brain activity to a monkey's subsequent pointing, the mind-reading researchers could now program a cursor to move in response to the monkey's thinking (**FIGURE 2.27**). Monkey think, computer do.

In 2004, the U.S. Food and Drug Administration approved the first clinical trial of neural prosthetics with paralyzed humans (Pollack, 2004). The first patient, a paralyzed 25-year-old man, is now able to mentally control a television, draw shapes on a computer screen, and play video games—all thanks to an aspirin-sized chip with 100 microelectrodes recording activity in his motor cortex (Patoine, 2005).

Sensory Functions

If the motor cortex sends messages out to the body, where does the cortex receive the *incoming* messages? Penfield identified a cortical area that specializes in receiving information from the skin senses and from the movement of body parts. This area, parallel to the motor cortex and just behind it at the front of the parietal lobes, we now call the **sensory cortex** (Figure 2.26). Stimulate a point on the top of this band of tissue, and a person may report being touched on the shoulder; stimulate some point on the side, and the person may feel something on the face.

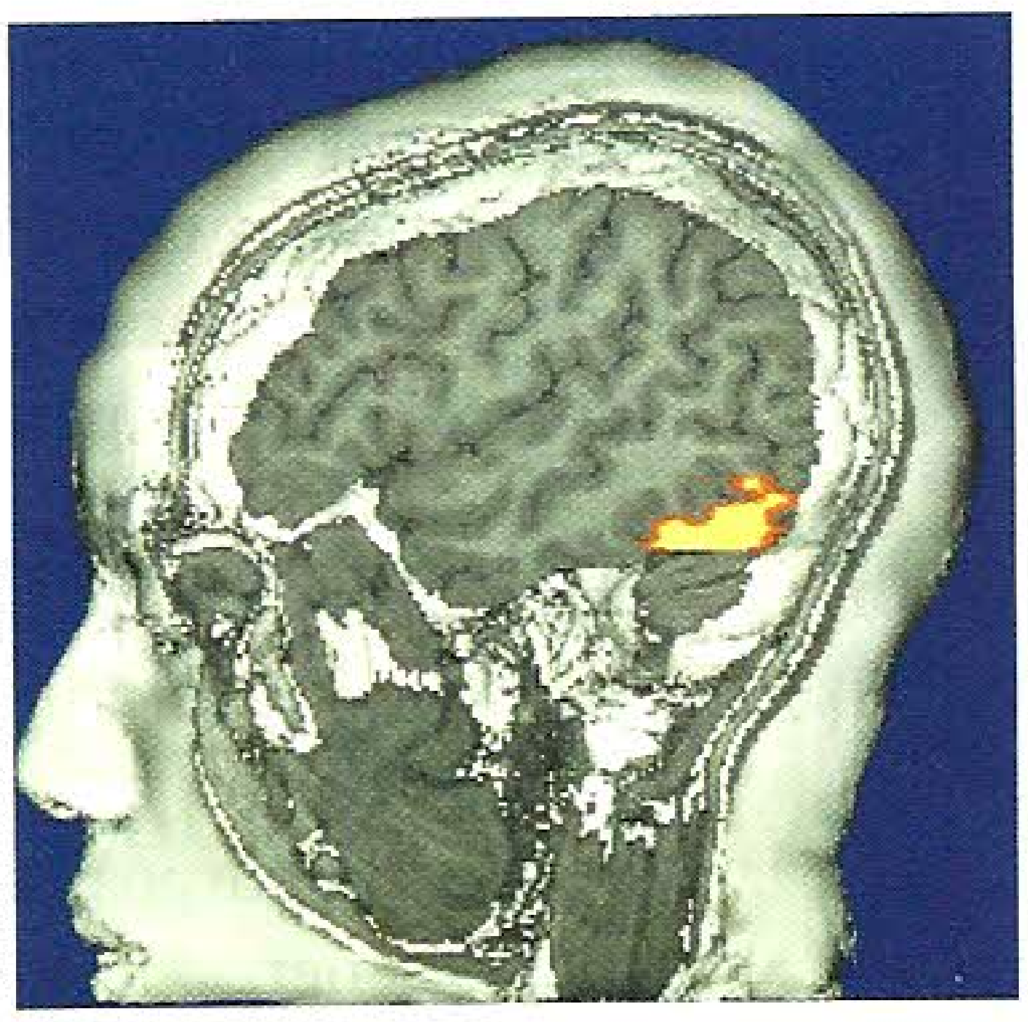
The more sensitive a body region, the larger the area of the sensory cortex devoted to it; your supersensitive lips project to a larger brain area than do your toes (Figure 2.26). (That's one reason we kiss with our lips rather than touch toes.) Similarly, rats

■ **sensory cortex** the area at the front of the parietal lobes that registers and processes body touch and movement sensations.

■ **association areas** areas of the cerebral cortex that are not involved in primary motor or sensory functions; rather, they are involved in higher mental functions such as learning, remembering, thinking, and speaking.

have a large area of the brain devoted to their whisker sensations, owls to their hearing sensations, and so forth.

Scientists have identified other areas where the cortex receives input from senses other than touch. At this moment, you are receiving visual information in the occipital lobes at the very back of your brain (**FIGURE 2.28**). A bad enough bash there would make you blind. Stimulated there, you might see flashes of light or dashes of color. (In a sense, we *do* have eyes in the back of our head!) From your occipital lobes, visual information goes to other areas that specialize in tasks such as identifying words, detecting emotions, and recognizing faces.



Courtesy of V. P. Clark, K. Keill, J. Ma. Maisog, S. Courtney, L. G. Ungerleider, and J. V. Haxby, National Institute of Mental Health

FIGURE 2.28
New technology shows the brain in action
This functional MRI scan shows the visual cortex—the occipital lobes—activated (color representation of increased bloodflow) as the subject looks at faces. When the person stops looking at faces, the region instantly calms down.

Any sound you now hear is processed by the auditory areas in your temporal lobe (**FIGURE 2.29**). (If you think of your clenched fist as a brain, and hold it in front of you, your thumb would roughly correspond to the temporal lobe.) Most of this auditory information travels a circuitous route from one ear to the auditory receiving area above your opposite ear. If you were stimulated there, you might hear a sound. The sound needn't be real. MRI scans of people with schizophrenia reveal that auditory areas of the temporal lobe are active during auditory hallucinations (Lennox & others, 1999). Even the phantom ringing sound experienced by people with hearing loss is—if heard in one ear—associated with activity in the temporal lobe on the brain's opposite side (Muhlnickel, 1998).

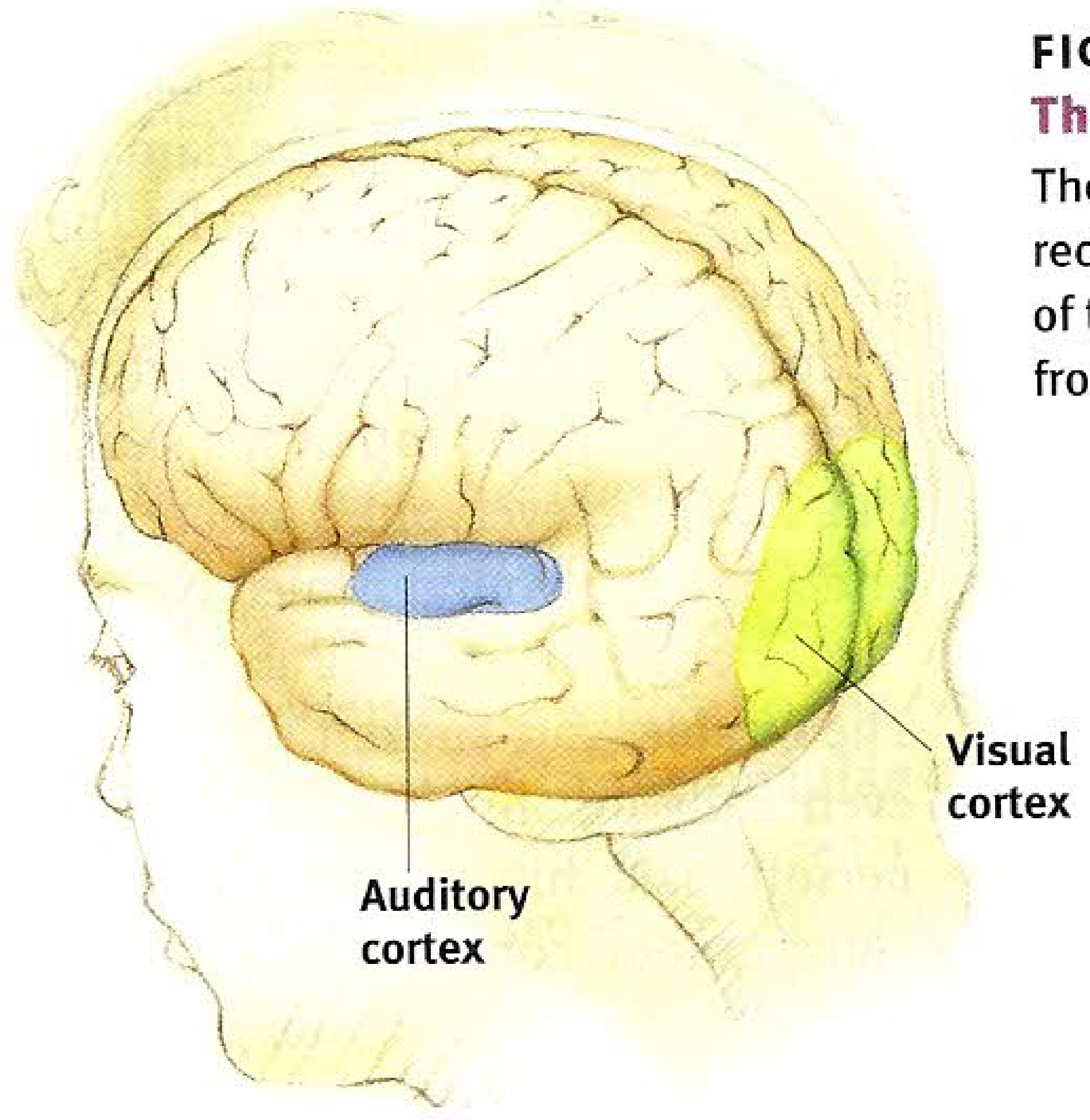


FIGURE 2.29
The visual cortex and auditory cortex
The occipital lobes at the rear of the brain receive input from the eyes. An auditory area of the temporal lobes receives information from the ears.

Association Areas

So far, we have pointed out small areas of the cortex that either receive sensory input or direct muscular output. In humans, that leaves a full three-fourths of the thin wrinkled layer, the cerebral cortex, uncommitted to sensory or muscular activity. What then goes on in this vast region of the brain? Neurons in these **association areas** (the peach-colored areas in **FIGURE 2.30**) integrate information. They associate various sensory inputs with stored memories—a very important part of thinking.

Electrically probing the association areas doesn't trigger any observable response. So, unlike the sensory and motor areas, we can't so neatly specify the functions of the

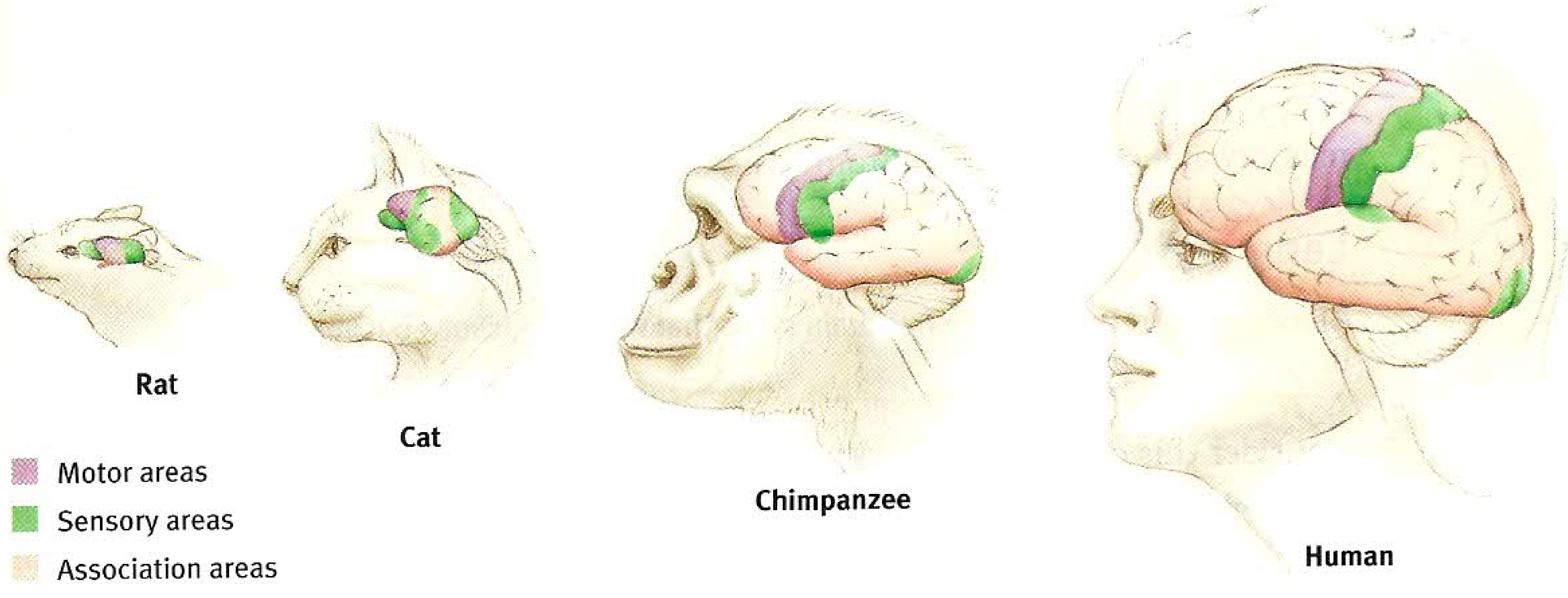


FIGURE 2.30
Areas of the cortex in four mammals
More intelligent animals have increased "uncommitted" or association areas of the cortex. These vast areas of the brain are responsible for integrating and acting on information received and processed by sensory areas.

association areas. Their silence seems to have led to one of pop psychology's most widespread falsehoods: that we ordinarily use only 10 percent of our brains (as if the odds are 90 percent that a bullet to your brain would land in an area you don't use). This fabrication—"one of the hardiest weeds in the garden of psychology," writes Donald McBurney (1996, p. 44)—implies that if we could activate our whole brain, we would be far smarter than those who drudge along on 10 percent brain power. But surgically lesioned animals and brain-damaged humans bear witness that the association areas are not dormant. (The brain has no appendix—no apparently purposeless tissue. Moreover, given that brain tissue demands a lot of energy, nature would not squander resources on unused brain.) Rather, these areas interpret, integrate, and act on information processed by the sensory areas.

Association areas are found in all four lobes. In the frontal lobes, these areas enable us to judge, plan, and process new memories. People with damaged frontal lobes may have intact memories, score high on intelligence tests, and be able to bake a cake—yet be unable to plan ahead to *begin* baking the cake for the birthday party.

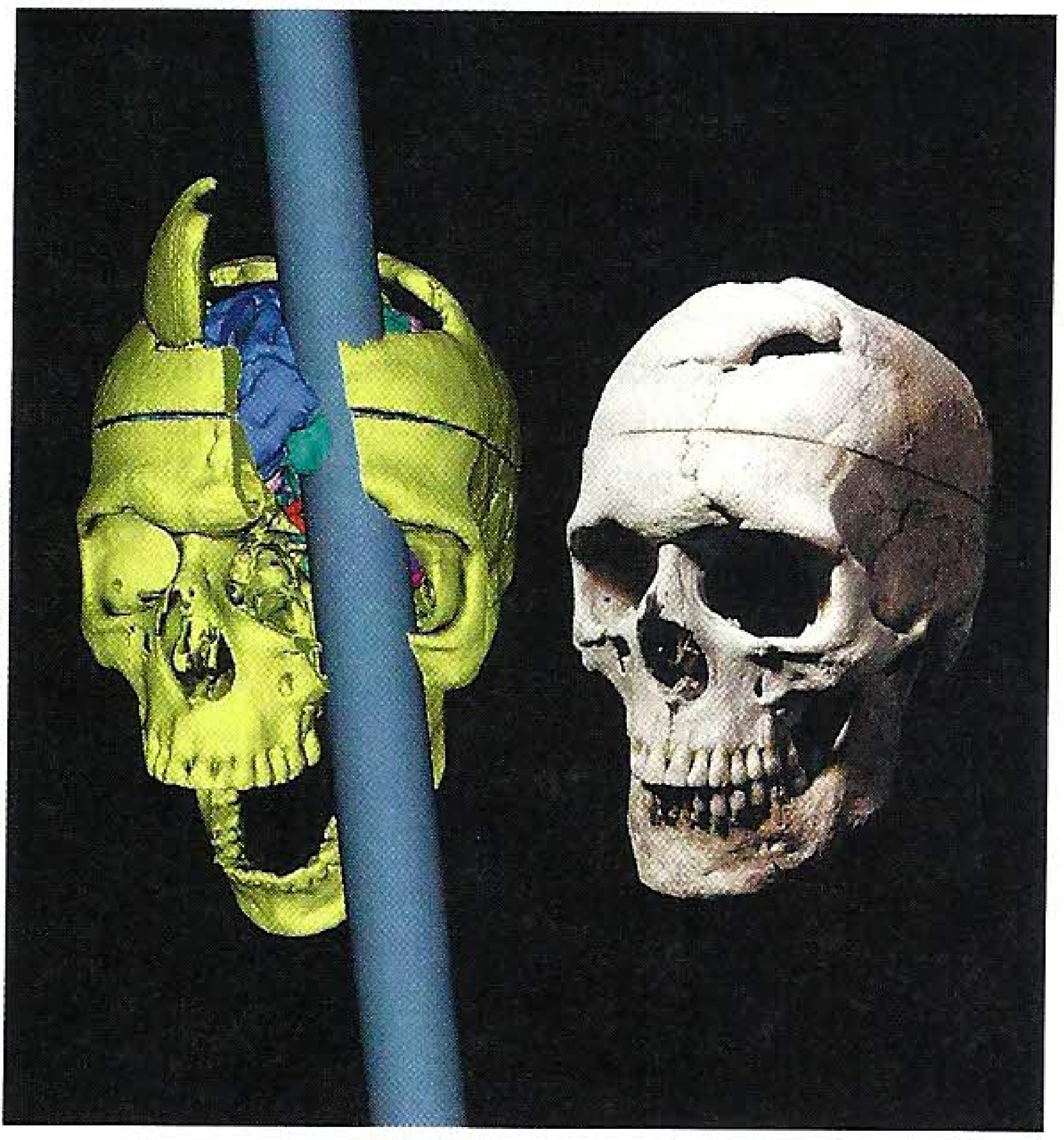


FIGURE 2.31
Phineas Gage reconsidered
Using measurements of his skull (which was kept as a medical record) and modern neuroimaging techniques, researcher Hanna Damasio and her colleagues (1994) have reconstructed the probable path of the rod through Gage's brain.

Frontal lobe damage also can alter personality, removing a person's inhibitions. Consider the classic case of railroad worker Phineas Gage. One afternoon in 1848, Gage, then 25 years old, was packing gunpowder into a rock with a tamping iron. A spark ignited the gunpowder, shooting the rod up through his left cheek and out the top of his skull, leaving his frontal lobes massively damaged (**FIGURE 2.31**). To everyone's amazement, Gage was immediately able to sit up and speak, and after the wound healed he returned to work.

Although his mental abilities and memories were intact, his personality was not. The affable, soft-spoken Phineas Gage was now irritable, profane, and dishonest. He eventually lost his job and ended up earning his living as a fairground exhibit. This person, said his friends, was "no longer Gage." With his frontal lobes ruptured, Gage's moral compass became disconnected from his behavior.

The same loss of moral compass was recently discovered to be true of two people who as young children had experienced frontal lobe damage similar to Gage's. Both of these individuals recovered, but they also matured as morally deficient—stealing, lying, and abusing and neglecting their out-of-wedlock children without remorse (Dolan, 1999). Although raised in good homes, they seemingly didn't know right from wrong.

Other association areas also perform mental functions. For example, the parietal lobes, parts of which were large and unusually shaped in Einstein's normal-weight brain, enable mathematical and spatial reasoning (Witelson & others, 1999). An area on the underside of the right temporal lobe enables us to recognize faces. If a stroke or head injury destroyed this area of your brain, you would still be able to describe facial features and to recognize someone's gender and approximate age, yet be strangely unable to identify the person as, say, Britney Spears or even your grandmother. But by and large, complex mental functions such as learning and memory don't reside in any one place. There is no one spot in a rat's small association cortex that, when damaged, will obliterate its ability to learn or remember a maze. Complex human abilities, such as memory and language, result from the intricate coordination of many brain areas.

Language

OBJECTIVE 17 | Describe the five brain areas that would be involved if you read this sentence aloud.

Consider this curious finding: Damage to any one of several cortical areas can cause **aphasia,** an impaired use of language. It is even more curious that some people with aphasia can speak fluently but cannot read (despite good vision), while others can comprehend what they read but cannot speak. Still others can write but not read, read but not write, read numbers but not letters, or sing but not speak. This is puzzling, because we think of speaking and reading, or writing and reading, or singing and speaking as merely different examples of the same general ability. So, how did researchers solve the mystery of how we use language? Consider these clues, which fit together as neatly as Lego blocks in a toy house.

Clue 1 In 1865, French physician Paul Broca reported that after damage to a specific area of the left frontal lobe (later called **Broca's area**) a person would struggle to speak words while still being able to sing familiar songs and comprehend speech.

Clue 2 In 1874, German investigator Carl Wernicke discovered that after damage to a specific area of the left temporal lobe (**Wernicke's area**) people could speak only meaningless words. Asked to describe a picture that showed two boys stealing cookies behind a woman's back, one patient responded: "Mother is away her working her work to get her better, but when she's looking the two boys looking the other part. She's working another time" (Geschwind, 1979).

Clue 3 It was later discovered that reading aloud involves a third brain area. The *angular gyrus* receives the visual information from the visual area and recodes it into the auditory form, which Wernicke's area uses to derive its meaning.

Clue 4 Nerve fibers interconnect these brain areas.

Norman Geschwind assembled these clues into an explanation of how we use language (**FIGURES 2.32 AND 2.33**, page 82). When you read aloud, the words (1) register in the visual area, (2) are relayed to a second brain area, the *angular gyrus,* which transforms the words into an auditory code that is (3) received and understood in the nearby Wernicke's area and (4) sent to Broca's area, which (5) controls the motor cortex as it creates the pronounced word. Depending on which link in this chain is damaged, a different form of aphasia occurs. Damage to the angular gyrus leaves the person able to speak and understand but unable to read. Damage to Wernicke's area disrupts understanding. Damage to Broca's area disrupts speaking. The now-familiar principle bears repeating: *Complex abilities result from the intricate coordination of many brain areas.*

Said another way, the brain operates by dividing its mental functions—speaking, perceiving, thinking, remembering—into subfunctions. Our conscious experience

aphasia impairment of language, usually caused by left hemisphere damage either to Broca's area (impairing speaking) or to Wernicke's area (impairing understanding).

Broca's area controls language expression—an area of the frontal lobe, usually in the left hemisphere, that directs the muscle movements involved in speech.

Wernicke's area controls language reception—a brain area involved in language comprehension and expression; usually in the left temporal lobe.

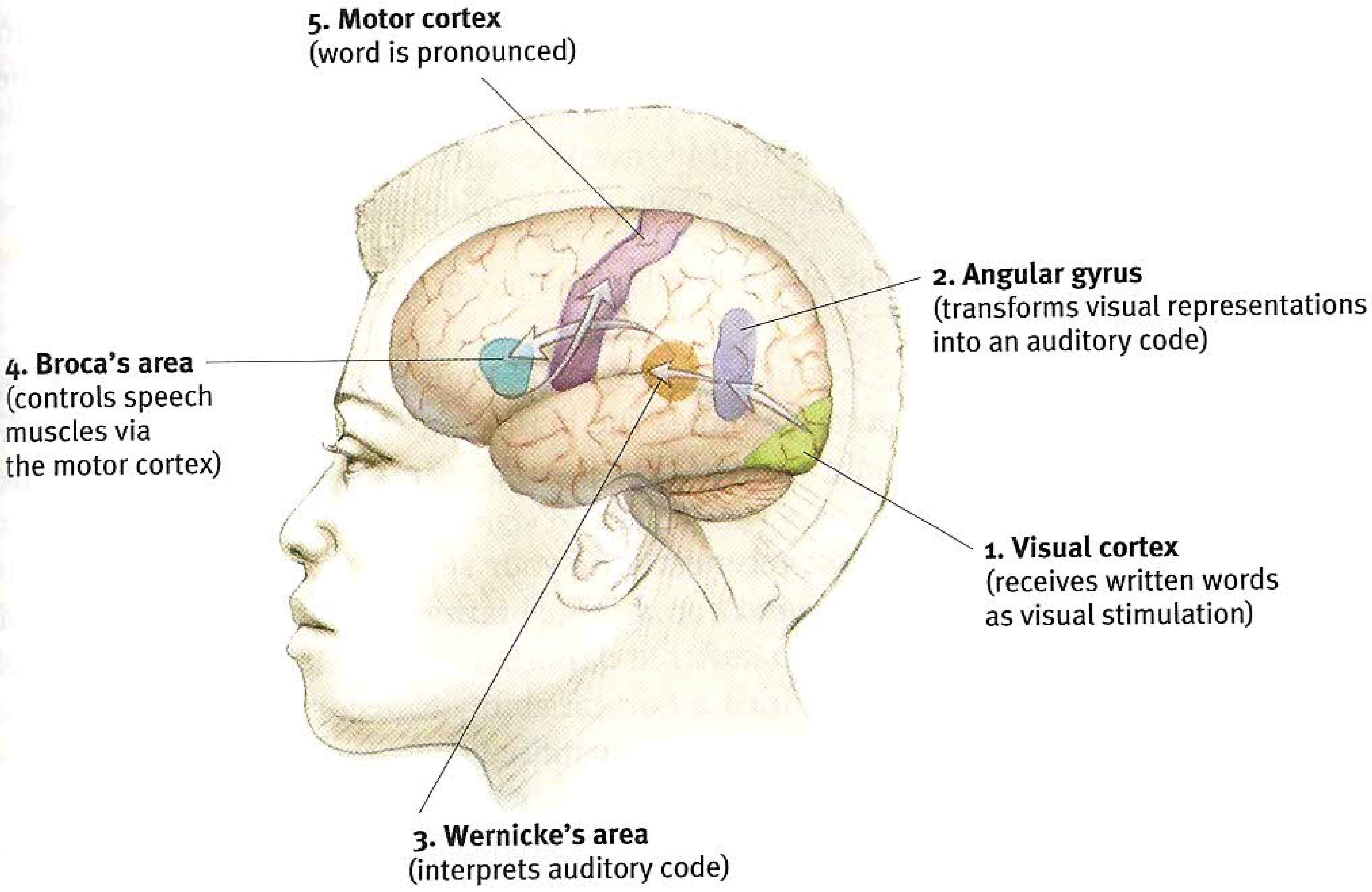
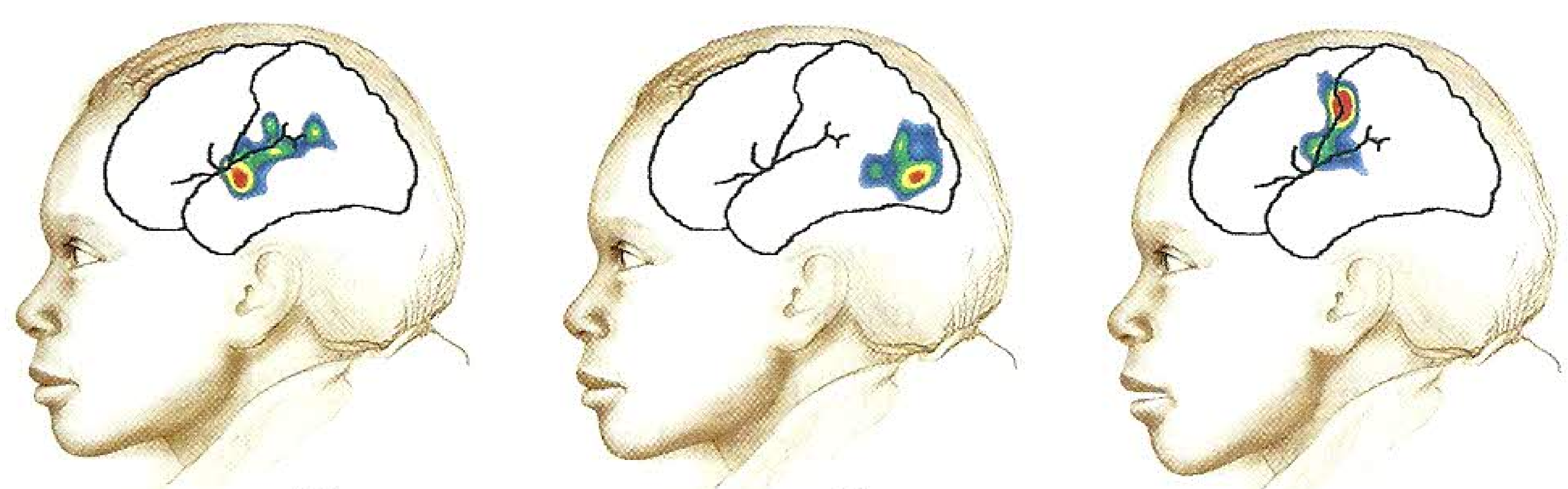


FIGURE 2.32
Specialization and integration in language

FIGURE 2.33
Brain activity when hearing, seeing, and speaking words
PET scans such as these detect the activity of different areas of the brain.



(a)
Hearing words
(auditory cortex and Wernicke's area)

(b)
Seeing words
(visual cortex and angular gyrus)

(c)
Speaking words
(Broca's area and the motor cortex)

seems indivisible. Right now, assuming you have sight, you are experiencing a whole visual scene as if your eyes were video cameras projecting the scene into your brain. Actually, as you will see in Chapter 5, your brain breaks vision into specialized subtasks, such as discerning color, depth, movement, and form. (After a localized stroke that destroys one of these neural work teams, people may lose just one aspect of vision, such as the ability to perceive movement.) Each of these specialized neural networks, having simultaneously done its own thing, then feeds its information to "higher-level" networks that combine the atoms of experience and relay them to progressively higher-level association areas, enabling us to recognize a face as "Grandmother."

The same is true of reading a word: The brain computes the word's form, sound, and meaning using different neural networks (Posner & Carr, 1992). Thus fMRI scans show that jokes playing on meaning ("Why don't sharks bite lawyers? . . . Professional courtesy") are processed in a different brain area than jokes playing on words ("What kind of lights did Noah use on the ark? . . . Flood lights") (Goel & Dolan, 2001). Think about it: *What you experience as a continuous, indivisible stream of perception is actually but the visible tip of the information-processing iceberg, most of which lies beneath the surface of your conscious awareness.*

To sum up, the mind's subsystems are localized in particular brain regions, yet the brain acts as a unified whole. Moving your hand; recognizing faces; even perceiving color, motion, and depth—all depend on specific neural networks. Yet complex functions such as listening, learning, and loving involve the coordination of many brain areas. Together, these two principles—specialization and integration—describe the brain's functioning.

The Brain's Plasticity

OBJECTIVE 18 | Discuss the brain's plasticity following injury or illness.

The brain is sculpted not only by our genes but also by our experiences. In Chapter 3, we'll focus more on how experience molds the brain, but for now, let's turn to evidence from studies of the brain's **plasticity,** its ability to modify itself after some types of damage.

Most severed neurons will not regenerate (if your spinal cord were severed, you likely would be permanently paralyzed). And some brain functions seem preassigned to particular areas. A newborn who suffered damage to the facial recognition areas on both temporal lobes never regained a normal ability to recognize faces (Farah & others, 2000). But some neural tissue can *reorganize* in response to damage. It happens within all of us, as the brain repairs itself after little mishaps. Plasticity is especially evident after serious damage. Lose a finger and the sensory cortex that received

plasticity the brain's capacity for modification, as evident in brain reorganization following damage (especially in children) and in experiments on the effects of experience on brain development.

its input will begin to receive input from the adjacent fingers, which then become more sensitive (Fox, 1984). MRI scans show that well-practiced pianists likewise have a larger-than-usual auditory cortex area that encodes piano sounds (Bavelier & others, 2000; Pantev & others, 1998). Our brains are most plastic when we are young children (Kolb, 1989; see **FIGURE 2.34**).

The brain's plasticity is good news for those blind or deaf. If a blind person uses one finger to read Braille, the brain area dedicated to that finger expands as the sense of touch invades the visual cortex that normally helps people see (Barinaga, 1992a; Sadato & others, 1996). Temporarily "knock out" the visual cortex with magnetic stimulation, and a lifelong-blind person will make more errors on a *language* task (Amedi & others, 2004). In deaf people whose native language is sign, the temporal lobe area normally dedicated to auditory information waits in vain for stimulation. Finally, it looks for other signals to process, such as those from the visual system. That helps explain why some studies find that deaf people have enhanced peripheral vision (Bosworth & Dolkins, 1999).

If a body part is amputated, sensory fibers that terminate on adjacent areas of the sensory cortex may invade the brain tissue that's no longer receiving sensory input. As Figure 2.26 on page 77 shows, the hand is between the face and the arm regions on the sensory cortex. This explains a mysterious phenomenon: When stroking the face of someone whose hand had been amputated, V. S. Ramachandran found the person felt the sensations not only on his face but also on his nonexistent ("phantom") fingers. Ditto when stroking the arm, whose sensory fibers had also invaded the brain area vacated by the hand. Note, too, that the toes region is adjacent to the genitals. So what do you suppose was the sexual intercourse experience of another Ramachandran patient whose lower leg had been amputated? "I actually experience my orgasm in my foot. And there it's much bigger than it used to be because it's no longer just confined to my genitals" (Ramachandran & Blakeslee, 1998, p. 36).

Although brain modification often takes the form of reorganization, new evidence suggests that, contrary to long-held belief, adult mice and humans can also, in two older brain regions, generate new brain cells (Kempermann & Gage, 1999; Van Praag & others, 2002). Moreover, monkey brains form thousands of new neurons each day. These baby neurons originate deep in the brain and may then migrate to the thinking frontal lobe and form connections with neighboring neurons (Gould & others, 1999). Master stem cells that can develop into any type of brain cell have also been discovered in the human embryo. If mass-produced in a lab and injected into a damaged brain, might neural stem cells turn themselves into replacements for lost brain cells? Might we someday be able to rebuild damaged brains, much as we reseed damaged lawns? Might new drugs spur the production of new nerve cells? Stay tuned. Today's biotech companies are hard at work on such possibilities (Gage, 2003).

Joe McNally/Joe McNally Photography

FIGURE 2.34
Brain plasticity
If an injury or a surgical procedure destroys one part of a child's brain or, as in the case of this 6-year-old, even an entire *hemisphere* (to eliminate seizures), the brain will compensate by putting other surplus areas to work. One Johns Hopkins medical team, reflecting on the 58 child hemispherectomies they had performed, reports being "awed" by how well children retain their memory, personality, and humor after removal of either brain hemisphere (Vining & others, 1997).

Our Divided Brain

OBJECTIVE 19 | Describe split-brain research, and explain how it helps us understand the functions of our left and right hemispheres.

For more than a century, clinical evidence has shown that the brain's two sides serve differing functions. Accidents, strokes, and tumors in the left hemisphere generally impair reading, writing, speaking, arithmetic reasoning, and understanding. Similar lesions in the right hemisphere seldom have such dramatic effects.

By 1960 the left hemisphere was therefore described as the "dominant" or "major" hemisphere, and its silent companion to the right as the "subordinate" or "minor"

"You wouldn't want to have a date with the right hemisphere."
Michael Gazzaniga (2000)