Structure of the Brain

Learning Outcomes

WHAT YOU NEED TO KNOW

- Differentiate the functions of the major divisions of the brain.
- Explain the functions of the cerebral cortex according to organization across hemispheres, within hemispheres, and within specific lobes.
- Identify the causes and consequences of brain plasticity.

Right now, your neurons and glial cells are busy humming away, giving you potentially brilliant ideas, consciousness, and feelings. But which neurons in which parts of the brain control which functions?

To answer that question, it can be helpful to talk about areas of the brain from "bottom to top," noting how the different regions are specialized for different kinds of tasks. In general, simpler functions are performed at the "lower" levels of the brain, whereas more complex functions are performed at successively "higher" levels (see **FIGURE 3.9a**). The brain can also be approached in a "side-by-side" fashion: Although each side (or "hemisphere") of the brain is roughly analogous, one half of the brain specializes in some tasks that the other half doesn't. Although these divisions make it easier to understand areas of the brain and their functions, keep in mind that none of these structures or areas in the brain can act alone. They all work together to support complex psychological functions (Avena-Koenigsberger et al., 2018; Sporns & Betzel, 2016).

Let's look first at the divisions of the brain, moving from the bottom to the top. Using this view, we can divide the brain into three parts: the hindbrain, the midbrain, and the forebrain (see Figure 3.9a).

ARNO BALZARINI/KEYSTONE/AP PHOTO

The high-wire artist Freddy Nock relied on his cerebellum to coordinate the movements necessary to walk on the rope of the Corvatsch cable car from more than 10,000 feet over sea level down to the base station in Silvaplana, Switzerland.

The Hindbrain

If you follow the spinal cord from your tailbone to where it enters your skull, you'll find it difficult to determine where your spinal cord ends and your brain begins. That's because the spinal cord is continuous with the **hindbrain,** *an area of the brain that coordinates information coming into and out of the spinal cord*. The hindbrain looks like a stalk on which the rest of the brain sits, and it controls the most basic functions of life: respiration, alertness, and motor skills. The structures that make up the hindbrain include the medulla, the reticular formation, the cerebellum, and the pons (see Figure 3.9b).

The **medulla** is *an extension of the spinal cord into the skull that coordinates heart rate, circulation, and respiration*. Beginning inside the medulla and extending upward is a small cluster of neurons called the **reticular formation,** which *regulates sleep, wakefulness, and levels of arousal*. In one early experiment, researchers stimulated the reticular formation of a sleeping cat. This caused the animal to awaken almost instantaneously and remain alert. Conversely, severing the connections between the reticular formation and the rest of the brain caused the animal to lapse into an irreversible coma (Moruzzi & Magoun, 1949). The reticular formation maintains the same delicate balance between alertness and unconsciousness in humans. In fact, many general anesthetics work by reducing activity in the reticular formation, rendering the patient unconscious.

Behind the medulla is the **cerebellum,** *a large structure of the hindbrain that controls fine motor skills*. (*Cerebellum* is Latin for "little brain," and this structure does look like a small replica of the brain.) The cerebellum orchestrates the proper sequence of movements when we ride a bike, play the piano, or maintain balance while walking and running. It contributes to the fine-tuning of behavior: smoothing our actions to allow their graceful execution (Smetacek, 2002). The initiation of behavior involves other areas of the brain.

The last major area of the hindbrain is the **pons,** *a structure that relays information from the cerebellum to the rest of the brain*. (*Pons* means "bridge" in Latin.) Although the detailed functions of the pons remain poorly understood, it essentially acts as a relay station or bridge between the cerebellum and other structures in the brain.

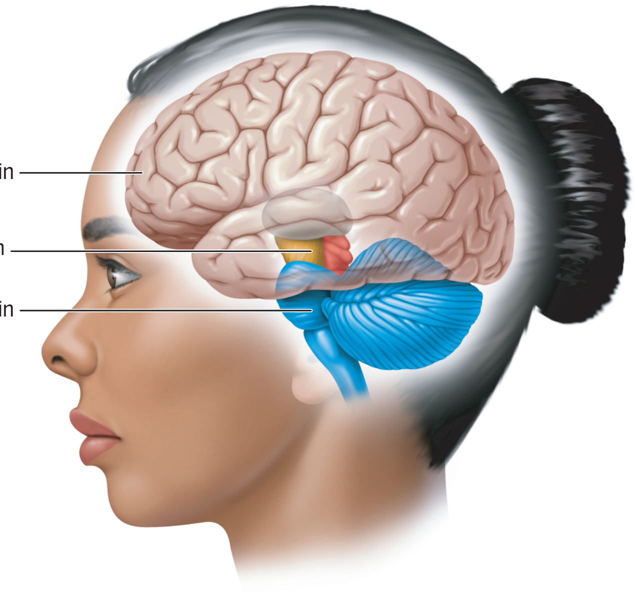
hindbrain The area of the brain that coordinates information coming into and out of the spinal cord.

medulla An extension of the spinal cord into the skull that coordinates heart rate, circulation, and respiration.

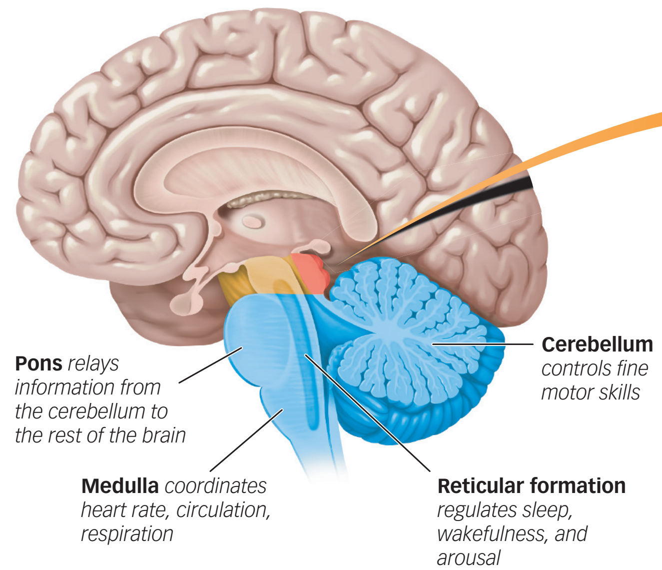
reticular formation A cluster of neurons that regulates sleep, wakefulness, and levels of arousal.

cerebellum A large structure of the hindbrain that controls fine motor skills.

pons A brain structure that relays information from the cerebellum to the rest of the brain.



(a)
The Major Divisions of the Brain
The brain can be organized into three parts, moving from the bottom to the top, from simpler functions to the more complex: the hindbrain, the midbrain, and the forebrain.



(b)
The Hindbrain
The hindbrain coordinates information coming into and out of the spinal cord and controls the basic functions of life.

Figure 3.9
Structure of the Brain

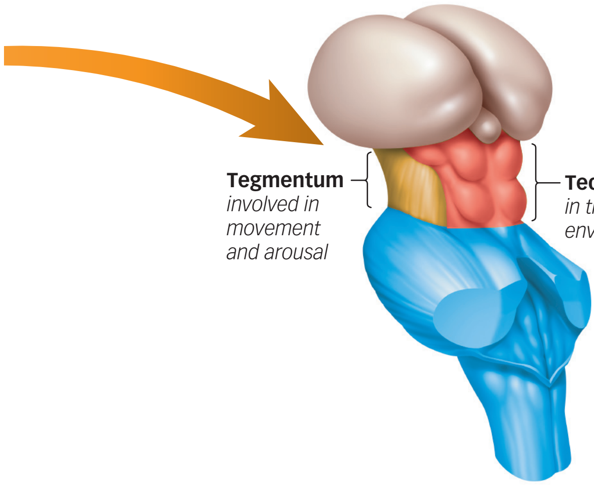
The Midbrain

Sitting on top of the hindbrain is the *midbrain,* which is relatively small in humans. As you can see in Figure 3.9c, the midbrain contains two main structures: the tectum and the tegmentum. The *tectum* orients an organism in the environment. The tectum receives stimulus input from the eyes, ears, and skin and moves the organism in a coordinated way toward the stimulus. For example, when you're studying in a quiet room and you hear a *click* behind and to the right of you, your body will swivel and orient to the direction of the sound; this is your tectum in action. The *tegmentum* is involved in movement and arousal; it also helps to orient an organism toward sensory stimuli.

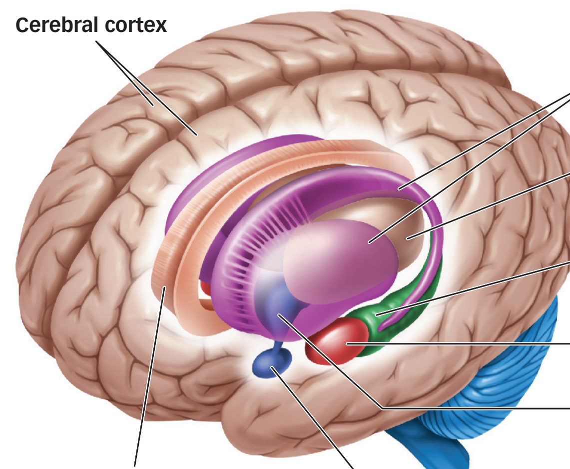
The midbrain may be relatively small, but it is critical. You could survive if you had only a hindbrain and a midbrain. The structures in the hindbrain would take care of all the bodily functions necessary to sustain life, and the structures in the midbrain would orient you toward or away from pleasurable or threatening stimuli in the environment. But this wouldn't be much of a life. To understand where the abilities that make us fully human come from, we need to consider the last division of the brain: the forebrain.

The Forebrain

When you appreciate the beauty of a poem, detect the sarcasm in a friend's remark, plan to go skiing next winter, or notice the faint glimmer of sadness on a loved one's face, you are enlisting the forebrain. The *forebrain* is the highest level of the brain—literally and figuratively—and controls complex cognitive, emotional, sensory, and motor functions. The forebrain itself is divided into two main sections: the cerebral cortex and the subcortical structures.



(c)
The Midbrain
The midbrain is important for orientation and movement.



(d)
The Forebrain
The forebrain is the highest level of the brain and is critical for complex cognitive, emotional, sensory, and motor functions. The forebrain is divided into two parts: the cerebral cortex and the underlying subcortical structures. The cerebral cortex, the outermost layer of the brain, is divided into two hemispheres, connected by the corpus callosum (see Figure 3.12).

The **cerebral cortex** is *the outermost layer of the brain and is divided into two hemispheres.* The **subcortical structures** are *areas of the forebrain housed under the cerebral cortex near the center of the brain* (see Figure 3.9d). Let's examine the subcortical structures first.

Subcortical Structures

The subcortical (meaning "beneath the cortex") structures are nestled deep inside the brain, where they are quite protected. They play an important role in relaying information throughout the brain, as well as in performing specific tasks that allow us to think, feel, and behave as humans. Here we'll give you a brief introduction to each, and you'll read more about many of these structures in later chapters.

- The **thalamus** *relays and filters information from the senses and transmits the information to the cerebral cortex.* The thalamus receives inputs from all the major senses except smell, filters the information, giving more weight to some inputs and less weight to others, then relays the information to a variety of locations in the brain, including the cerebral cortex. The thalamus also closes the pathways of incoming sensations during sleep, providing a valuable function in *not* allowing information to pass to the rest of the brain.
- The **hypothalamus,** located below the thalamus (*hypo-* is Greek for "under"), *regulates body temperature, hunger, thirst, and sexual behavior*. Clusters of neurons in the hypothalamus keep body temperature, blood sugar levels, and metabolism within an optimal range for typical human functioning. Lesions to some areas of the hypothalamus result in overeating, whereas lesions to other areas leave an animal with no desire for food at all, highlighting that the hypothalamus plays a key role in regulating food intake (Berthoud & Morrison, 2008).

cerebral cortex The outermost layer of the brain, divided into two hemispheres.

subcortical structures Areas of the forebrain housed under the cerebral cortex near the center of the brain.

thalamus A subcortical structure that relays and filters information from the senses and transmits the information to the cerebral cortex.

hypothalamus A subcortical structure that regulates body temperature, hunger, thirst, and sexual behavior.


PIOLA666/GETTY IMAGES

A scary movie is designed to stimulate your amygdala, but only a little.

- The **hippocampus** (from Latin for "sea horse," due to its shape) is *critical for creating new memories and integrating them into a network of knowledge so that they can be stored indefinitely in other parts of the cerebral cortex*. Individuals with damage to the hippocampus can acquire new information and keep it in awareness for a few seconds, but as soon as they are distracted, they forget the information and the experience that produced it (Scoville & Milner, 1957; Squire, 2009). For example, people with damage to the hippocampus can remember how to drive and talk, but they cannot recall where they have recently driven or a conversation they have just had (see A World of Difference regarding implications for Alzheimer's disease).
- The **amygdala** (from Latin for "almond," also due to its shape), *located at the tip of each horn of the hippocampus, plays a central role in many emotional processes, particularly the formation of emotional memories* (Aggleton, 1992). The amygdala attaches significance to previously neutral events that are associated with fear, punishment, or reward (LeDoux, 1992). When we are in emotionally arousing situations, the amygdala stimulates the hippocampus to remember many details surrounding the situation (Kensinger & Schacter, 2005). For instance, people who lived through the terrorist attacks of September 11, 2001, remember vivid details about where they were, what they were doing, and how they felt when they heard the news, even years later (Hirst et al., 2009, 2015). The emotional tone attached to these memories is the work of the amygdala.
- The **basal ganglia** are *a set of subcortical structures that directs intentional movements and plays a role in reward processing*. The basal ganglia receive input from the cerebral cortex and send outputs to the motor centers in the brain stem (Nelson & Kreitzer, 2015). People who suffer from Parkinson's disease typically show symptoms of uncontrollable shaking and sudden jerks of the limbs and are unable to initiate a sequence of movements to achieve a specific goal. This happens because Parkinson's disease damages parts of the midbrain that normally supply the basal ganglia with dopamine (Dauer & Przedborski, 2003). The basal ganglia have also been linked to various kinds of rewards, including social rewards such as approval from others (Kohls et al., 2013; Williams et al., 2020; see The Real World: What the Brain Likes: The Instagram Effect).

The Endocrine System

One way in which the subcortical structures affect behavior is by interacting with the **endocrine system,** *a network of glands that produce and secrete into the bloodstream chemicals known as hormones, which influence a wide variety of basic functions, including metabolism, growth, and sexual development*. Some of the main glands in the endocrine system include the thyroid, which regulates bodily functions such as body temperature and heart rate; the adrenals, which regulate stress responses; the pancreas, which controls digestion; and the pineal, which secretes melatonin, influencing the sleep/wake cycle. The overall functioning of the endocrine system is orchestrated by the **pituitary gland,** *the "master gland" of the body's hormone-producing system, which releases hormones that direct the functions of many other glands in the body* (see **FIGURE 3.10**).

The hypothalamus sends hormonal signals to the pituitary gland, which in turn sends hormonal signals to other glands to control stress, digestive activities, and

hippocampus A subcortical structure critical for creating new memories and integrating them into a network of knowledge so that they can be stored indefinitely in other parts of the cerebral cortex.

amygdala A subcortical structure that plays a central role in many emotional processes, particularly the formation of emotional memories.

basal ganglia A set of subcortical structures that directs intentional movements and plays a role in reward processing.

endocrine system A network of glands that produce and secrete into the bloodstream chemicals known as hormones, which influence a wide variety of basic functions, including metabolism, growth, and sexual development.

pituitary gland The "master gland" of the body's hormone-producing system, which releases hormones that direct the functions of many other glands in the body.

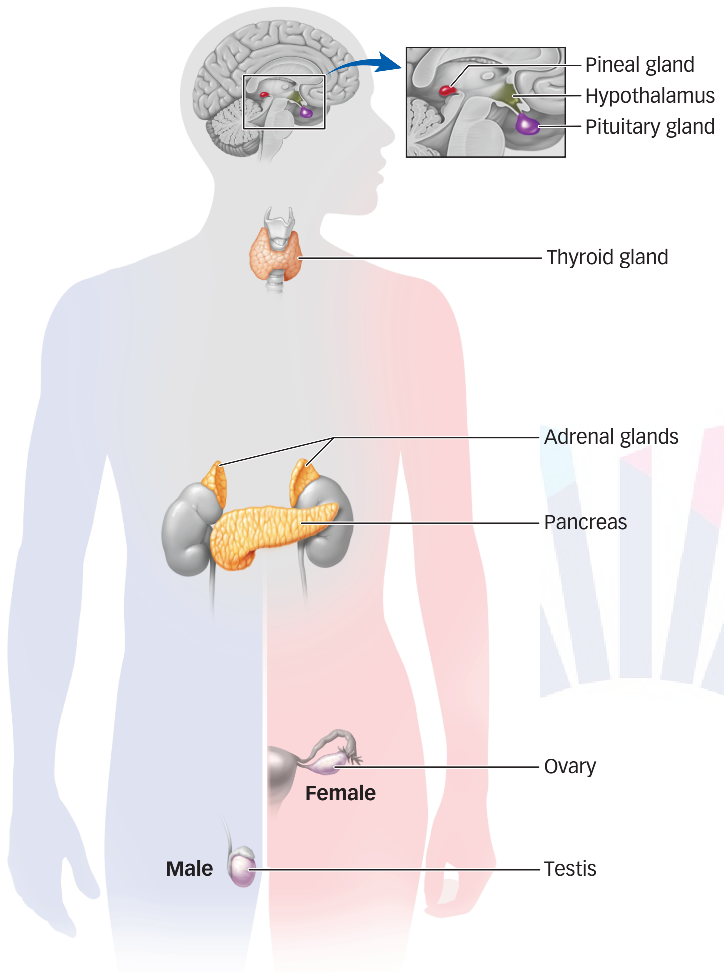


Figure 3.10
Major Glands of the Endocrine System
The endocrine system is a network of glands that works with the nervous system and impacts many basic functions by releasing hormones into the bloodstream.

reproductive processes. For example, when we sense a threat, sensory neurons send signals to the hypothalamus, which stimulates the release of adrenocorticotropic hormone (ACTH) from the pituitary gland. ACTH, in turn, stimulates the adrenal glands to release hormones that activate the sympathetic nervous system (Selye & Fortier, 1950). As you read earlier in this chapter, the sympathetic nervous system prepares the body either to meet the threat head on or to flee from the situation.

The Cerebral Cortex

Our tour of the brain has taken us from the very small (neurons) to the very large: the cerebral cortex. The cortex is the highest level of the brain, and it is responsible for the most complex aspects of perception, emotion, movement, and thought (Fuster, 2003). It sits over the rest of the brain, like a mushroom cap shielding the underside and stem, and it is the wrinkled surface you see when looking at the brain with the naked eye.

The cerebral cortex occupies roughly the area of a newspaper page, so fitting that much cortex into a human skull is a tough task. But if you crumple a sheet of newspaper, you'll see that the same surface area now fits compactly into a much smaller space. The cortex, with its wrinkles and folds, holds a lot of brainpower in a relatively

The Real World • What the Brain Likes: The Instagram Effect

On May 26, 2021, Instagram announced that users would have the option to hide their like counts (https://about.fb.com/news/2021/05/giving-people-more-control/). This move reflects the potentially harmful power of like counts on these platforms, which can create intense social pressure and possibly mental health problems (Wong, 2019). In one recent study (Lee et al., 2020), ninth grade students interacted via social media for 3 minutes with an online partner (who, unknown to the students, was a member of the research team). Students who were randomly assigned to a condition in which they received few likes in response to their posts reported more negative feelings and thoughts about themselves, and even greater depressive symptoms, than students who were randomly assigned to a condition that yielded many likes.

In another study, Sherman et al. (2016) scanned adolescent participants while they performed a social media task designed to simulate Instagram. Participants submitted photos from their own Instagram accounts, then viewed some of their own photos, along with other photos. They were further informed that they would see how often each photo had been liked by previous participants, and that they were able to add their own likes to any of the photos as they wished.

Participants more frequently liked photos that were shown as having received more versus fewer likes by others, highlighting the social influence on adolescents' "like" responses. Meanwhile, the researchers examined activity in different parts of the participants' brains, using fMRI (see the section Investigating the Brain, later in this chapter). The researchers were particularly interested in parts of the basal ganglia that play a role in the brain's reward circuitry. This region showed increased activity for photos that received many likes versus few likes, and especially when participants viewed photos of their own that received many likes.

Another way of phrasing these results is that reward processing regions showed *less* activity for photos that received fewer likes. That finding is of interest in relation to a result from the Lee et al. (2020) study described earlier, which reported that feelings of rejection among adolescents were linked to insufficient positive feedback during the experimental social media interaction. Lee et al.'s finding suggests that the reward associated with receiving likes on Instagram or Facebook, linked to the engagement of underlying reward processing regions, is something that adolescents crave and that is missed acutely when it is not delivered. We don't yet know whether the new Instagram policies allowing users to hide like counts will alleviate the distress associated with receiving few likes in adolescents (or anyone else), but the new policy corresponds well with the recent findings from studies of the adolescent brain and mind (Crone & Konjin, 2018).

DZMITRY KLIAPITSKI/ALAMY STOCK PHOTO

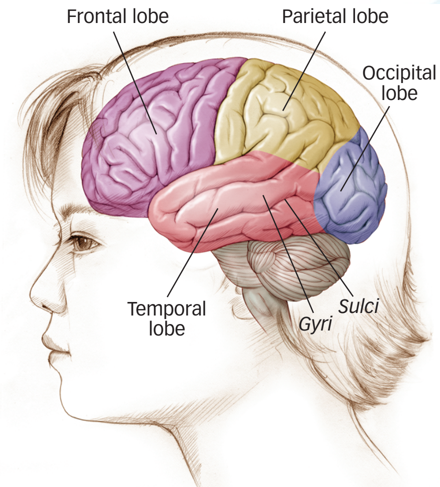


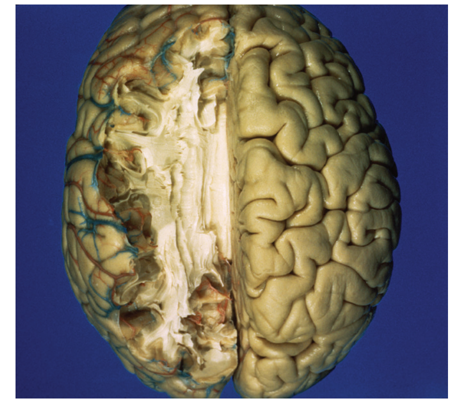
Figure 3.11
Cerebral Cortex and Lobes The four major lobes of the cerebral cortex are the occipital lobe, the parietal lobe, the temporal lobe, and the frontal lobe.

small package that fits comfortably inside the human skull (see **FIGURE 3.11**). The functions of the cerebral cortex can be understood at three levels: the separation of the cortex into two hemispheres, the functions of each hemisphere, and the role of specific cortical areas.

1. **Organization Across Hemispheres** The first level of organization divides the cortex into the left and right hemispheres. The two hemispheres are more or less symmetrical in their appearance and, to some extent, in their functions. However, each hemisphere controls the functions of the opposite side of the body. This means that your right cerebral hemisphere perceives stimuli from and controls movements on the left side of your body, whereas your left cerebral hemisphere perceives stimuli from and controls movement on the right side of your body.

   The cerebral hemispheres are connected to each other by *commissures,* bundles of axons that make possible communication between parallel areas of the cortex in each half. The largest of these commissures is the **corpus callosum,** which *connects large areas of the cerebral cortex on each side of the brain and supports communication of information across the hemispheres* (see **FIGURE 3.12**). This means that information received in the right hemisphere, for example, can pass across the corpus callosum and be registered, virtually instantaneously, in the left hemisphere.

2. **Organization Within Hemispheres** The second level of organization in the cerebral cortex distinguishes the functions of the different regions within each hemisphere of the brain. Each hemisphere of the cerebral cortex is divided into four areas, or *lobes*: From back to front, these are the occipital lobe, the parietal lobe, the temporal lobe, and the frontal lobe, as shown in Figure 3.11.
   - The **occipital lobe,** located at the back of the cerebral cortex, *processes visual information*. Sensory receptors in the eyes send information to the thalamus, which in turn sends information to the primary areas of the occipital lobe, where simple features of the stimulus are extracted, such as the location and orientation of an object's edges (see the Sensation and Perception chapter for more details). These features are then processed into a more complex "map" of the stimulus onto the occipital cortex, leading to comprehension of what's being seen. Damage to the primary visual areas of the occipital lobe can leave a person with partial or complete blindness. Information still enters the eyes, which work just fine. But without the ability to process and make sense of the information at the level of the cerebral cortex, the information is as good as lost (Zeki, 2001).
   - The **parietal lobe,** located in front of the occipital lobe, carries out functions that include *processing information about touch*. The parietal lobe contains the *somatosensory cortex,* a strip of brain tissue running from the top of the brain down to the sides (see **FIGURE 3.13**). Within each hemisphere, the somatosensory cortex represents the skin areas on the contralateral surface of the body. Each part of the somatosensory cortex maps onto a particular part of the body. If a body area is more sensitive, a larger part of the somatosensory cortex is devoted to it. For example, the part of the somatosensory cortex that corresponds to the lips and tongue is larger than the area corresponding to the feet. The somatosensory cortex can be illustrated as a distorted figure, called a *homunculus* ("little man"), in which the body parts are rendered according to how much of the somatosensory cortex is



VIDEOSURGERY/SCIENCE SOURCE

Figure 3.12
Cerebral Hemispheres The corpus callosum connects the two hemispheres of the brain and supports communication between them. (Parts of the cerebral cortex have been cut away to reveal the corpus callosum below.)

corpus callosum A bundle of axons that connects large areas of the cerebral cortex on each side of the brain and supports communication of information across the hemispheres.

occipital lobe A region of the cerebral cortex that processes visual information.

parietal lobe A region of the cerebral cortex that processes information about touch.

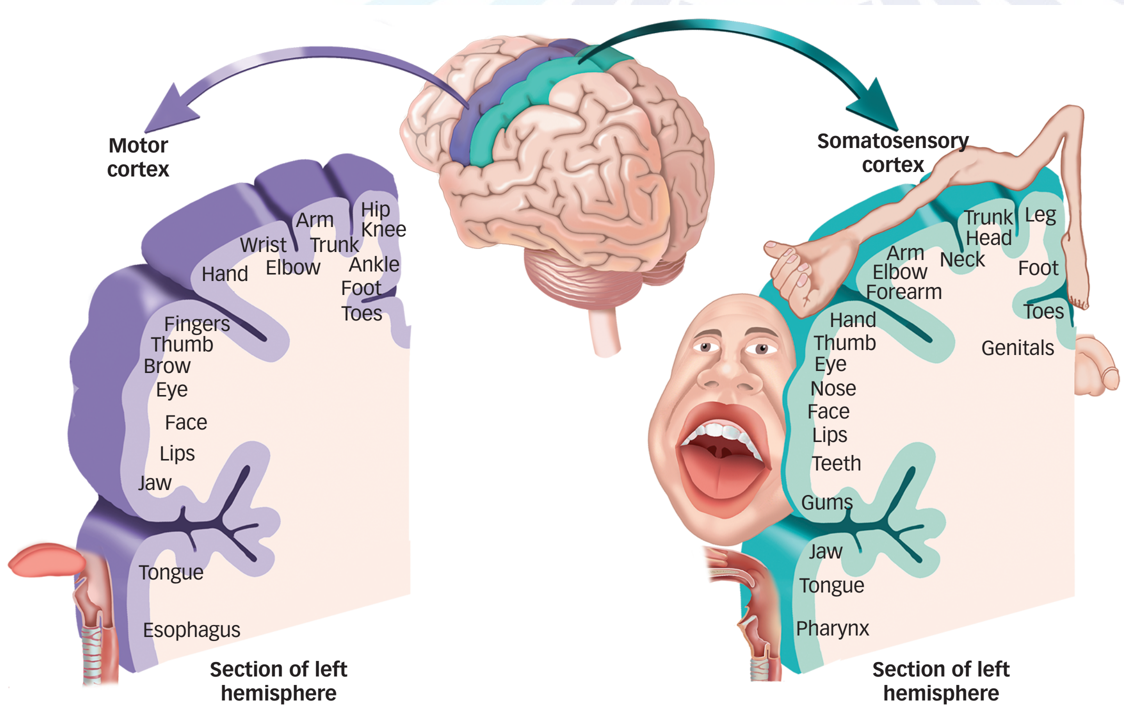


Figure 3.13
Somatosensory and Motor Cortices
The motor cortex, a strip of brain tissue in the frontal lobe, represents and controls different skin and body areas on the contralateral side of the body. Directly behind the motor cortex, in the parietal lobe, lies the somatosensory cortex. Like the motor cortex, the somatosensory cortex represents skin areas of particular parts on the contralateral side of the body.

devoted to them (Penfield & Rasmussen, 1950). Directly in front of the somatosensory cortex, in the frontal lobe, is a parallel strip of brain tissue called the *motor cortex*. As in the somatosensory cortex, different parts of the motor cortex correspond to different body parts. The motor cortex initiates voluntary movements and sends messages to the basal ganglia, cerebellum, and spinal cord. The motor and somatosensory cortices, then, are akin to sending and receiving areas of the cerebral cortex, taking in information and sending out commands.

- The **temporal lobe,** located on the lower side of each hemisphere, is *responsible for hearing and language*. The *primary auditory cortex* in the temporal lobe is analogous to the somatosensory cortex in the parietal lobe and the primary visual areas of the occipital lobe: It receives sensory information from the ears (Recanzone & Sutter, 2008). Secondary areas of the temporal lobe then process the information into meaningful units, such as speech and words. The temporal lobe also houses areas that interpret the meaning of visual stimuli and help us recognize common objects in the environment (Martin, 2007).
- The **frontal lobe,** which sits behind the forehead, has *specialized areas for movement, abstract thinking, planning, memory, and judgment*. It contains the *motor cortex*, which lies directly in front of the somatosensory cortex, and which coordinates movements of muscle groups throughout the body. Like the somatosensory cortex, different parts of the motor cortex correspond to different body parts. The motor cortex initiates voluntary movements and sends messages to the basal ganglia, cerebellum, and spinal cord. Other areas in the frontal lobe coordinate thought processes that help us manipulate information and retrieve memories, which we can use to plan our behaviors and interact socially with others. In short, the frontal cortex functions as a kind of executive that allows us to do the kind of thinking, imagining, planning, and anticipating that sets humans apart from most other species (Schoenemann et al., 2005; Stuss & Benson, 1986; Suddendorf & Corballis, 2007).

3. **Organization Within Specific Lobes** The third level of organization in the cerebral cortex involves the representation of information within specific lobes in the cortex. A hierarchy of processing stages from primary areas handles fine details of information all the way up to **association areas,** which are *composed of neurons that help provide sense and meaning to information registered in the cortex*. For example, neurons in the primary visual cortex are highly specialized: Some detect features of the environment that are in a horizontal orientation, others detect movement, and still others process information about human versus nonhuman forms. Association areas interpret the information extracted by these primary areas (shape, motion, etc.) to make sense of what's being perceived—in this case, perhaps a large cat leaping toward your face (Martin, 2007). Similarly, neurons in the primary auditory cortex register sound frequencies, but it's the association areas of the temporal lobe that allow you to turn those noises into the meaning of your friend screaming, "Look out for the cat!" Association areas, then, help stitch together the threads of information in the various parts of the cortex to produce a meaningful understanding of what's being registered in the brain.

A striking example of this property of association areas comes from the discovery of the mirror-neuron system. **Mirror neurons** are *active when an animal performs a behavior, such as reaching for or manipulating an object,*

temporal lobe A region of cortex responsible for hearing and language.

frontal lobe A region of cortex that contains specialized areas for movement, abstract thinking, planning, memory, and judgment.

association areas Areas of cortex composed of neurons that help provide sense and meaning to information registered in the cortex.

mirror neurons Neurons that are active when an animal performs a behavior, such as reaching for or manipulating an object, and are also activated when another animal observes that animal performing the same behavior.

and are also activated when another animal observes that animal performing the same behavior. Mirror neurons are found in the frontal lobe (near the motor cortex) and in the parietal lobe (Rizzolatti & Craighero, 2004; Rizzolatti & Sinigaglia, 2010). They have been identified in birds, monkeys, and humans, and their name reflects the function they serve. Neuroimaging studies with humans have shown that mirror neurons are active when people watch someone perform a behavior, such as grasping in midair. But they are more highly activated when that behavior has some purpose or context, such as grasping a cup to take a drink (Iacoboni et al., 2005), and they seem to be related to recognizing the goal someone has in carrying out an action and the outcome of the action, rather than to the particular movements a person makes while performing that action (Hamilton & Grafton, 2006, 2008; Iacoboni, 2009; Rizzolatti & Sinigaglia, 2010).

There is controversy about how to interpret the activity of mirror neurons, particularly in humans (Hickok, 2009, 2014), and about whether, as claimed by some researchers, impairments to the mirror neuron system contribute to difficulties with understanding the minds of other people, as occurs in autism spectrum disorder (Hamilton, 2013; see the chapter on Psychological Disorders). Nonetheless, the existence of mirror neurons is supported by experimental evidence (Rizzolatti & Rozzi, 2018).

DAVID LONGSTREATH/AP PHOTO

When one animal observes another engaging in a particular behavior, some of the same neurons become active in the observer's brain as in the brain of the animal exhibiting the behavior. These mirror neurons seem to play an important role in social behavior.

Brain Plasticity

The cerebral cortex may seem to be a fixed structure, one big sheet of neurons designed to help us make sense of our external world. Remarkably, however, sensory cortices are not fixed. They can adapt to changes in sensory inputs, a quality that researchers call *plasticity* (i.e., the ability to be molded). As an example, if you lose your middle finger in an accident, the part of the somatosensory area that represents that finger is initially unresponsive (Kaas, 1991). After all, there's no longer any sensory input going from that location to that part of the brain. However, over time, that area in the somatosensory cortex becomes responsive to stimulation of the fingers *adjacent* to the missing finger. The brain is plastic: Functions that were assigned to certain areas of the brain may be capable of being reassigned to other areas of the brain to accommodate changing input from the environment (Feldman, 2009). This suggests that sensory inputs "compete" for representation in each cortical area.

New Mapping

A striking example comes from people who have undergone amputation of a limb who continue to experience sensations where the missing limb would be, a phenomenon called *phantom limb syndrome.* Patients can feel their missing limbs moving, even in coordinated gestures such as shaking hands. Some even report feeling pain in their phantom limbs (Kuffler, 2018; Ramachandran & Brang, 2015). Why does this happen?

To find out, researchers stimulated the skin surface in various regions around the face, torso, and arms while monitoring brain activity in volunteers who have undergone amputation and those who have not (Ramachandran & Blakeslee, 1998; Ramachandran et al., 2010; Ramachandran et al., 1992). Brain-imaging techniques displayed the somatosensory cortical areas that were activated when the skin was stimulated.

Brain scans of the people who have undergone amputation revealed that stimulating areas of the face and upper arm activated an area in the somatosensory cortex that previously would have been activated by a now-missing hand (**FIGURE 3.14**).