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PART I
Fundamentals

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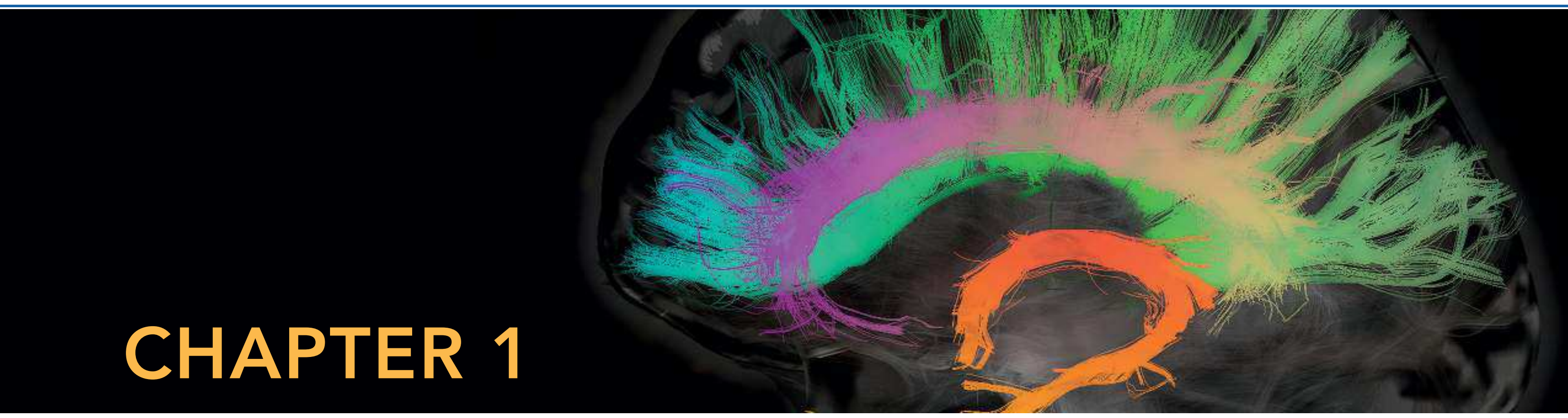

CHAPTER 1

Introduction to the Nervous System

WHAT IS COGNITIVE NEUROSCIENCE?

In this book, we explore how the neurological organization of the brain influences the way people think, feel, and act. **Cognitive neuroscience** is critical to our understanding of this linkage between brain and mind. Cognitive neuroscience comprises investigations of all mental functions that are linked to neural processes, ranging from investigations in animals to humans and from experiments performed in the laboratory to computer simulations. Much of the early work in this area comes from **human neuropsychology**, which also focuses on understanding mental processes in humans, but with an emphasis on examining the changes in behavior as a result of brain trauma.

Since the mid-1970s, our knowledge in the realm of cognitive neuroscience and neuropsychology has grown rapidly, and so has the number of scientists and clinicians who specialize in these areas of inquiry. *Cognitive neuroscientists* attempt to understand the relationship between the brain and mind from a variety of conceptual vantage points simultaneously. Borrowing from computer science, they view the brain as an information processing system whose primary goal is to solve problems. These scientists attempt to understand how the brain is organized to perform specific computations, such as recognizing a face. To do so, they rely on integrating findings from different approaches. For example, they record the activity of cells to determine what stimulus makes the cells respond, use brain imaging to ascertain exactly which brain regions become active during a specific mental task, and build computer models to provide principles and gain insights into how different mental operations might be performed by the brain.

Experimental neuropsychologists work to understand the neural bases of cognition by doing scientific studies comparing individuals who have sustained brain damage with those who are neurologically intact. These researchers use a variety of techniques to divide complicated mental functions into meaningful categories, such as language and memory, and to isolate the contribution of specific brain regions to each of these functions.

Clinical neuropsychologists work in health care settings, such as hospitals and clinics, with individuals who have sustained brain damage through either trauma or disease. They diagnose the cognitive deficits resulting from brain trauma, plan programs of rehabilitation, evaluate the degree to which a patient is regaining function, and determine how environmental factors (e.g., family structure, educational background, and so forth) may moderate or exacerbate the effects of brain dysfunction. In this book, we provide an overview of the current state of knowledge in cognitive neuroscience as derived from findings in both the laboratory and the clinic.

The endeavor of understanding the relationship between the brain and the mind may be undertaken from two distinct vantage points, one that emphasizes the neurological organization of the brain and one that emphasizes the psychology of the mind. The neurologically oriented approach emphasizes the brain's anatomy; therefore, the major objective of this approach is to understand the function of specific circumscribed regions of brain tissue. For instance, a researcher might want to investigate a particular brain structure, such as the hippocampus, to determine its anatomical characteristics, its connections to other brain regions and the pattern of that connectivity, and its role in mental functioning. Information derived from this approach can be extremely useful to medical personnel such as neurosurgeons who need to know what functions might be affected by different surgical approaches.

In contrast, the psychologically oriented approach emphasizes the brain's mental capabilities. The major objective of this approach is to understand how different aspects of cognition, such as language, memory, and attention, are supported by the neurological organization of the brain. For example, cognitive neuroscientists may want to know whether the brain structures supporting the ability to read are the same as, or distinct from, those supporting the ability to write. One way of addressing this question is to determine whether the pattern of brain activation observed when people are reading is distinct from that observed when they are writing.

In this book we lean more toward the psychologically oriented approach than the neurologically oriented one. This bias can be seen most clearly by taking a quick glance at the table of contents, which includes chapter titles such as "Language," "Memory," and "Attention," indicating that our discussion of the relationship between the brain and the mind emphasizes cognitive functions. If this book were written from a more neurologically oriented approach, the chapters would have been organized by brain regions and been titled "The Basal Ganglia," "The Cerebellum," and "The Frontal Lobes." Although we take a more psychologically oriented approach, a working knowledge and understanding of the neurological organization of the brain is indispensable, for only with that knowledge can we intelligently discuss the relationship between psychological functions and the specific regions of brain tissue that support those functions.

Now is a particularly exciting time to study cognitive neuroscience. Vast advances in our knowledge in neuroscience, medical science, cognitive psychology, and computer science provide the opportunity to synthesize findings in ways that were impossible just a few years ago. Research in cognitive psychology has tremendously increased the sophistication of models of mental functioning. For example, we can take a complicated function such as language and divide it into specific subcomponents and subprocesses. At the same time, incredible advances in medical technology now allow us to examine the neuroanatomy and physiological functioning of the brain in ways unimagined even as recently as two deacdes ago. We discuss these advances in methods in more detail in Chapter 3.

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Before we begin to attempt to link cognitive functions to the brain, however, we need a common base of knowledge about the anatomy and physiology of the brain. This chapter is designed to provide this knowledge base. The first part of the chapter introduces the vocabulary scientists use when discussing the brain – the terms that describe the location of brain structures and their characteristics – as well as the major building blocks and subdivisions of the nervous system. The second part takes a closer look at the brain at both a micro and a macro level. We discuss how nerve cells communicate with one another and how disruptions in this process can have important implications for mental functions. The final section provides more details about the major lobes of the cerebral cortex and their associated mental functions.

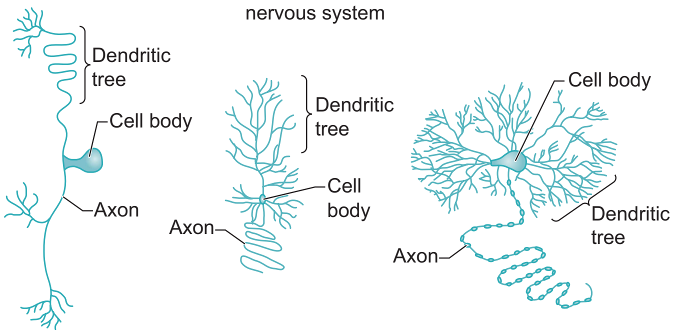

FIGURE 1.1 Examples of some nervous system cells (not to scale).
(A) Sensory neurons, (B) interneurons, and (C) motor neurons. Note that the appearance of the different kinds of neurons is distinctive; the appearance of each kind of neuron is due to its function. A sensory neuron collects information from a source and passes it on to an interneuron. The many branches of interneurons suggest that they collect information from many sources. Motor neurons are distinctively large and collect information from many sources; they pass this information on to command muscles to move.

BASIC BUILDING BLOCKS OF THE NERVOUS SYSTEM: NEURONS AND GLIA

The human nervous system, which consists of the brain, spinal cord, nerves, and ganglia, controls the body's response to internal and external stimuli. It is comprised of two main classes of cells: neurons and glia. **Neurons** are the cells in the nervous system that carry information from one place to another by means of a combination of electrical and chemical signals. **Glia**, which outnumber neurons by at least 10 to 1, are support cells.

Neurons have three main parts: a dendritic tree, a cell body, and an axon (see Figure 1.1). The **dendritic tree** is the part of the neuron that receives input from other cells. The **cell body** is the part of the cell containing the nucleus and other cellular apparatus responsible for manufacturing the proteins and **enzymes** that sustain cell functioning. The **axon** is the appendage of the cell along which information is carried. It can vary in length; in some cases it is very short, extending not much further than the length of the dendrites and cell body. In other instances the axon is very long, spanning large distances between brain regions.

Some neurons, known as *sensory neurons*, bring information to the central nervous system. Others, known as *interneurons*, associate information within the central nervous system. Finally, there are *motor neurons*, which send information from the brain and spinal cord to the muscles. Although all neurons have these same basic component parts, they come in a variety of sizes and shapes (Figure 1.1). We examine neurons in more detail later in the chapter, when we present a bit more information about how they work. When doing so, we highlight those aspects of neuronal function that are important for discussions in later chapters.

Compared to that of neurons, our knowledge about glia is relatively scant. Nonetheless, new knowledge has revealed that glia are much more than just "bit-part" players overshadowed by the leading role that neurons play in the nervous system. Although glia are not the main carriers of information, they are critical to the functioning of the nervous system. They influence the communication between neurons by modifying the chemical milieu between them, as well as refining and sculpting the physical connections between neighboring neurons. Developmentally, glia guide neurons as they migrate from the site of creation to their final position within the brain. Glia also aid with reorganization after brain damage by removing dead neurons, and they serve some of the nutritive needs of neurons and provide structural support (Zuchero and Bares, 2015).

Glia are also critical to maintaining the **blood–brain barrier**, which is the mechanism by which many harmful substances, such as toxins, are prevented from reaching the brain. The blood–brain barrier consists of tightly packed glial cells between blood vessels and neurons. This creates a physical obstruction that keeps not only toxins, but also nutrients, drugs, and immune system cells in the bloodstream from directly reaching the nervous system (Figure 1.2). As you can see, although glia are not directly responsible for transmitting information across the nervous system, such transmission would be impossible without them.

NEUROANATOMICAL TERMS AND BRAIN "GEOGRAPHY"

Anytime you begin a long journey, you need a road map to guide your path, plus some understanding of common directional terms such as *north, south, east*, and *west*. So, to begin our trip around the "geography" of the central nervous system, we must identify the major neural regions and introduce terms that can help to orient us during the journey. Distinguishing between regions of the central nervous system, and in particular the brain, serves a function similar to drawing boundary lines on a map. Such lines on a map may tell us about differences in the geography of different regions, and also about differences in the behavior, attitudes, and customs of the people on either side of a boundary. Likewise, boundaries between brain regions are often drawn to demarcate differences in the structure and function of brain tissue. Sometimes boundaries between brain regions are based on large and obvious anatomical landmarks, similar to major geographical features such as rivers or mountains on a map. In other cases, the physical distinction between regions is not obvious from the neuroanatomical terrain.

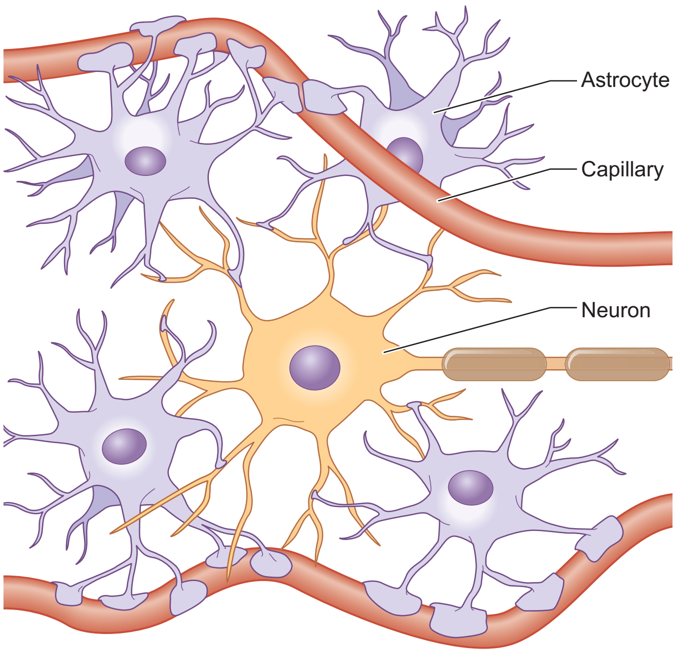

FIGURE 1.2 The relationship between glia and neurons. Glia support the cell in many different ways. As shown here, they provide a support matrix around the neuron. In addition, by their close association with the blood supply they help to maintain the blood–brain barrier.

We must first learn the anatomical equivalents of north, south, east, and west. Unlike most geographical maps, which have only two dimensions, the brain has three. Thus, we need terms not only for the brain's left, right, top, and bottom, but also for its back and front. The front of the brain is referred to as **anterior** and the back as **posterior**. Because the head of an animal is situated in front of its tail, regions toward the front can be referred to as **rostral** (toward the head), whereas regions toward the rear are referred to as **caudal** (toward the tail). The top of the brain is referred to as **superior**, and the bottom is referred to as **inferior**. In the human brain, **dorsal** and **ventral** have meanings similar to superior and inferior, respectively. However, in other portions of the central nervous system, such as the spinal cord, *dorsal* and *ventral* are better understood in reference to a four-legged animal or a fish. In these cases, dorsal means toward an animal's back, whereas ventral means toward an animal's stomach. If you have aquatic interests, you can remember that dorsal means top because the dorsal fin of a shark sticks out of the water. Finally, areas in the middle or center of the brain are referred to as **medial**, whereas areas that are toward the outside of the brain are called **lateral** (Figure 1.3).

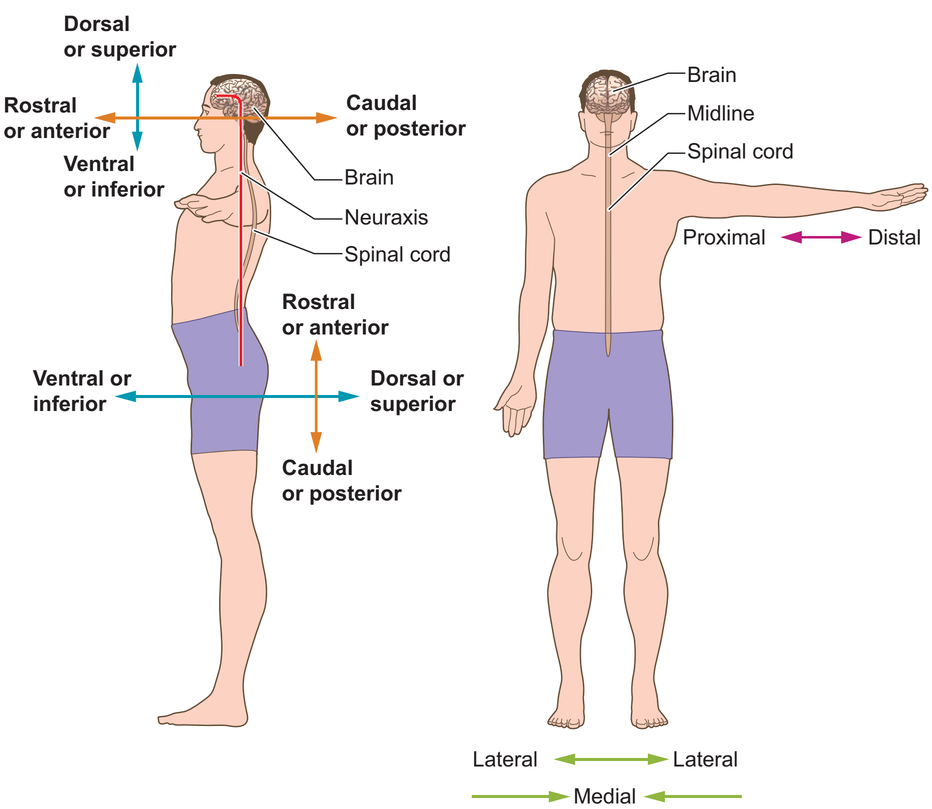

FIGURE 1.3 Anatomical terms for directions. (Left) In a four-legged animal, dorsal/superior and ventral/inferior typically refer to the areas toward the back and stomach respectively, as shown at the hips of the figure on the left. However, because humans walk upright instead of on all fours, dorsal/superior and ventral/inferior also refer to the top and bottom of the head, respectively. (Right) Shown here are anatomical directions relative to the body midline.

Throughout this text, the brain is portrayed in one of three planes. When the brain is sliced ear-to-ear to separate the front from the back, the view is **coronal**. If the brain is sliced so that the top of the brain is separated from the bottom, the view is **horizontal** (also sometimes referred to as *axial* or *transverse*). Finally, if the brain is cut so that the left side of the brain is separated from the right side, the view is **sagittal**. A sagittal slice down the middle of the brain is known as a **midsagittal**, or medial, section, whereas a section taken more toward one side is known as a lateral section (Figure 1.4).

Knowledge of these terms can help us understand the location of specific brain structures. For example, when we are introduced to the anatomical structure called the *lateral ventricle* (a *ventricle* is a space within the nervous system that is filled with fluid), we can deduce that it must be positioned away from the midline of the brain (i.e., laterally). As another example, consider how we might go about locating **nuclei**, distinct groups of neurons whose cell bodies are all situated in the same region in a brain structure called the *thalamus*. As discussed later in this chapter, the thalamus helps to regulate and organize information coming from the outer reaches of the nervous system as it ascends toward the cortex. The thalamus also modifies information descending from the cortex. If we need to find the anterior ventral nucleus of the thalamus, we know from our discussion of anatomical terms that it should be located at the front and bottom part of the thalamus.

Other terms we need to know include **contralateral**, meaning on the opposite side, and **ipsilateral**, meaning on the same side. So, for example, the left half of your brain is contralateral to your right hand, whereas it is ipsilateral to your left hand. To make these definitions more concrete, remember the familiar adage that the right side of your brain controls the motor

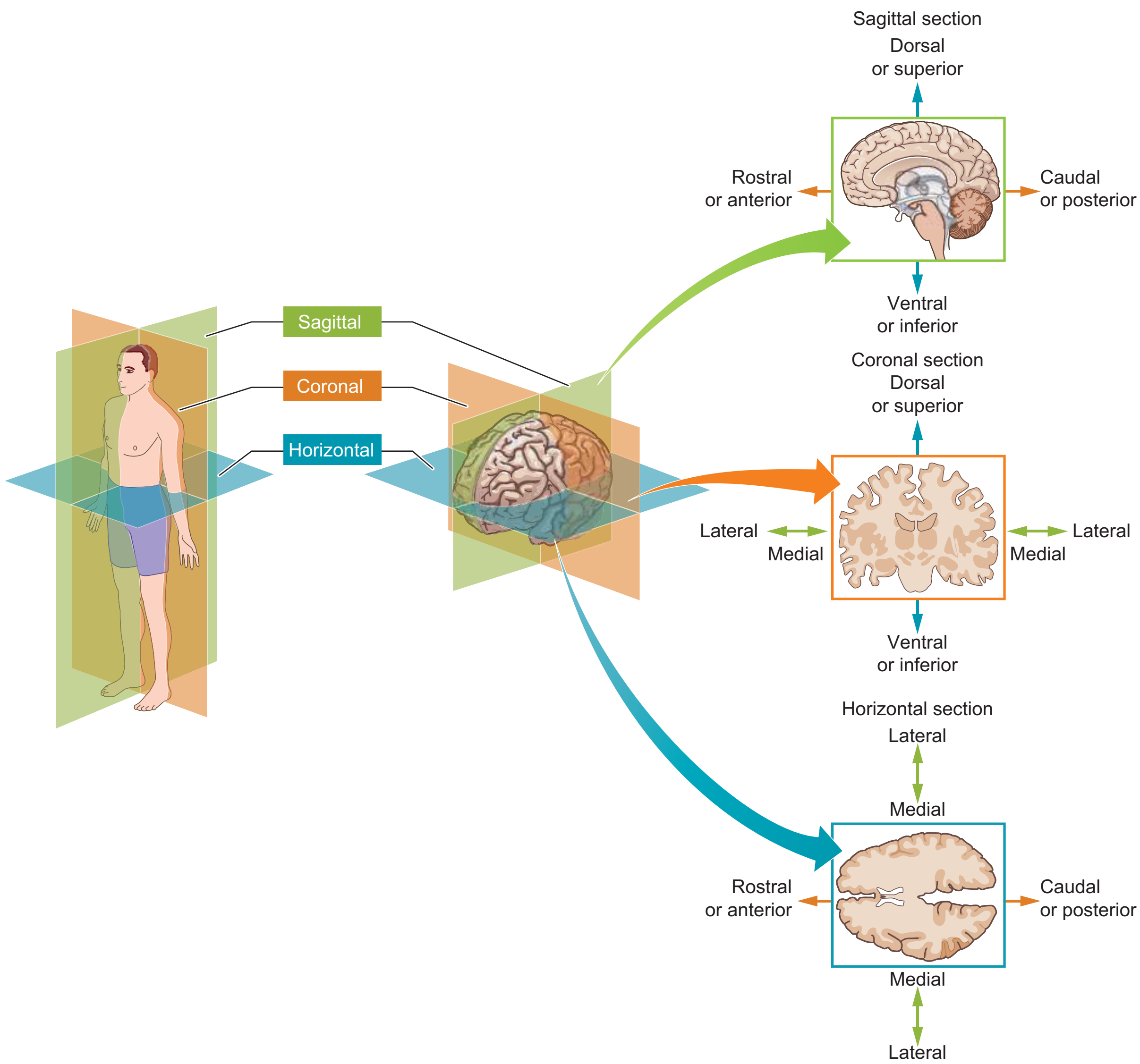

FIGURE 1.4 The main planes in which the brain is viewed.
A sagittal section divides left from right, a coronal section divides front from back, and a horizontal section divides top from bottom. The anatomical terms describing the brain as seen in each of these sections are shown on the right.

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movements of the limbs on the left side of your body, and vice versa. Put in the terms we just learned, motor control occurs contralaterally.

Unilateral applies to only one side of the brain, whereas **bilateral** applies to both sides of the brain. For example, when injury occurs to one side of the brain, it is unilateral damage, but when injury occurs to both sides, it is bilateral damage. Other terms often used to describe brain regions and their relation to body parts are **proximal**, which means near, and **distal**, which means far. Thus, distal muscles are in your far extremities, such as your hands.

MAJOR SUBDIVISIONS OF THE CENTRAL NERVOUS SYSTEM

We now start our journey across the different territories, or regions, of the **central nervous system (CNS)**. The central nervous system encompasses the brain and the spinal cord, whereas the **peripheral nervous system** comprises all neural tissue beyond the central nervous system, such as neurons that receive sensory information or that send information to muscles, and those that relay information to or from the spinal cord or the brain. Because of its fragility, the entire central nervous system is encased in bone. The spinal cord is enclosed within the spinal column and the brain is enclosed within the skull. Although these bony structures protect the central nervous system, at times they can cause damage. For example, if the spinal column presses against the spinal cord, it can pinch a nerve and cause pain. Likewise, as discussed in Chapter 16, the brain can be damaged by compression against the skull.

Between the neurons and their bony encasements is **cerebrospinal fluid (CSF)**, which is similar in composition to blood plasma. Essentially, the brain floats in CSF, which makes it buoyant and cushions it from being knocked around every time we move. The fluid-filled spaces that contain CSF are known as **ventricles**, the most prominent of which are the lateral ventricles (Figure 1.5). CSF also serves metabolic needs, allowing nutrients to reach neurons. Typically, cells outside the nervous system receive nutrients from the blood. However, the blood–brain barrier precludes direct transport of nutrients from the blood to the brain. Rather, nutrients from the blood reach nerve cells through CSF.

Having discussed the basic organization of the nervous system, we now turn to examine the seven main subdivisions of the central nervous system depicted in Figure 1.6: (1) the spinal cord, (2) the medulla, (3) the cerebellum, (4) the pons, (5) the midbrain, (6) the hypothalamus and thalamus (diencephalon), and (7) the cerebral cortex. In addition, we discuss two major subcortical systems, the basal ganglia and the limbic system.

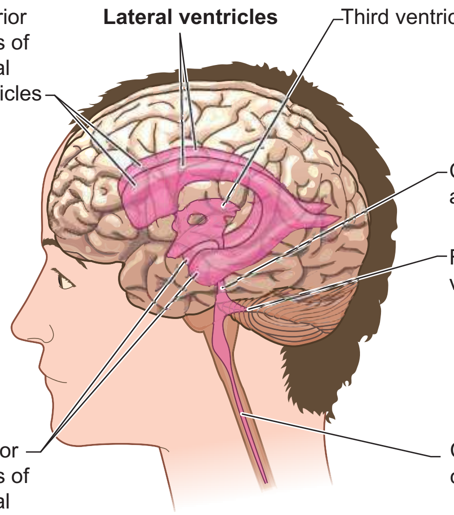

FIGURE 1.5 The ventricular system of the brain.
This system of spaces in the brain is filled by cerebrospinal fluid. It consists of the two lateral ventricles, one in each of the cerebral hemispheres, and the third and fourth ventricles positioned along the midline, which are connected via the cerebral aqueduct. The cerebrospinal fluid in the ventricles helps to cushion the brain and also aids in allowing nutrients to reach neurons.

Spinal Cord

The **spinal cord** is the portion of the nervous system through which most sensory neurons relay information on the way to the brain, and through which motor commands from the brain are sent to the muscles. The *spinal column*, the bony structure housing the spinal cord, is composed of many sections, or vertebrae. At each vertebra, sensory information enters the cord and motor information leaves it. If the spinal cord were cut in cross-section, two clumps of nerve cells, one located ventrally and another located dorsally, would be prominent, as shown in Figure 1.7. Cells in the dorsal section of the spinal cord (remember, dorsal is located toward the back) receive sensory information. In contrast, cells in the ventral region (remember, ventral is located toward the stomach) are responsible for conveying motor commands to the muscles as well as receiving input from the brain and from other regions of the spinal cord.

Damage to the spinal cord leaves a person without sensation in or motor control for all body areas that are connected to the brain by spinal cord segments distal to the point of injury. Impulses from the periphery cannot be carried up the spinal cord past the point of injury and therefore cannot reach the brain. Likewise, information from the brain cannot be relayed down past the point of injury to the muscles. How much of the body is paralyzed and how much sensation is lost depends on where in the spinal cord the damage occurs.

The vertebrae where information from each part of the body enters the spinal cord are shown in Figure 1.8. Compression of the spinal column that causes a vertebra to be broken or crushed may result in a damaged or severed spinal cord. For example, when damage to the spinal cord occurs at the level of the fifth cervical vertebra (C-5), the person is often left quadriplegic, without control of muscles in or sensation from either

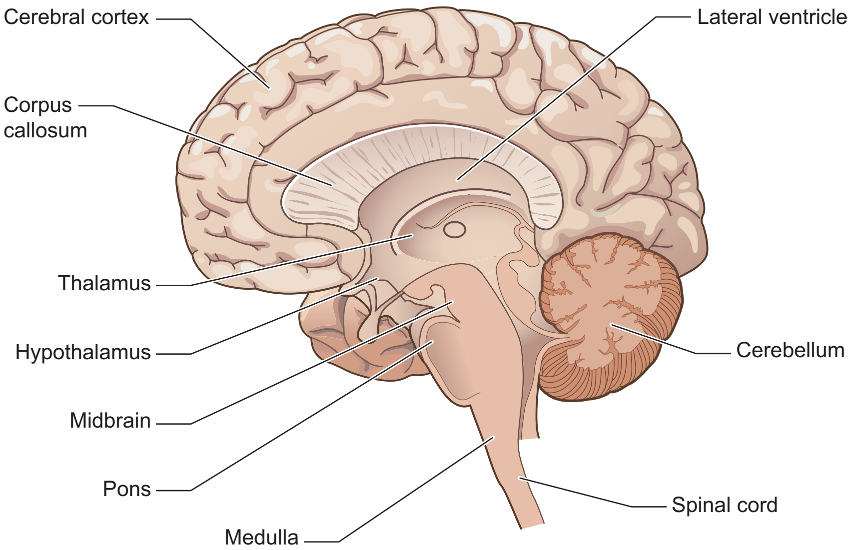

FIGURE 1.6 The major subdivisions of the human brain.
A sagittal view of the major subdivisions: the spinal cord, medulla, cerebellum, pons, midbrain, diencephalon (thalamus and hypothalamus), and cerebral cortex. The medulla, pons, and midbrain are often referred to as the *brainstem*. Sometimes the brain is conceived of as having three broad sections: the hindbrain (medulla, pons, and cerebellum), the midbrain, and the forebrain (diencephalon and cerebral cortex).

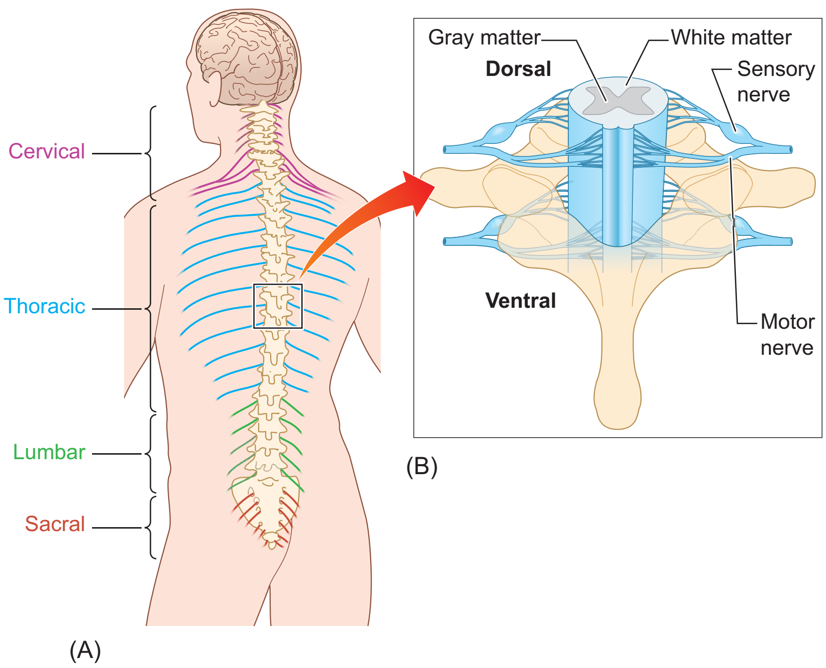

FIGURE 1.7 The spinal cord.
(A) The four sections of the spinal cord: cervical, thoracic, lumbar, and sacral. A spinal nerve exists at each vertebra of the spinal column. (B) A cross-section of the spinal cord. Sensory information enters the spinal cord through the dorsal region, and nerves exit through the ventral region to control muscle movements. The gray matter consists largely of cell bodies. The surrounding white matter is composed of myelinated axons that carry information to other levels of the spinal cord and the brain.

the arms or the legs (see Figure 1.8). If, however, the damage is sustained at a lower level, perhaps waist level (e.g., at vertebra T-12, the twelfth thoracic vertebra), the person is often paraplegic, with loss of sensory information and motor control for just the bottom half of the body.

Medulla: Control of Basic Functions

For the purposes of this text, we should know a few main facts about the **medulla**, the section of the brain directly superior to the spinal cord. First, it is the region of the brain that contains many (though not all) of the cell bodies of the 12 **cranial nerves**. Whereas the spinal cord is the point of entry and exit for sensory and motor nerves of the body, some cranial nerves are responsible for receipt of sensory information and motor control of the head. Other cranial nerves are responsible for the neural control of internal organs. A list of the 12 cranial nerves and their functions, and a diagram of the region of the brain where their nuclei are located, are presented in Figure 1.9.

Second, at the medulla, most of the motor fibers cross from one side of the body to the other, with the result that the left side of the brain controls the right side of the body, and the right side of the brain controls the left side of the body. Third, the medulla controls many vital functions and reflexes, such as respiration and heart rate. Because the medulla serves these functions, damage to it can be fatal. One common accompaniment of either diffuse or specific brain damage is swelling of the entire brain. When this swelling puts enough pressure on the medulla to interfere with its functions, death can result.

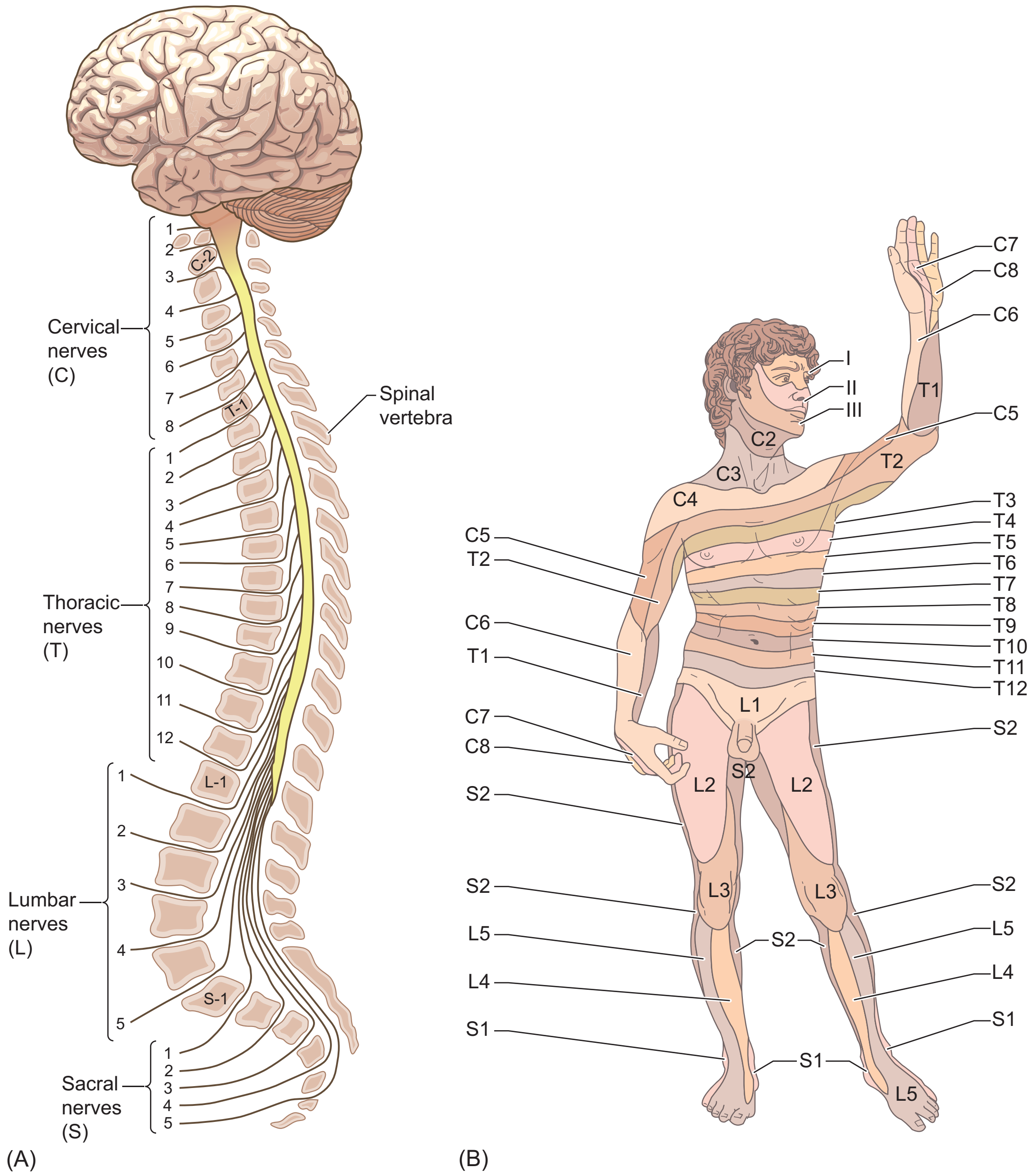

FIGURE 1.8 The location of the spinal nerves and the portions of the body they innervate.
(A) Shown on the left are the positions where each of the spinal nerves exits the spinal column. (B) On the right is a map indicating which sensory nerve carries information from that portion of the body to the spinal cord. Determining the locations of sensory loss after trauma to the spinal cord by using such maps helps medical personnel determine the level of the spinal cord at which the damage occurred. Information from the face reaches the brain via the cranial nerves.

Fourth, the medulla is home to part of a set of the neurons known as the **reticular activating system (RAS)**. These neurons receive input from the cranial nerves and project diffusely to many other regions of the brain. The reticular activating system is important for overall arousal and attention, as well as for regulation of sleep–wake cycles. Chapter 10 discusses this system in more detail.

Cerebellum: Fluid Movement

Located posterior to the medulla (see Figure 1.6) is the **cerebellum**, a brain region important for the regulation of muscle tone and guidance of motor activity. In large part, it is the region of the brain that allows a pianist to play a piece of music seamlessly or a pitcher to throw a ball fluidly. Damage to the cerebellum does not result in paralysis, but instead interferes with precision of movement and disrupts balance and equilibrium. The classic test used to detect cerebellar damage is one in which the doctor asks a person to alternate between touching his or her own nose, and then the doctor's. Although a person with cerebellar damage can follow this command, the path taken by the hand from one nose to the other will be imprecise and jagged. Damage to the cerebellum also contributes to lack of balance and motor control. A common manifestation of

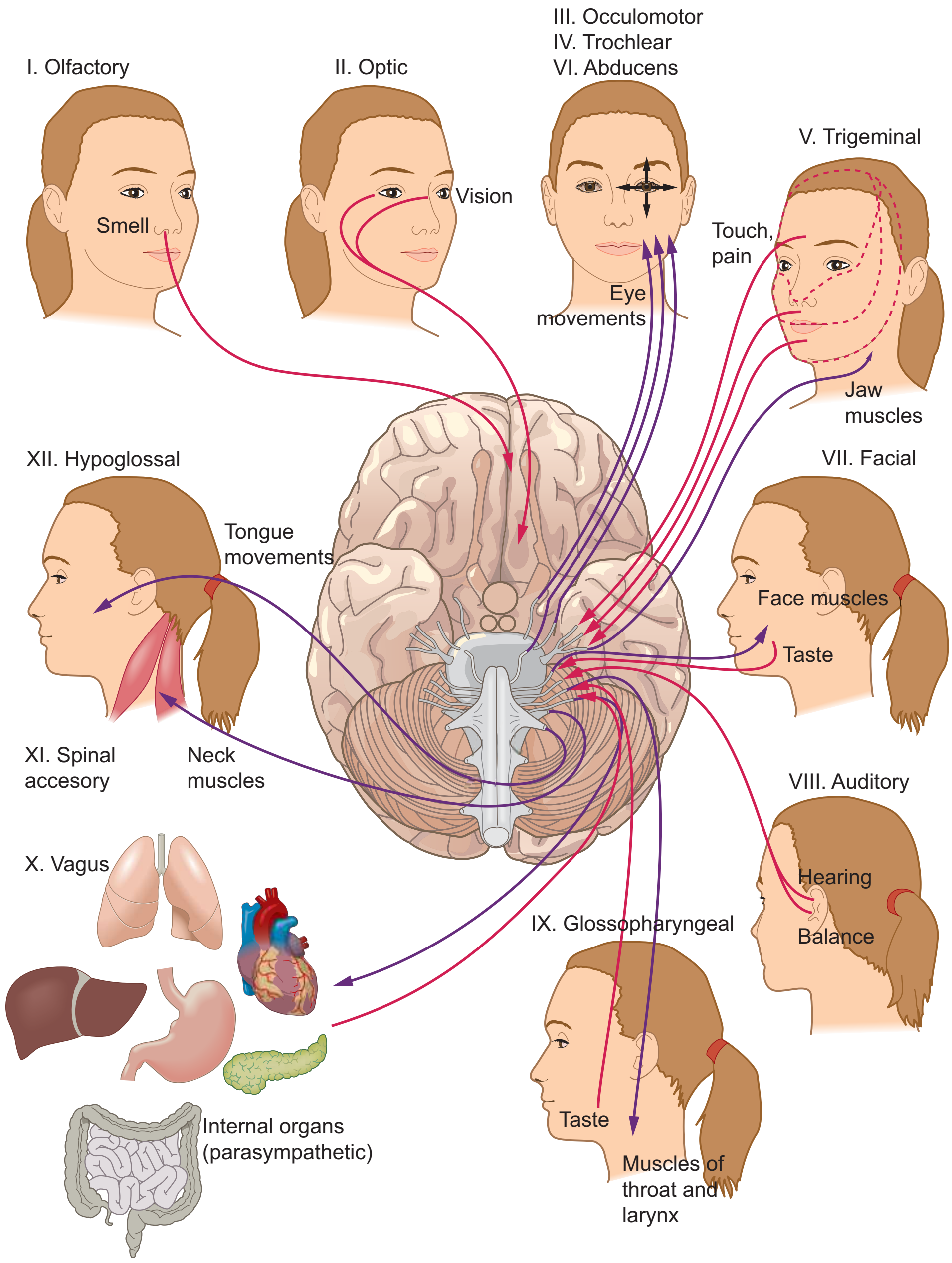

FIGURE 1.9 Locations at which the 12 cranial nerves enter or exit the brain, and each nerve's functions. A ventral (bottom) surface view of the brain is shown in the middle. The majority of cranial nerves enter at the medulla and the pons. The magenta lines represent sensory functions; the purple lines show motor functions. Some cranial nerves are sensory only, some are motor only, and some are mixed.

temporary disruption to the cerebellum is seen in *punch-drunk syndrome*, in which an individual temporarily loses balance and coordination after sustaining a hard blow to the head.

Recent evidence suggests that a specific region of the cerebellum, the lateral cerebellum, may also be linked to certain aspects of cognitive processing, allowing for fluidity and precision in mental processes (Stoodley, 2012). The lateral cerebellum may also be critical for the timing of discrete temporal intervals, acting as the brain's internal clock (Breska and Ivry, 2016).

Pons: A Connective Bridge

Directly superior to the medulla and anterior to the cerebellum, we find the multifunctional **pons** (Figure 1.10). Because of its anatomical location, it acts as the main connective bridge from the rest of the brain to the cerebellum, and as the point of connection between most of the cranial nerves and the brain. The pons also acts as an important center for the control of certain types of eye movements and for vestibular functions (e.g., balance). Finally, the pons is the site of the *superior olive*, one of the points through which auditory information is relayed from the ear to the brain. At the superior olive, information from both ears converges, allowing comparison of the information received from each ear. Such comparison is thought to be important for localization of sounds (see Chapter 5).

Midbrain: Orienting by Sound and Sight

Superior to the pons lies the **midbrain** (Figure 1.10). Like the pons and medulla, this region of the brain contains the nuclei of the cells that form some of the cranial nerves. The midbrain