17

The Anatomical Organization of the Central Nervous System

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IN THE EARLIER PARTS OF THIS book we learned that neurons in different regions of the vertebrate nervous system, and indeed in all nervous systems, are quite similar. What distinguishes one brain region from another and one brain from the next are the number and types of its neurons and how they are interconnected. It is from the patterns of interconnections that the distinctiveness of behavior emerges. Whether it be a simple reflex response or a complex mental act, behavior results from the pattern of signaling between appropriately interconnected cells.

This fundamental simplicity in the organization of neuronal circuits is more than counterbalanced by numerical complexity. Even a relatively simple behavior recruits the activity of many neurons. Consider the act of hitting a tennis ball ([Figure 17-1](#)). For this task several sensory systems are called into play. Visual information about the motion of the approaching ball is processed in the visual system, which identifies the flying object and computes its direction and velocity. Proprioceptive information about the position of the player's arms, legs, and trunk in space are also computed by the brain to plan the appropriate positioning of the body for interception of the ball. All of this sensory information ultimately

P.318

reaches multisensory processing regions in the cerebral cortex called association areas, where the information is combined to elicit the memory of earlier attempts to hit a tennis ball.
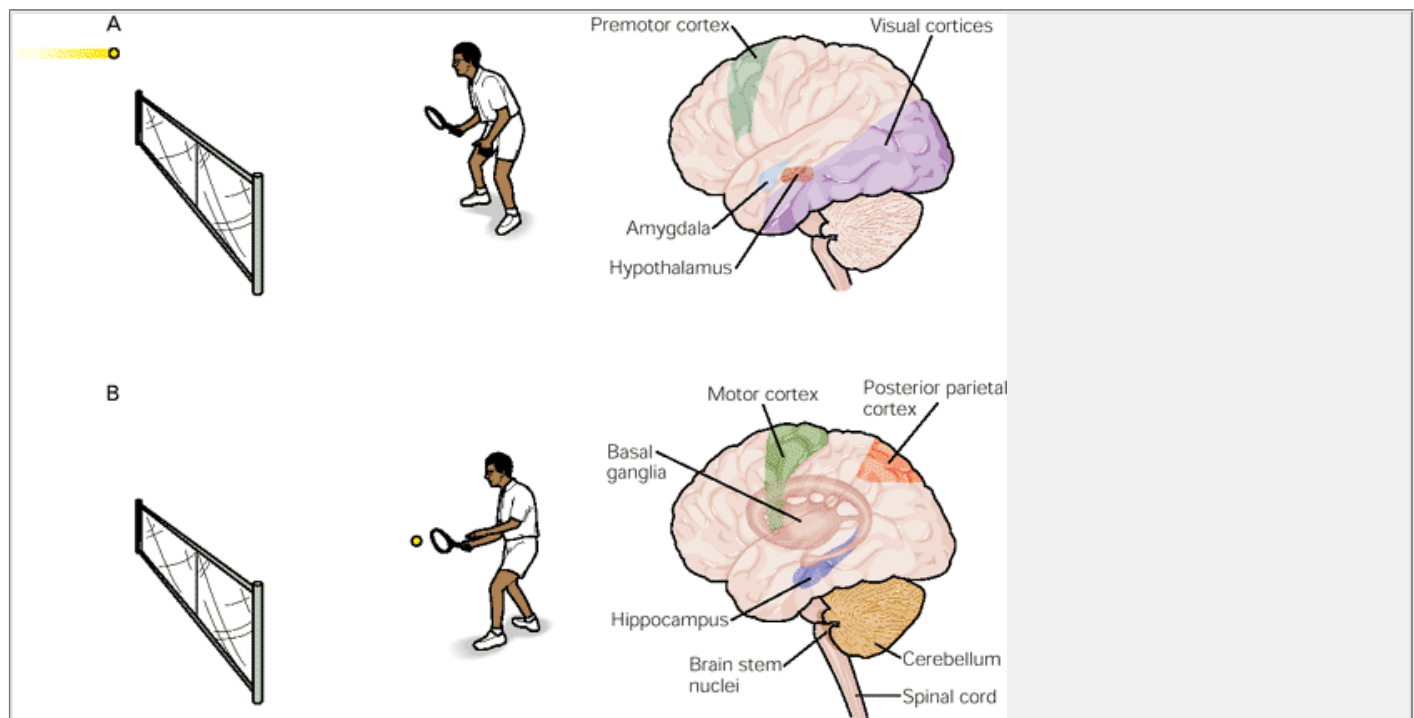

Figure 17-1 Even simple behaviors use many parts of the brain.

A. The tennis player is watching the approaching ball. He uses his visual cortex to identify the ball and judge its size, direction, and velocity. His premotor cortex develops a motor program that will allow him to approach the ball and hit it back. The amygdala adjusts the heart rate, respiration, and other homeostatic mechanisms to allow successful performance of the behavior. The amygdala also activates the hypothalamus to motivate the player to hit a good shot.

B. To execute the shot the player must use all of the structures illustrated in **A** as well as others. The player's motor cortex must send signals to the spinal cord that will activate and inhibit many muscles in the arms and legs. The basal ganglia become involved in initiating motor patterns and perhaps in recalling learned movements to hit the ball properly. The cerebellum fine tunes the movements based on proprioceptive information from peripheral sensory receptors. The posterior parietal cortex provides the player with a sense of where his body is located in three-dimensional space and where his racket arm is located with respect to the rest of the body. During this entire process, brain stem nuclei are involved in regulating heart rate, respiration, and arousal. The hippocampus is not involved in hitting the ball, but it is involved in recording in memory all of the details of the point so that the player can brag about it later. In fact, many other brain regions are also active during this simple behavior. The common sense notion that only a fraction of the brain is used at any one time is clearly wrong. It is more likely that virtually all of the brain is active in even simple behaviors such as hitting a tennis ball.

In addition, the afferent information for the planned behavior recruits activity in the amygdala, a structure concerned with emotion and social behavior. The amygdala in turn activates the autonomic nervous system to prepare the body for action. Finally, brain systems concerned with voluntary movement are recruited to initiate the behavior. The multisensory association areas make connections with higher-order motor centers that compute a program for moving the racket into position. This program is then passed on to the primary motor cortex for execution. The motor commands from the brain must be targeted to the correct muscles in the back, shoulder, arm, and hand. They must also be timed so that contraction and relaxation of appropriate muscle groups are coordinated, and they must regulate body posture as a whole.

Once the behavior is initiated the job of the brain is not over. As the arm is raised and the ball approaches, many minor adjustments of the initial motor program are made based on more recent sensory information about the exact trajectory of the approaching ball before the arm moves the racket against the ball. Of course, as

P.319

the behavior is being executed, the brain is also engaged in maintaining the player's heart rate, respiration, and other autonomic functions that are typically outside the awareness of the player.

As this example illustrates, our behavior is shaped in response to stimuli in our environment, and the environment that we know is created in the brain from our senses: sight, sound, smell, taste, touch, pain, and the sensation of body movements. Perception begins with receptor cells at the periphery that are sensitive to

one or another kind of stimulus and encode information about the stimulus, such as its location and intensity. The receptors in turn excite sensory neurons that form connections with discrete sets of neurons in the spinal cord. The information from each receptor is then analyzed in the brain stem, thalamus, and cerebral cortex in the context of information from all other receptors. For example, when we hold something in the hand, touch receptors produce action potentials in afferent fibers from the hand. These signals eventually reach the processing centers of the somatic sensory system—in the dorsal column nuclei, the thalamus, and several connected areas of the cortex—where they cause certain populations of cells to discharge.

Initially, sensory information is processed in a series of relays, each of which involves more complex information processing than the preceding relay. Sensory fibers project in an orderly pattern from the periphery to the central nervous system, and from one part of the brain to the next, thereby creating a topographically organized neural map of the receptive surface in the brain. In fact, most sensory systems have several serial pathways that process different types of information simultaneously. This *parallel processing* of sensory information by different components of one sensory system, and by all sensory systems together, is the way our brain first analyzes sensory information. In addition, the perceptions generated by the sensory systems recruit the amygdala, which colors perception with emotion, and the hippocampus, which stores aspects of perception in long-term memory. Finally, our sensory experiences initiate and guide our actions: The ascending stream of sensory information connects with the motor systems, which convey signals down motor pathways to the spinal cord for reflexive and volitional movement.

Thus, to understand behavior, it is necessary to break down a behavior into component behaviors, identify the regions of the brain that contribute to each component, and analyze how the participating regions connect. Although the anatomy of the brain and the pattern of its interconnections appear complex, the functional organization of the nervous system is governed by a relatively simple set of principles that make the many details of brain anatomy comprehensible. In this chapter we review the major anatomical components of the central nervous system and outline the organizational principles of the major functional systems. In the next chapter we shall use the somatosensory system to examine the principles underlying the neural basis of perception and movement.

The Central Nervous System Has Seven Major Divisions

All behavior is mediated by the central nervous system, which consists of the spinal cord and the brain. The brain is composed of six regions, each of which can be further subdivided into several anatomically and functionally distinct areas. The six major brain divisions are the medulla, pons, cerebellum, midbrain, diencephalon, and cerebral hemispheres or telencephalon (Figure 17-2). Each of these divisions is found in both hemispheres of the brain, but may differ in size and shape. The orientation of components of the central nervous system within the body is described with reference to three axes (Figure 17-3).

Spinal Cord

The spinal cord is the most caudal part of the central nervous system and, in many respects, the simplest part. It extends from the base of the skull to the first lumbar vertebra. The spinal cord receives sensory information from the skin, joints, and muscles of the trunk and limbs and contains the motor neurons responsible for both voluntary and reflex movements.

Along its length the spinal cord varies in size and shape, depending on whether the emerging motor nerves innervate the limbs or trunk. The cord is divided into gray matter and surrounding white matter. The gray matter, which contains nerve cell bodies, is typically divided into dorsal and ventral horns (so-called because the gray matter appears H-shaped in transverse sections). The *dorsal horn* contains an orderly arrangement of sensory relay neurons that receive input from the periphery, while the *ventral horn* contains motor nuclei that innervate specific muscles. The white matter is made up of longitudinal tracts of myelinated axons that form the ascending pathways through which sensory information reaches the brain and the descending pathways that carry motor commands and modulatory influences from the brain (see Figure 18-1).

The nerve fibers that link the spinal cord with muscles and sensory receptors in the skin are bundled in 31 pairs of spinal nerves, each of which has a sensory division

that emerges from the dorsal aspect of the cord (the *dorsal root*) and a motor division that emerges from the ventral aspect (the *ventral root*). The dorsal roots carry sensory information into the spinal cord from muscles and skin. Different classes of axons coursing in the dorsal roots mediate sensations of pain, temperature, and touch. The cord also receives sensory information from internal organs. The ventral roots are bundles of the outgoing axons of motor neurons that innervate muscles. The motor neurons of the spinal cord comprise the "final common pathway," since all higher brain levels controlling motor activity must ultimately act through these neurons in the ventral horn and their connections to muscles. Ventral roots from certain levels of the spinal cord also include sympathetic and parasympathetic axons
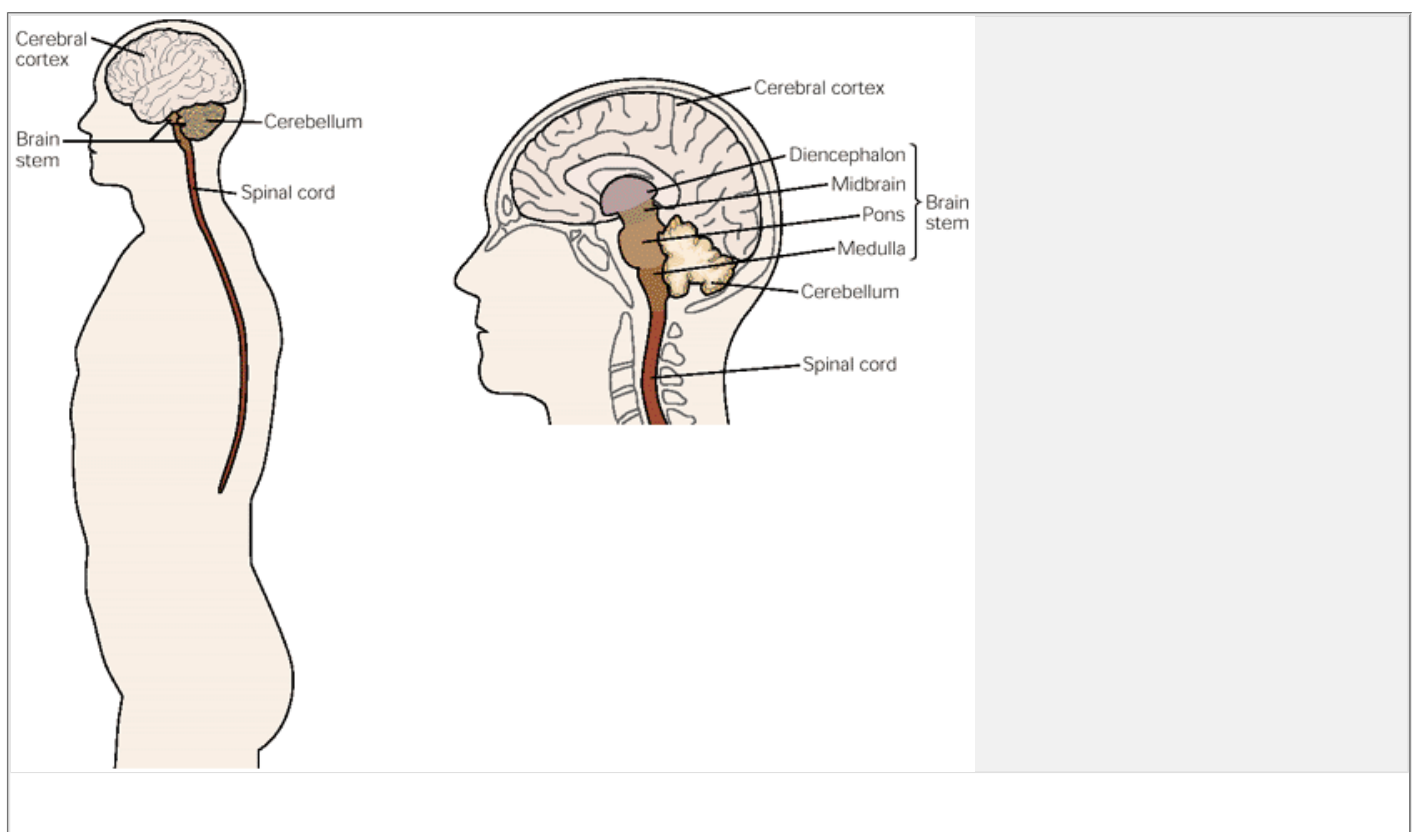
The next three divisions of the central nervous system rostral to the spinal cord—the medulla, pons, and midbrain—are collectively termed the *brain stem.* The brain stem is continuous with the spinal cord and contains distinct nerve cell clusters that contribute to a variety of sensory and motor systems. The sensory input and motor output of the brain stem is carried by 12 cranial nerves that are functionally analogous to the 31 spinal nerves. Whereas the spinal cord mediates sensation and motor control of the trunk and limbs, the brain stem is concerned with sensation from and motor control of the head, neck, and face.

The brain stem is also the site of entry for information from several specialized senses, such as hearing, balance, and taste. Motor neurons in the brain stem control the muscles of the head and neck. Neurons in the brain stem also mediate many parasympathetic reflexes, such as decreases in cardiac output and blood pressure, increased peristalsis of the gut, and constriction of the pupils. The brain stem contains ascending and descending pathways that carry sensory and motor information to other divisions of the central nervous system. In addition, a relatively diffuse network of neurons distributed throughout the core of the brain stem, known as the *reticular formation*, receives a summary of much of the sensory information that enters the spinal cord and brain stem and is important in influencing the arousal level of an organism.

Medulla

The medulla is the direct rostral extension of the spinal cord and resembles the spinal cord both in organization and function. Neuronal groups in the medulla participate in regulating blood pressure and respiration. The

P.321

P.322

medulla also contains neuronal cell groups that form some of the early relay nuclei involved in taste, hearing, and maintenance of balance as well as the control of neck and facial muscles.
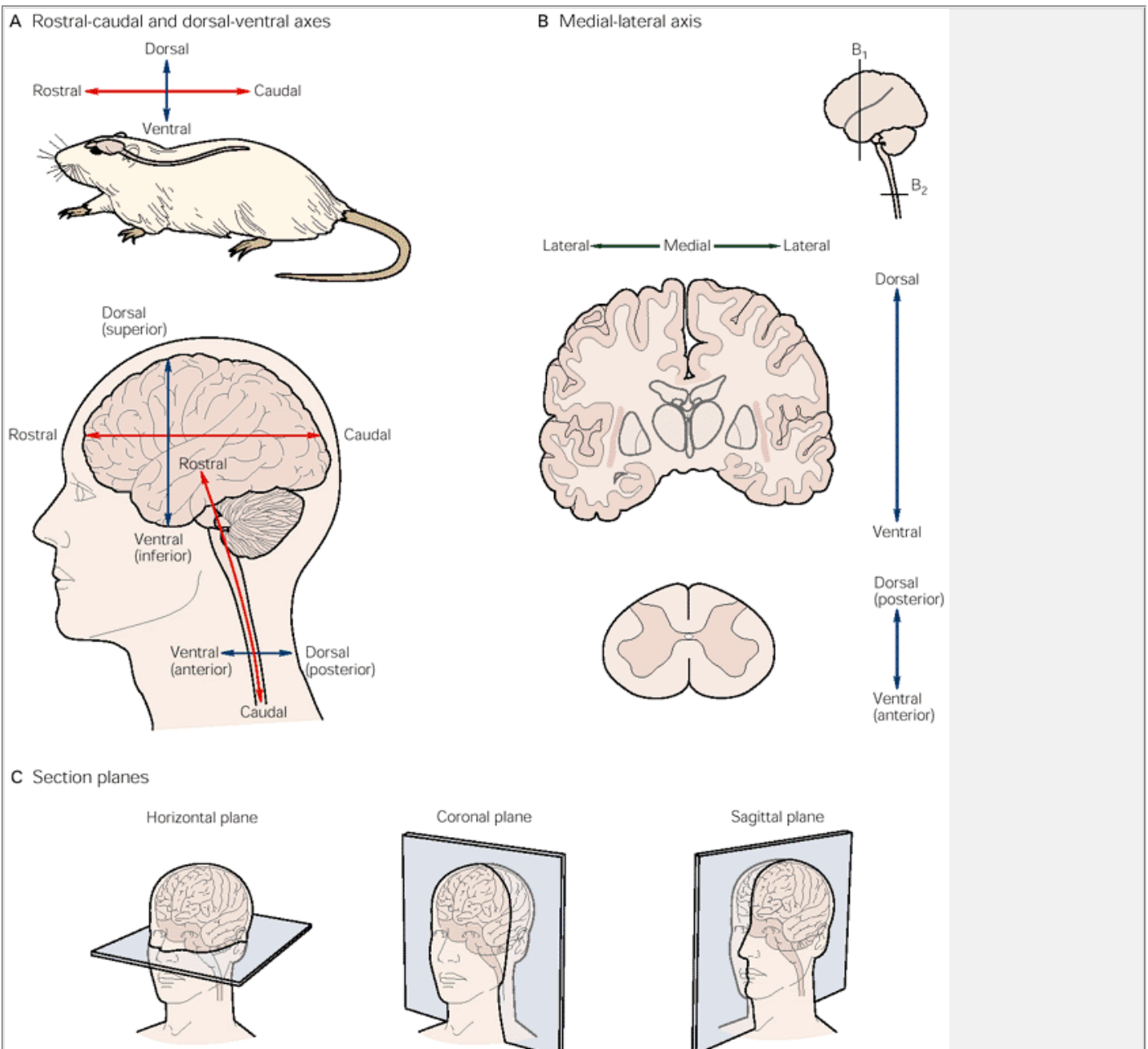

A Rostral-caudal and dorsal-ventral axes

Dorsal

Rostral ← → Caudal

Ventral

Dorsal (superior)

Rostral ← → Caudal

Rostral

Ventral (inferior)

Ventral (anterior) ← → Dorsal (posterior)

Caudal

B Medial-lateral axis

B₁

B₂

Lateral ← Medial → Lateral

Dorsal

Ventral

Dorsal (posterior)

Ventral (anterior)

C Section planes

Horizontal plane

Coronal plane

Sagittal plane

Pons

The pons lies rostral to the medulla and protrudes from the ventral surface of the brain stem. The ventral portion of the pons contains a large number of neuronal clusters, the pontine nuclei, that relay information about movement and sensation from the cerebral cortex to the cerebellum. The dorsal portion of the pons contains structures involved in respiration, taste, and sleep.

Midbrain

The midbrain, the smallest part of the brain stem, lies rostral to the pons. Neurons in the midbrain provide important linkages between components of the motor systems, particularly the cerebellum, the basal ganglia, and the cerebral hemispheres. For example, the substantia nigra, a distinct nucleus of the midbrain, provides important input to a portion of the basal ganglia that regulates voluntary movements. The substantia nigra is the focus of intense clinical and research interest since its dopaminergic neurons are damaged in Parkinson's disease, resulting in the pronounced motor disturbances that are associated with the disease (Chapter 43). The midbrain also contains components of the auditory and visual systems. Finally, several regions of the midbrain are connected to the extraocular muscles of the eye and provide the major pathway for controlling eye movements.

Cerebellum

The cerebellum, which lies over the pons, contains a far greater number of neurons than any other single subdivision of the brain, including the cerebral hemispheres. Nevertheless, it contains relatively few neuronal types, and as a result, its circuitry is well understood.

The surface, or cortex, of the cerebellum is divided into several lobes separated by distinct fissures. The cerebellum receives somatosensory input from the spinal cord, motor information from the cerebral cortex, and input about balance from the vestibular organs of the inner ear. It is important for maintaining posture and for coordinating head and eye movements and is also involved in fine tuning the movements of muscle and in learning motor skills. In the past, the cerebellum was considered to be purely a motor structure, but modern functional imaging studies of the human brain reveal that it is also involved in language and other cognitive functions. Underlying these functions is substantial input from sensory association regions of the neocortex to the pontine nuclei.

Diencephalon

The diencephalon contains two major subdivisions: the thalamus and hypothalamus. The *thalamus* is an essential link in the transfer of sensory information (other than olfactory) from receptors in the periphery to sensory processing regions of the cerebral hemispheres. It was previously thought that the thalamus acted only as a relay station for sensory information traveling to the neocortex, but it is now clear that it plays a gating and modulatory role in relaying sensory information. In other words, the thalamus determines whether sensory information reaches conscious awareness in the neocortex. The thalamus participates in the integration of motor information from the cerebellum and the basal ganglia and transmits this information to the regions of the cerebral hemispheres concerned with movement. The diencephalon also has regions that, like the reticular formation, are thought to influence levels of attention and consciousness.

The *hypothalamus* lies ventral to the thalamus and regulates several behaviors that are essential for homeostasis and reproduction. For example, it controls a variety of bodily functions, including growth, eating, drinking, and maternal behavior, by regulating the hormonal secretions of the pituitary gland. The hypothalamus also influences behavior through its extensive afferent and efferent connections with practically every region of the central nervous system. It is an essential component of the motivational system of the brain, initiating and maintaining behaviors the organism finds rewarding. One part of the hypothalamus, the suprachiasmatic nucleus, regulates circadian rhythms, cyclical behaviors that are entrained to the daily light-dark cycle.

Cerebral Hemispheres

The cerebral hemispheres form the largest region of the human brain. They consist of the cerebral cortex, the underlying white matter, and three deep-lying structures: the basal ganglia, the amygdala, and the hippocampal formation. The cerebral hemispheres are concerned with perceptual, motor, and cognitive functions, including memory and emotion. The two hemispheres are interconnected by the corpus callosum, a prominent set of fibers that connect symmetrical regions in both hemispheres.

The corpus callosum, which is visible on the medial surface of the hemispheres, is the largest of the commissures, structures that contain fibers that mainly link similar regions of the left and right sides of the brain. The amygdala is concerned with social behavior and the expression of emotion, the hippocampus with memory, and the basal ganglia with the control of fine movement.

Five Principles Govern the Organization of the Major Functional Systems

The central nervous system consists of several discrete functional systems. There are, for example, discrete systems for each of the modalities of sensation (touch, vision, hearing, taste, smell) and for action.

Each Functional System Involves Several Brain Regions That Carry Out Different Types of Information Processing

The neural circuits of several functional systems course through some of the same brain structures. In a number of sensory systems, for example, receptors in the periphery project to one or more regions in the spinal cord, brain stem, and thalamus. The thalamus projects to the primary sensory cortices, which in turn project to other regions of the cerebral cortex. Thus one structure may contain components of several functional systems.

The components of a functional system are often called relays because of their serial organization. The term *relay* is misleading, however, since it implies passage of information without modification. In fact, information is transformed at every step, and the output of one stage of a functional system is rarely the same as its

input. Information may be amplified at one stage of the system or it may be attenuated, depending, for example, on the arousal level of the animal. At each stage a single neuron typically receives inputs from thousands of presynaptic neurons, and it is the summation of all of these influences that governs the output of the neuron to the next stage

Although a variety of neurons are involved at each stage in information processing, these neurons generally fall into two functional classes: principal (or projection) neurons and local interneurons. The axons of principal neurons convey information to the next stage in the system. Interneurons may receive inputs from the same sources as the principal cells, but they contact only local cells involved in the same processing stage. Whereas principal neurons tend to excite the neurons to which they project, interneurons often inhibit their target neurons (see Chapters 2 and 4).

Identifiable Pathways Link the Components of a Functional System

Axons leaving one component of a functional system are bundled together in a *pathway* that projects to the next component. Each pathway is located in approximately the same region in every brain. Thus many large bundles of axons can be seen with the unaided eye in the gross brain and were named by the classical neuro-anatomists. The pyramidal tracts, for example, project conspicuously from the cerebral cortex to the spinal cord. The corpus callosum is another prominent fiber bundle. Most pathways are not nearly as prominent but can be demonstrated with modern neuroanatomical tracing techniques (see Box 5-1). These more subtle pathways, too, are typically found in the same position in all individuals.

Each Part of the Brain Projects in an Orderly Fashion Onto the Next, Thereby Creating Topographical Maps

One of the most striking features of the organization of most sensory systems is that the peripheral receptive surface—the retina of the eye, the cochlea of the inner ear, and the surface of the skin—is represented *topographically* throughout successive stages of processing. Neighboring groups of cells in the retina, for example, project to neighboring groups of cells in the visual portion of the thalamus, which in turn project to neighboring regions of the visual cortex. In this way an orderly *neural map* of information from the receptive surface is retained at each successive level in the brain.

Such neural maps reflect not only the position of receptors but also their density, since density of innervation determines the degree of sensitivity to sensory stimuli. For example, the central region of the retina, the fovea, has the highest density of receptors and thus affords the greatest visual acuity. Correspondingly, in the visual cortex the area devoted to information from the fovea is greater than the area representing the peripheral portion of the retina, where the density of receptors (and visual acuity) is lower.

In the motor system, neurons that regulate particular body parts are clustered together to form a motor map; the most well-defined motor map is in the primary motor cortex. The motor map, like the sensory maps, does not represent every part of the body equally. The extent of the representation of an individual body part reflects the density of innervation of that part and thus the fineness of control required for movements in that part.

P.324

Functional Systems Are Hierarchically Organized

In most brain systems information processing is organized hierarchically. In the visual system, for example, each neuron in the lateral geniculate nucleus (within the thalamus) is responsive to a spot of light in a particular region of the visual field. The axons of several adjacent thalamic neurons converge on cells in the primary visual cortex, where each cell fires only when a particular arrangement of presynaptic cells is active. For example, a cortical cell may fire only when the inputs signal a bar of light with a particular orientation.

In turn, cells in the primary visual cortex converge on individual cells in the association cortex. These cells respond even more selectively to information, for example a bar of light moving in a certain direction. Information passes both serially and in parallel through as many as 35 or more cortical regions dedicated to the processing of visual information. At very advanced stages of visual information processing in the cortex, individual neurons are responsive to highly complex information, such as the shape of a face.

Functional Systems on One Side of the Brain Control the Other Side of the Body

An important, but as yet unexplained, feature of the organization of the central nervous system is that most neural pathways are bilaterally symmetrical and cross over to the opposite (contralateral) side of the brain or spinal cord. As a result, sensory and motor activities on one side of the body are mediated by the cerebral hemisphere on the opposite side. Thus, movement on the left side of the body is largely controlled by neurons in the right motor cortex.

The pathways of different systems cross at different anatomical levels within the brain. For example, the ascending pathway for pain crosses in the spinal cord almost immediately upon entering the central nervous system. The pathway for fine touch, however, ascends on the same side of the spinal cord that it enters and ascends to the medulla, where it makes its first synapse. There, second-order fibers cross over to the thalamus on the contralateral side. Crossings of this kind within the brain stem and spinal cord are called *decussations.*
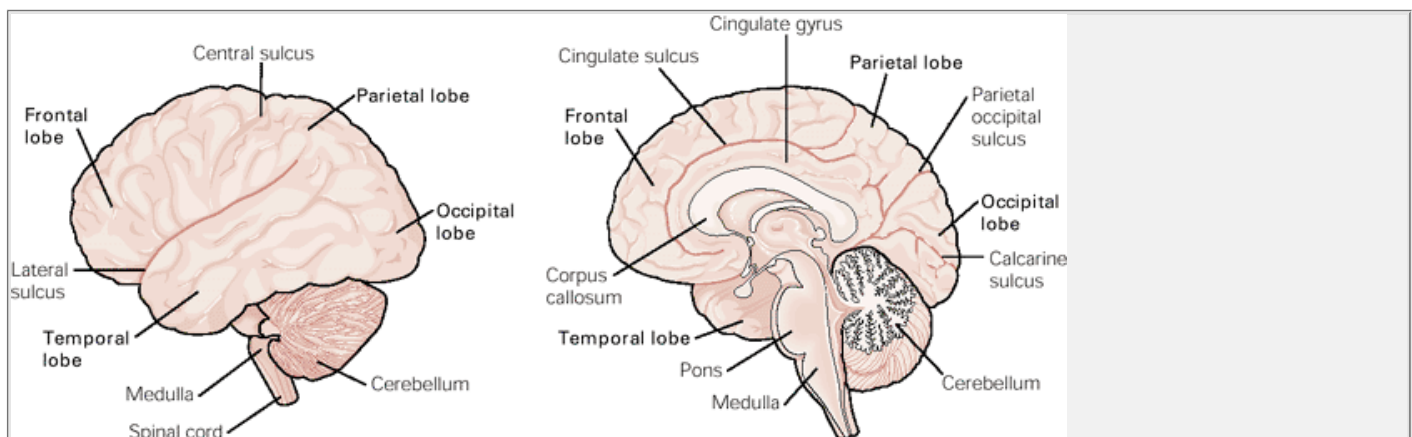

Figure 17-4 The major lobes of the cerebral cortex, some prominent sulci, and other brain regions are illustrated in lateral (left) and medial (right) views of the human brain. (Adapted from Martin 1989.)

The Cerebral Cortex Is Concerned With Cognitive Functioning

While many life-sustaining functions are mediated by regions of the spinal cord, brain stem, and diencephalon, it is the cerebral cortex—the thin outer layer of the

cerebral hemispheres—that is responsible for much of the planning and execution of actions in everyday life. Phylogenetically, humans have the most elaborated cerebral cortex, and much of modern neuroscience is directed at understanding the functions and disorders of the human cortex.

The cerebral cortex has a highly convoluted shape, formed by grooves (*sulci*) that separate elevated regions (*gyri*). The precise reason for this convoluted shape is not known. It is likely that it arose during evolution to accommodate an increase in the number of neurons. The thickness of the cortex does not vary substantially in different species; it is always around 2 to 4 mm thick. The surface area, however, is dramatically larger in higher primates, particularly in the human brain. The number of neurons in the cerebral cortex is one of the crucial determinants of the cortex's capacity for information processing. As we shall see shortly, the neocortex is organized in functional layers. Information in the neocortex is processed *across* the layers in an interconnected

set of neurons called *columns*, or *modules* (see Chapter 23). An increase in the surface area of the cortex permits a greater number of modules and thus provides greater capacity for processing information.
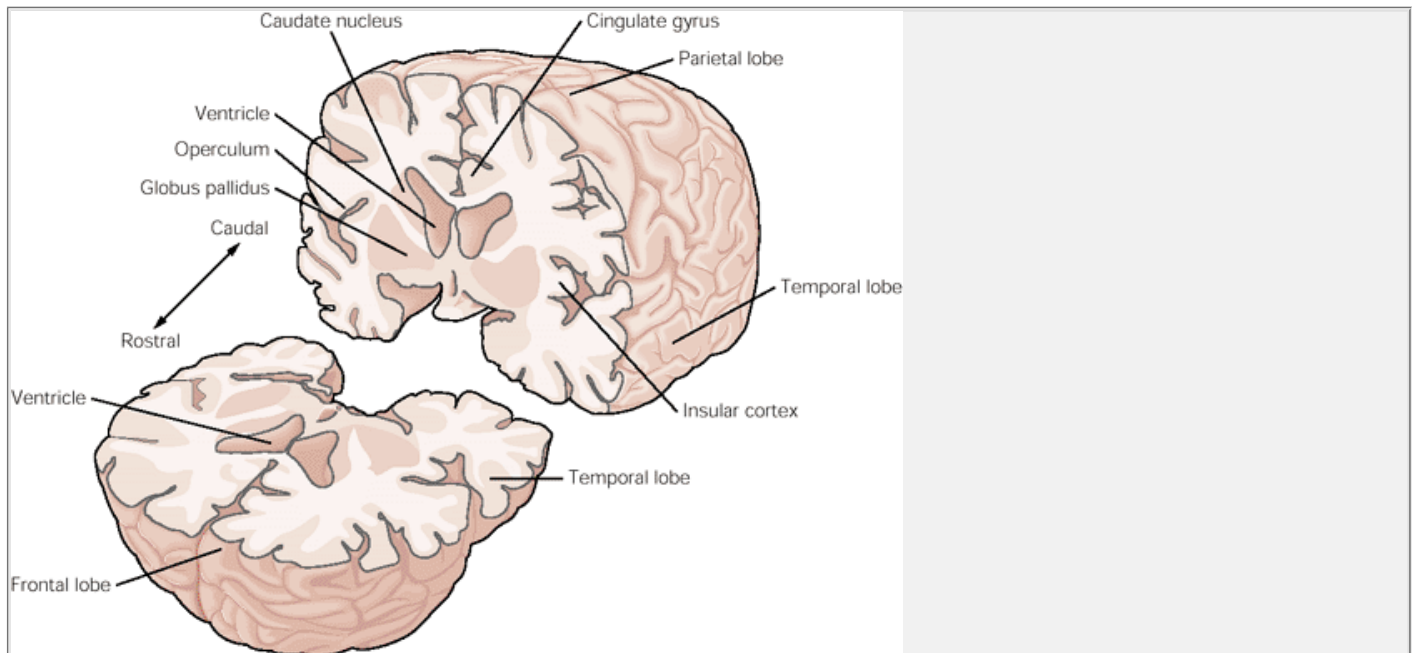

Figure 17-5 Some structures of the cerebral hemispheres cannot be seen from the surface of the brain. For example, the basal ganglia (caudate nucleus and globus pallidus) and insular cortex can be seen only after the brain has been sectioned. Large cavities in the brain called *ventricles* are filled with cerebrospinal fluid. (Adapted from England and Wakely 1991.)

The Cerebral Cortex Is Anatomically Divided Into Four Lobes

The cerebral cortex is divided into four major lobes named after the overlying cranial bones: frontal, parietal, temporal, and occipital (Figures 17-4 and 17-5). Each lobe includes many distinct functional domains. The temporal lobe, for example, has distinct regions that carry out auditory, visual, or memory functions. Two additional regions of the cerebral cortex are the cingulate cortex, which surrounds the dorsal surface of the corpus callosum, and the insular cortex (insula), which is not visible on the surface owing to the overgrowth of the frontal, parietal, and temporal lobes. (The overhanging portion of the cerebral cortex that buries the insula within the lateral sulcus is called the operculum.)

The four lobes are conspicuously defined by particularly prominent sulci of the cortex that have a relatively consistent position in human brains. One of the most prominent indentations of the cerebral cortex—the lateral sulcus or sylvian fissure—separates the temporal lobe from the frontal and parietal lobes. The insular cortex forms the medial limit of the lateral sulcus. Another prominent indentation, the central sulcus, runs medially and laterally on the dorsal surface of the hemisphere and separates the frontal and parietal lobes (Figure 17-4).

Pierre Paul Broca first drew attention to the continuity of medial portions of the cerebral hemispheres, where portions of the frontal, parietal, and temporal lobes encircle and border the fluid-filled ventricles of the brain. Broca called this region the limbic lobe (Latin *limbus*, border). The limbic lobe is no longer considered one of the major subdivisions of the cerebral cortex. However, the cingulate cortex, which surrounds the corpus callosum (Figure 17-4), is considered a separate division of the neocortex, much like the insular cortex.

The Cerebral Cortex Has Functionally Distinct Regions

Many areas of the cerebral cortex are concerned primarily with processing sensory information or delivering motor commands. In addition, an area dedicated to a particular sensory modality or motor function includes several specialized areas that have different roles in processing information. These areas are known as primary, secondary, or tertiary sensory or motor areas, depending

on their proximity to the peripheral sensory and motor pathways. For example, the primary motor cortex mediates voluntary movements of the limbs and trunk; it is called *primary* because it contains neurons that project directly to the spinal cord to activate somatic motor neurons. The primary sensory areas receive most of their information directly from the thalamus; only a few synaptic relays are interposed between the thalamus and the peripheral receptors.
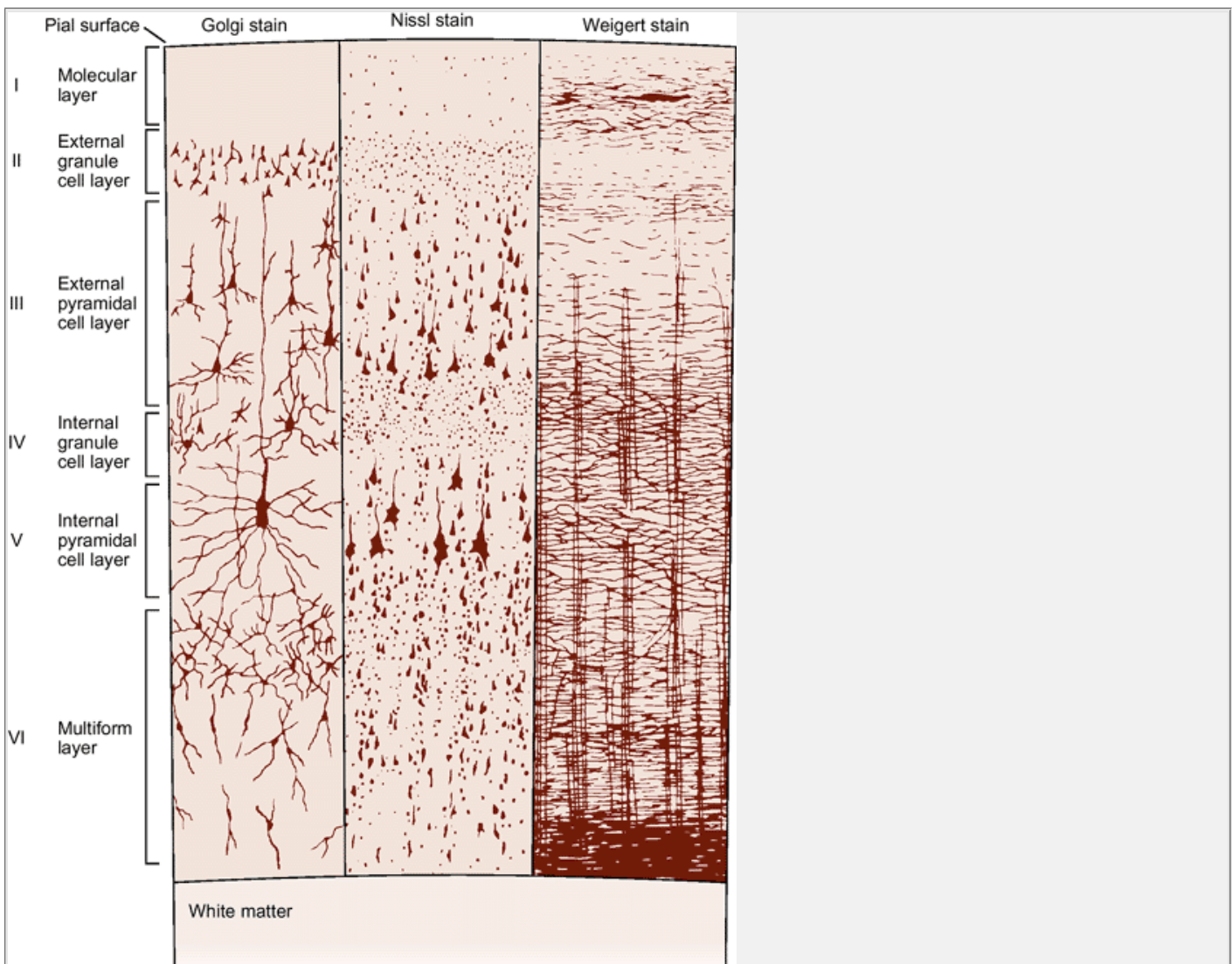
Figure 17-6 The neurons of the cerebral cortex are arranged in distinctive layers. The appearance of the cortex depends on what is used to stain it. The Golgi stain reveals neuronal cell bodies and dendritic trees. The Nissl method shows cell bodies and proximal dendrites. A Weigert stain for myelinated fibers reveals the pattern of axonal distribution. (From Heimer 1994.)

The primary visual cortex is located caudally in the occipital lobe and is predominantly associated with the prominent calcarine sulcus (Figure 17-4). The primary auditory cortex is located in the temporal lobe, where it is associated with a series of gyri (Heschl's gyri) on the lateral sulcus. The primary somatosensory cortex is located caudal to the central sulcus on the postcentral gyrus, in the parietal lobe.

Each primary sensory area conveys information to an adjacent, higher-order area (or unimodal association area), which refines the information of a single sensory modality. Each higher-order area sends its outputs to one or another of three major multimodal association areas that integrate information from two or more sensory modalities and coordinate this information with plans for action (see Chapter 19).

The primary motor cortex, located just rostral to the central sulcus, is intimately associated with the motor systems of the spinal cord. Cortical cells influence neurons in the ventral horn of the spinal cord responsible for muscle movements. Whereas the primary sensory areas of cortex are the *initial* site of cortical processing of sensory information, the primary motor cortex is the *final* site in the cortex for processing motor commands. Higher-order motor areas, located rostral to the primary motor cortex in the

frontal lobe, compute programs of movement that are conveyed to the primary motor cortex for implementation.

The Cerebral Cortex Is Organized in Layers

The cerebral cortex is organized into cell layers. The number of layers and the details of their functional organization vary throughout the cortex. The most typical form of neocortex contains six layers, numbered from the outer surface (pia mater) of the cortex to the white matter (Figure 17-6).

- Layer I is an acellular layer called the *molecular layer*. It is occupied by dendrites of the cells located deeper in the cortex and axons that travel through or form connections in this layer.

- Layer II is comprised mainly of small spherical cells called granule cells and therefore is called the *external granule cell layer*.

- Layer III contains a variety of cell types, many of which are pyramidally shaped; the neurons located deeper in layer III are typically larger than those located more superficially. Layer III is called the *external pyramidal cell layer*.

- Layer IV, like layer II, is made up primarily of granule cells and is called the *internal granule cell layer*.

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Layer V, the *internal pyramidal cell layer*, contains mainly pyramidally shaped cells that are typically larger than those in layer III.

- Layer VI is a fairly heterogeneous layer of neurons and is thus called the *polymorphic or multiform layer*. It blends into the white matter that forms the deep limit of the cortex and carries axons to and from the cortex.

Although each layer of the cerebral cortex is defined primarily by the presence or absence of neuronal cell bodies, each layer also contains additional elements. Thus, layers I-III contain the apical dendrites of neurons that have their cell bodies in layers V and VI, while layers V and VI contain the basal dendrites of neurons with cell bodies in layers III and IV. The profile of inputs to a particular cortical neuron depends more on the distribution of its dendrites than on the location of its cell body.

Not all cortical regions have the same laminar organization. For example, the precentral gyrus, which functions as the primary motor cortex, has essentially no internal granule cell layer (layer IV) and thus is called agranular cortex. In contrast, the region of the occipital cortex that functions as the primary visual cortex has an extremely prominent layer IV that typically is further subdivided into at least three sublayers (Figure 17-7). These two cortical areas are among the easiest to identify in histological sections.

The prominence or lack of prominence of layer IV can be understood in relation to its connections with the thalamus. Layer IV is the main target of sensory information arriving from the thalamus. In highly visual animals, such as humans, the lateral geniculate nucleus provides a large and highly organized input to layer IV of the primary visual cortex. The motor cortex, on the other hand, is primarily an output region of the neocortex and thus receives little sensory information directly from the thalamus.

The distinctive laminar structure of the primary visual or motor cortices is not typical of the neocortical surface. However, early students of the cerebral cortex, such as Korbinian Brodmann, used the relative prominence of the layers above and below layer IV or the distinctive cell size or packing characteristics in cortical regions to define borders between cortical areas. Based on such differences, Brodmann in 1909 divided the cerebral cortex into 47 cytoarchitectonic regions (Figure 17-7).

While Brodmann's demarcation appears to coincide in part with more recent information on the functions of the neocortex, the cytoarchitectonic method alone does not capture the subtlety or variety of function of all the distinct regions of the cortex. For example, Brodmann listed five regions (areas 17-21) as being concerned with visual function in the monkey. In contrast, modern connectional neuroanatomy and electrophysiology have identified more than 35 functionally distinct cortical regions within the region studied by Brodmann.

The Layers Organize Inputs and Outputs

What is the functional significance of the layered organization? The neocortex receives inputs from the thalamus, from other cortical regions on both sides of the brain, and from a variety of other sources. The output of the neocortex is also directed to several brain regions, including other regions of the neocortex on both sides of the brain, the basal ganglia, the thalamus, the pontine nuclei, and the spinal cord. Different inputs to the neocortex appear to be processed in different ways and the outputs of the neocortex arise from different populations of neurons. The layering of neurons provides an efficient means of organizing the input-output relationships of neocortical neurons (Figure 17-8).

Within the neocortex information passes serially from one processing center to another. In the visual system, for example, the connections between the primary visual cortex and secondary and tertiary visual areas, called associational or feed-forward connections, originate

mainly from cells in layer III and terminate mainly in layer IV. Feedback projections from later to earlier stages of processing are also typical; these originate from cells in layers V and VI and terminate in layers I/II and VI (Figure 17-9).
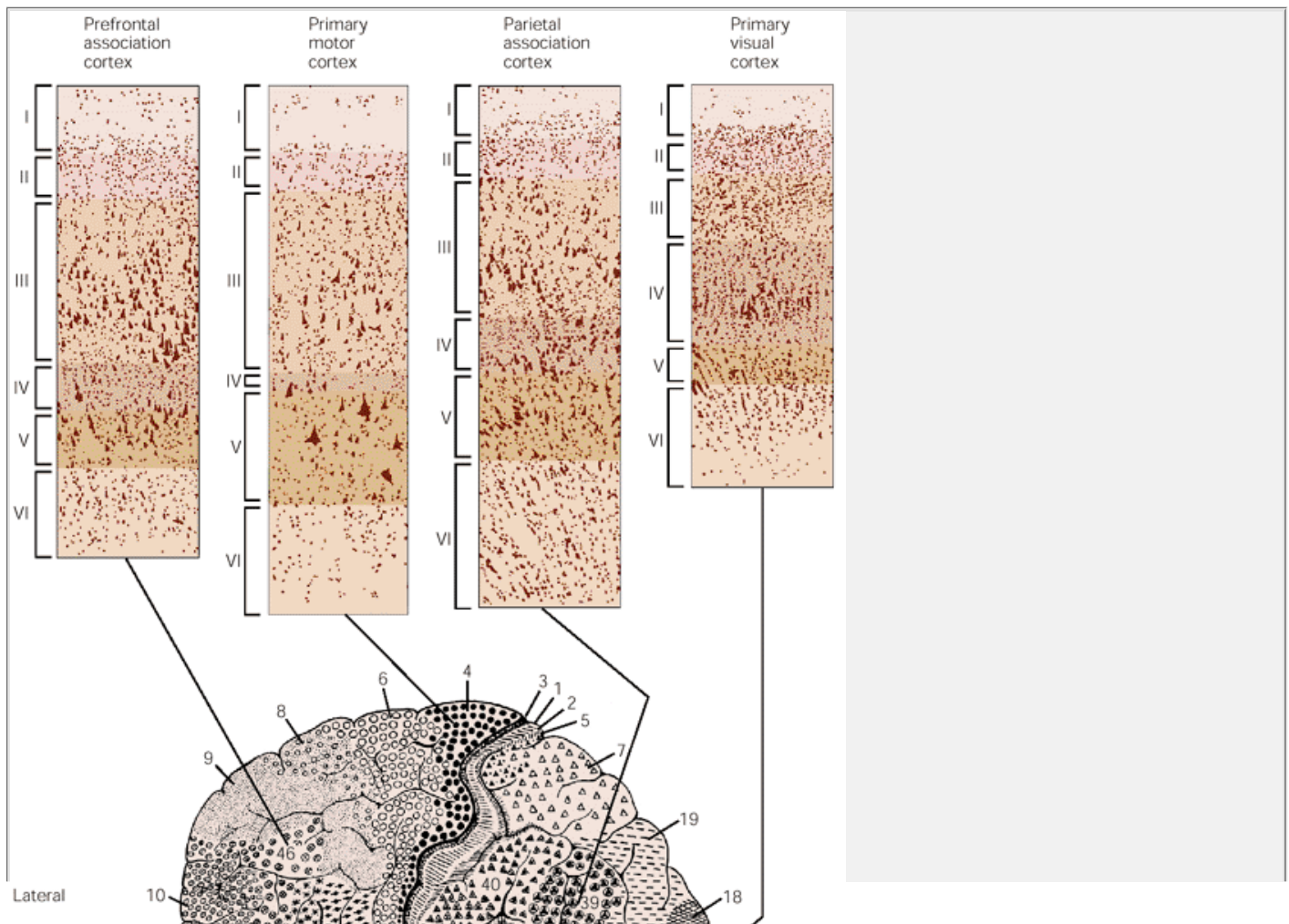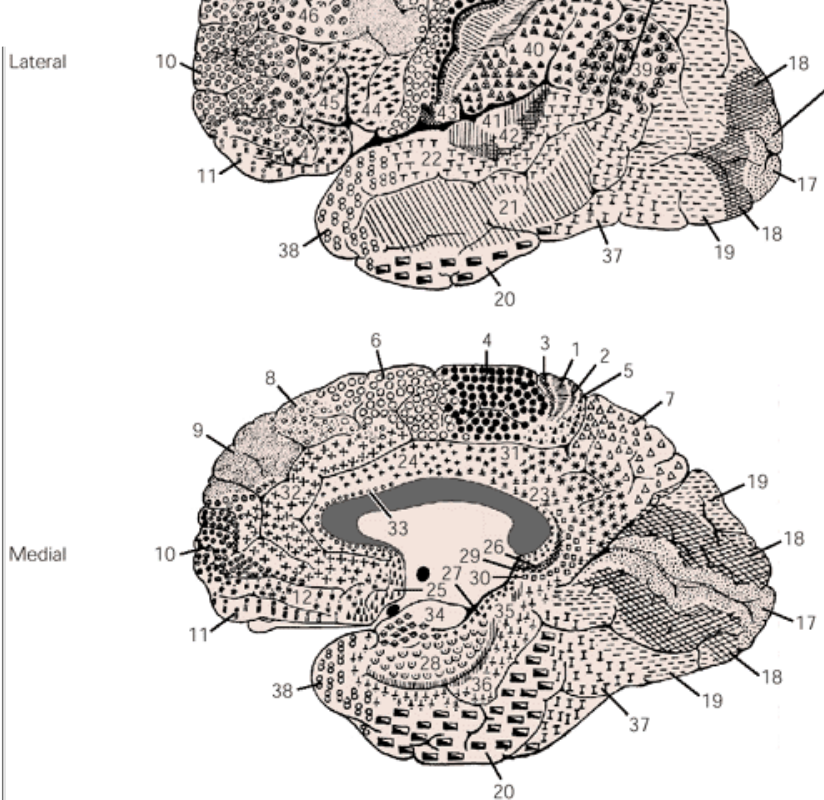
Figure 17-7 The prominence of particular cell layers of the cerebral cortex varies throughout the cortex. Sensory cortices, such as the primary visual cortex, tend to have very prominent internal granule cell layers. Motor cortices, such as the primary motor cortex, have a very meager layer IV but prominent output layers, such as layer V. These differences led Brodmann and others working at the turn of the century to divide the brain into various cytoarchitectonic regions. The subdivision by Brodmann (1909) seen in the **bottom half** of this illustration is a classic analysis but was based on a single human brain! (From Martin 1996.)
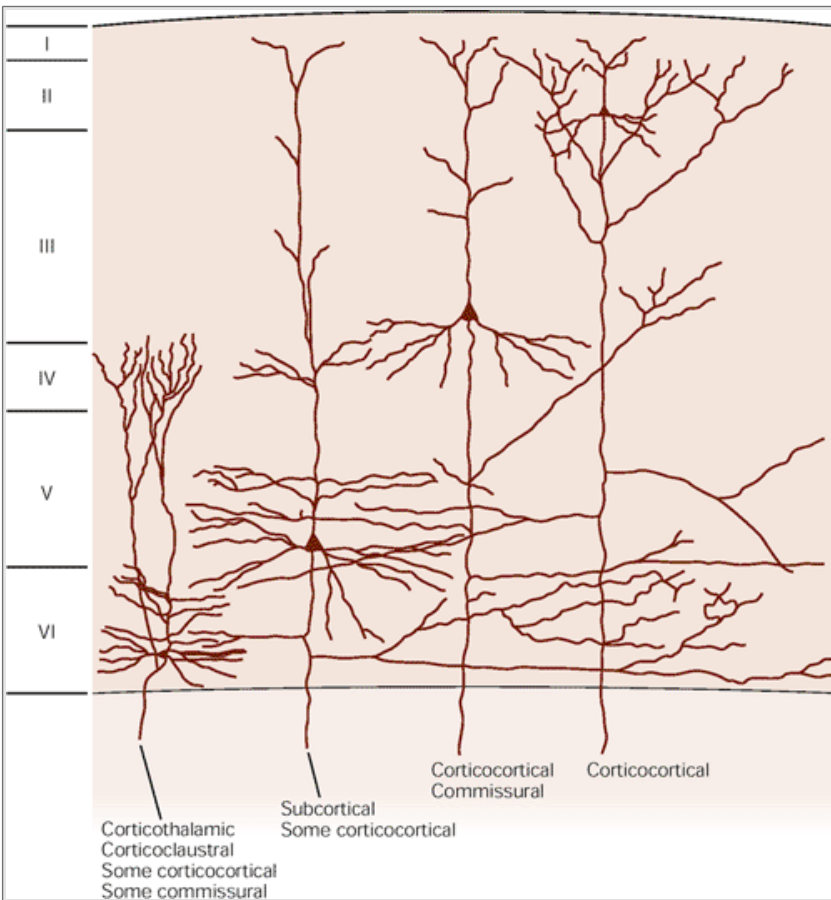

Figure 17-8 Neurons in different layers of the neocortex project to different parts of the brain. Projections to other parts of the neocortex, the so-called corticocortical or associational connections, arise primarily from neurons in layers II and III. Projections to subcortical regions arise mainly from layers V and VI. (From Jones 1986.)

The Cerebral Cortex Has Two Major Neuronal Cell Types: Projection Neurons and Interneurons

The neurons of the cortex have a variety of shapes and sizes. Raphael Lorente de Nó, a student of Santiago Ramón y Cajal, used the Golgi method to identify more than 40 different types of cortical neurons based only on the distribution of their dendrites and axons. In general, the neurons of the cortex, as elsewhere, can be broadly defined as projection neurons and local interneurons. *Projection neurons* typically have pyramidally shaped cell bodies (Figure 17-10). They are located

mainly in layers III, V, and VI and use the excitatory amino acid glutamate as their primary transmitter. *Local interneurons* use the inhibitory neurotransmitter γ-amino-butyric acid (GABA), constitute 20-25% of the neurons in the neocortex, and are located in all layers.

Several types of GABA-ergic interneurons have been distinguished based on their pattern of connections and the cotransmitters they contain (Figure 17-11). Some have axons that terminate on the cell bodies of target neurons; these are typically called *basket cells.* Others have axons that terminate exclusively on the axons of target neurons; the multiple arrays of synaptic terminals formed by these GABA-ergic axons resemble a chandelier, and these cell types are typically called *chandelier cells.* Some GABA-ergic neurons contain other neuro- active peptides, such as somatostatin, cholecystokinin, or the opiate peptides. The neocortex also has a population of excitatory interneurons, located primarily in layer IV. These cells have a stellate plexus of dendrites, use the amino acid glutamate as a transmitter, and form synapses with neurons near the cell body. These excitatory interneurons are the primary recipients of sensory information received in the neocortex from the thalamus.

Neurons in the neocortex are not only distributed in layers but also in columns that traverse the layers, although the columnar organization is not particularly

evident in standard histological preparations. A cortical column would fit within a cylinder a fraction of a millimeter in diameter. Neurons within a particular column tend to have very similar response properties, presumably because they form a local processing network. Columns are thought to be the fundamental computational modules of the neocortex (see Chapter 21).
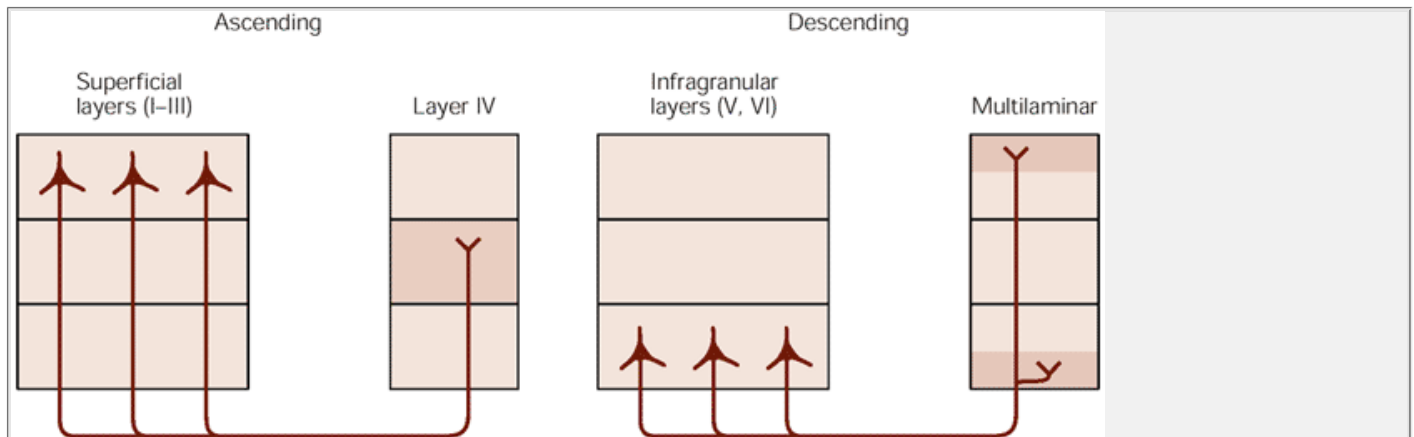

Figure 17-9 Information is processed in the neocortex in a series of relays that produce progressively more complex information. How does one know that a particular cortical area is higher or lower in the hierarchy? This illustration demonstrates that ascending or feed-forward projections generally originate in superficial layers of the cortex and invariably terminate in layer IV. Descending or feedback projections generally originate from deep layers and terminate in layers I and VI. (Adapted from Felleman and Van Essen 1991.)
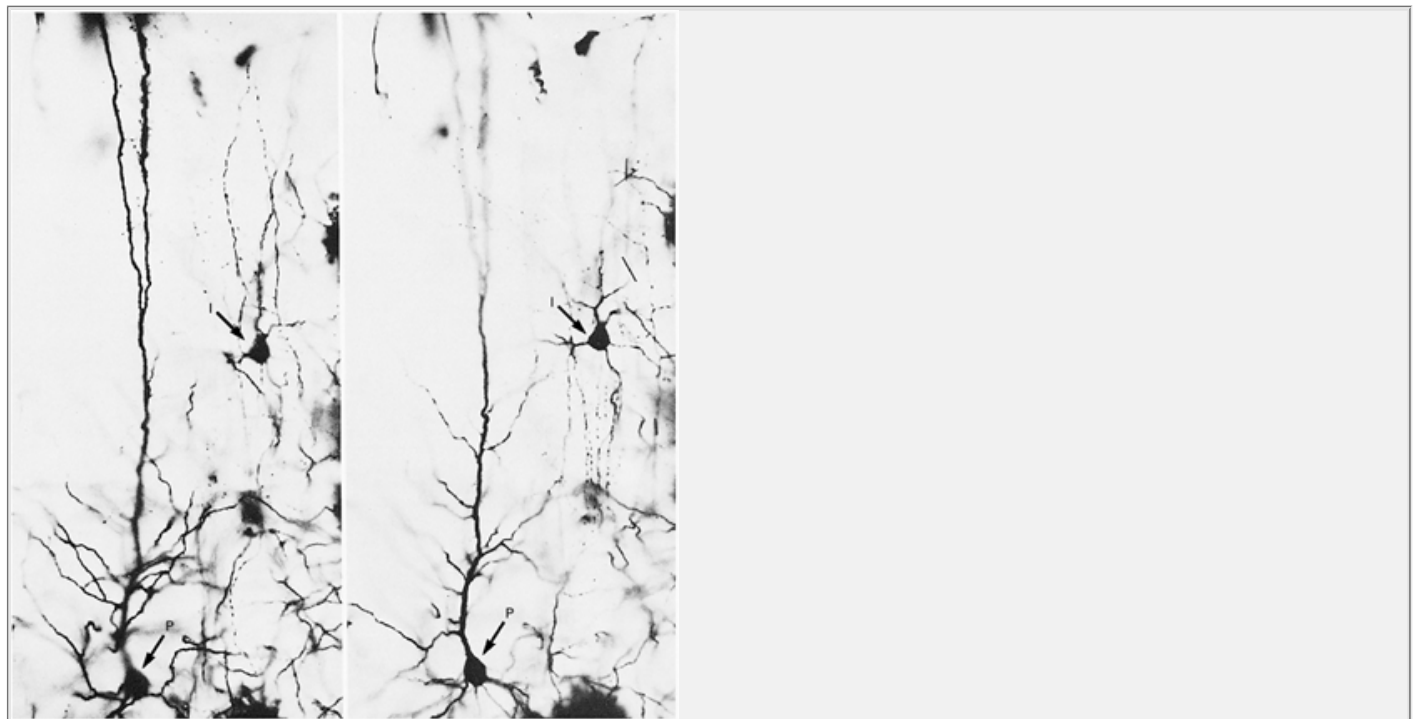

Figure 17-10 A projection neuron (P) and interneuron (I) in the somatic sensory cortex of a monkey are shown in these photomicrographs made at different depths of focus through the same Golgi-stained preparation. The pyramidal cell (Golgi type I) is seen better on the left, while the interneuron (Golgi type II) is seen better on the right. (From Jones and Peters, Vol. 1, 1986.)

As we have seen, the thickness of the neocortex is always found to be between 2 and 4 mm. In fact, the number of neurons stacked on top of each other through the thickness of the cortex is remarkably similar in different cortical regions and in different species. The one exception is the primary visual cortex, which has about twice as many neurons in a column. Thus, what mainly differentiates the cerebral cortex of a human from that of a rat is not the thickness of the cortex or the organization of the cortical columns, but the total number of columns. The massive expansion of the surface area of the cerebral cortex in humans accommodates many more columns and thus provides greater computational power.

Subcortical Regions of the Brain Contain Functional Groups of Neurons Called Nuclei

The ability of the cerebral cortex to process sensory information, to associate it with emotional states, to store it as memory, and to initiate action is modulated by three structures that lie deep within the cerebral hemispheres: the basal ganglia, the hippocampal formation, and the amygdala. The major components of the basal ganglia are the caudate nucleus, putamen, and globus pallidus (Figure 17-12). Neurons in the basal ganglia regulate movement and contribute to certain forms of cognition such as the learning of skills. They receive input from all parts of the cerebral cortex but send their output only to the frontal lobe through the thalamus.

The hippocampus and associated cortical regions form the floor of the temporal horn of the lateral ventricle. Together these structures are responsible for the formation of long-term memories about our daily experiences. The hippocampus is not the permanent storage site of memories, however (see Chapter 62). Damage to the hippocampus causes people to become unable to form new memories but does not significantly impair old memories.

The amygdala, which lies just rostral to the hippocampus, is involved in analyzing the emotional or motivational significance of sensory stimuli and in coordinating the actions of a variety of brain systems to allow an individual to make an appropriate response. The amygdala receives input directly from the major sensory systems. In turn, it projects back to the neocortex, to the basal ganglia, the hippocampus, and a variety of subcortical structures including the hypothalamus. Through its projections to the brain stem the amygdala can modulate somatic and visceral components of the peripheral nervous system and thus orchestrate the body's response to a particular situation. Responses to danger—the sense of fear and the change in heart rate and respiration that result from seeing a snake, for example—are mediated by the amygdala and its connections.
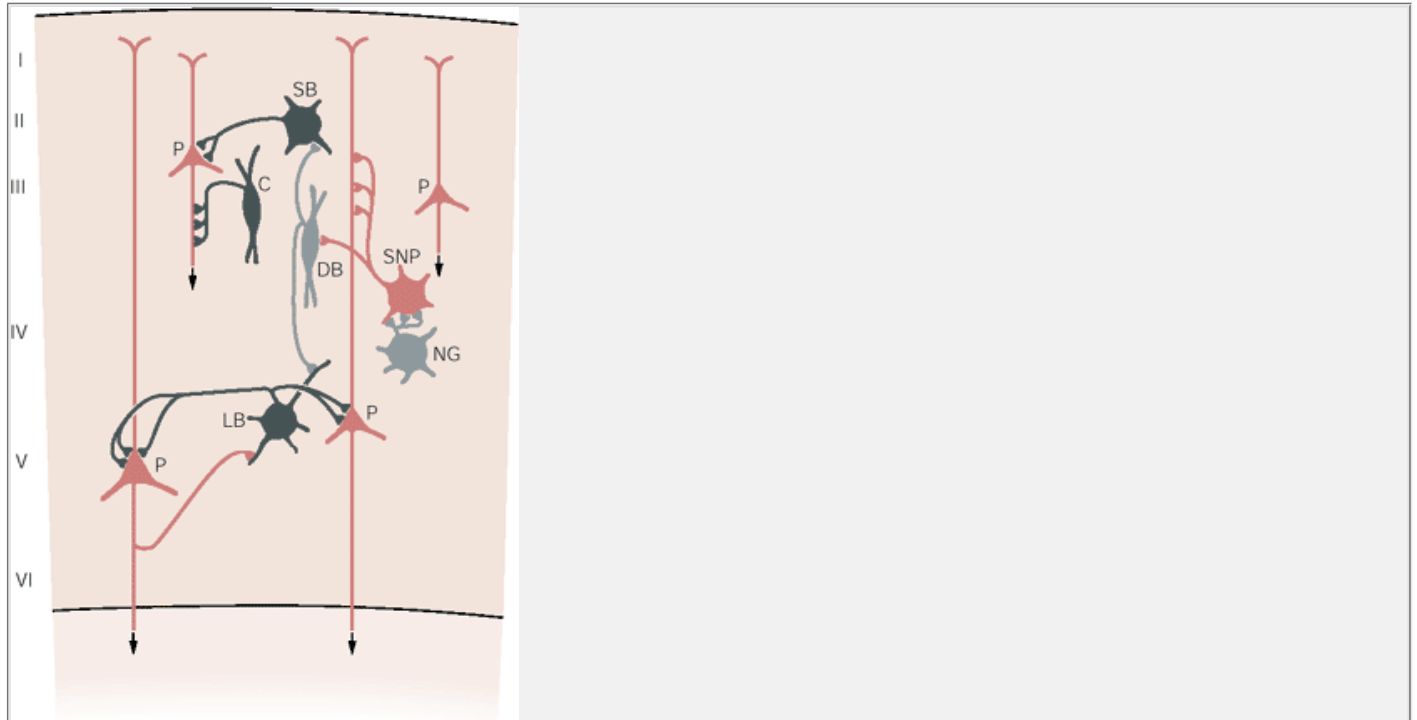

Figure 17-11 Different types of GABA-ergic neurons (dark gray) and putative GABA-ergic neurons (light gray) have different connections with pyramidal (P) and spiny nonpyramidal (SNP) cells in the neocortex. The GABA-ergic cells include chandelier cells (**C**), which terminate exclusively on the axons of other neurons, and the large and small basket cells (**LB, SB**), whose axons terminate mainly on other cell bodies. Double bouquet (**DB**) and neurogliaform cells (**NG**) may also be GABA-ergic. (Adapted from Houser et al. 1986.)

In thin histological sections through the brain stem stained by any of the common methods to demonstrate neuronal cell bodies, the neuronal cell bodies appear to be grouped in clusters of different sizes and shapes. These clusters of neurons are commonly called *nuclei* (see lateral geniculate nucleus in Figure 17-13).

Most nuclei are not homogeneous populations of cells but instead include a variety of cells organized into

P.332

subnuclei, divisions, or layers. Neurons in the lateral geniculate nucleus of the thalamus, for example, are grouped into alternating bands of smaller or larger neurons with different functions (Figure 17-14). Even within a nucleus that appears homogeneous when viewed with the nonspecific Nissl method (Figure 17-13), the use of other stains that highlight the structure of dendrites (such as the Golgi technique) or the chemical composition of the neurons (such as histochemistry or immunohistochemistry) reveal substantial heterogeneity of neuronal cell types.
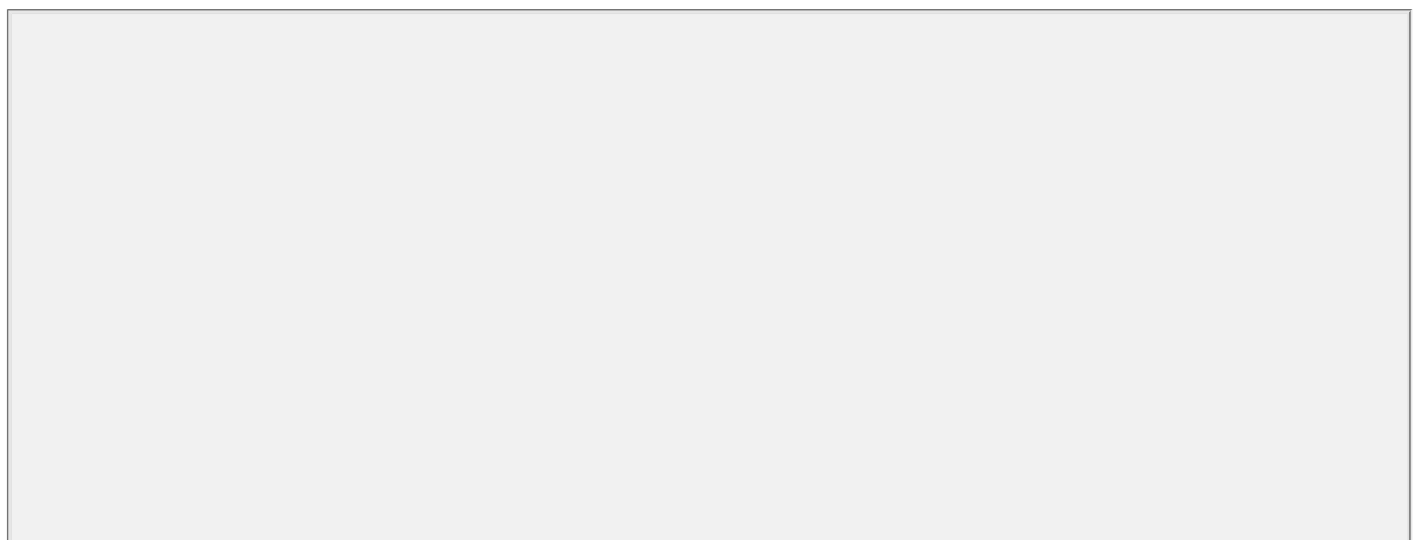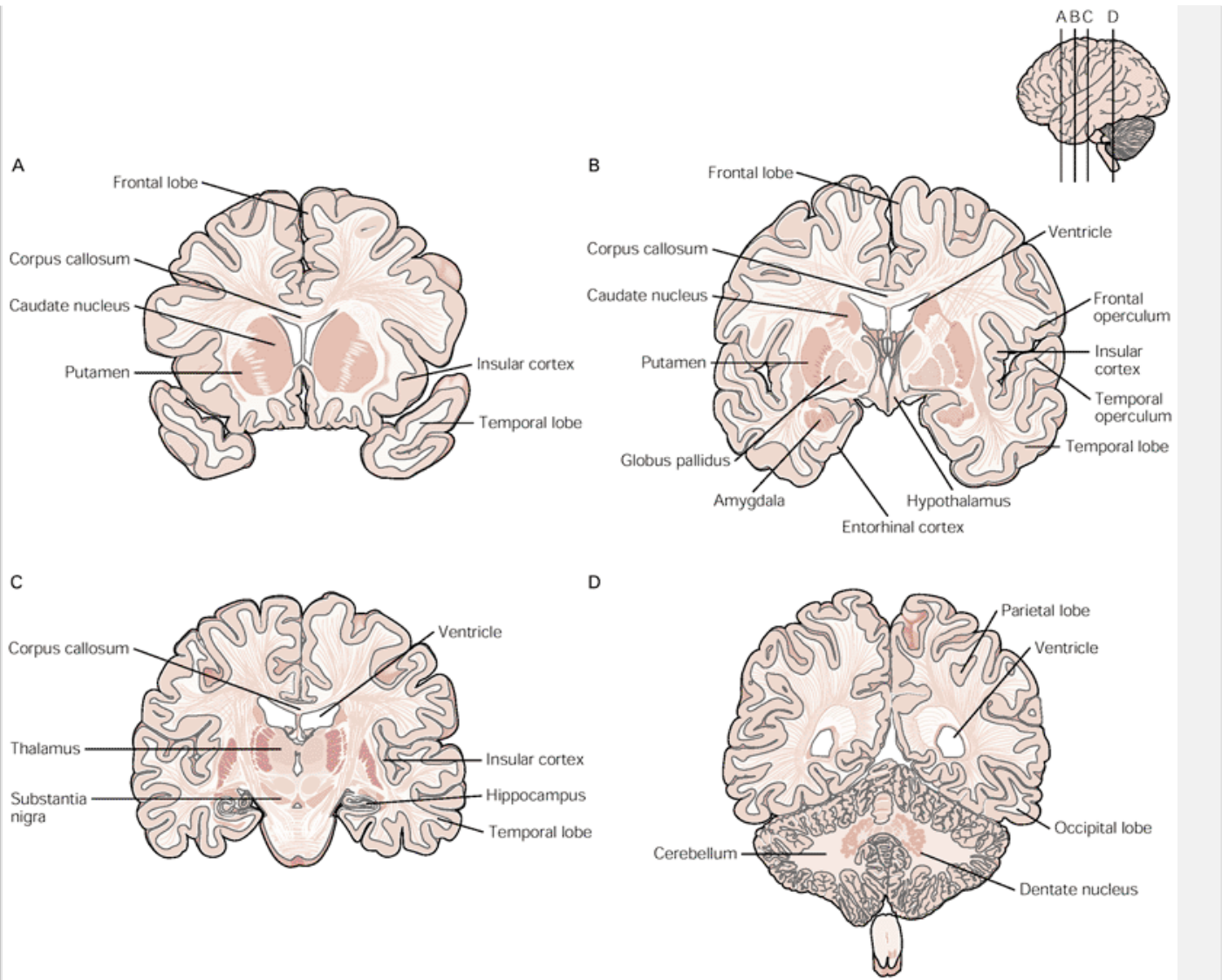
Figure 17-12 Several brain regions are shown in these coronal sections of the human brain. The sections are arranged from rostral (**A**) to caudal (**D**) and the approximate location of these sections are shown on the lateral surface view of the brain shown above. (From Nieuwenhuys et al. 1988.)

The definition of nuclei in the brain is thus dependent on the method by which the neurons are visualized. And, in fact, modern neuroanatomy has made great progress in adding new differential criteria to the definition of brain regions and brain types. One particularly telling example occurred in the 1970s when Bengt Falck and Nils Hillarp developed a histofluorescence technique for staining monoamine neurotransmitters. This histofluorescence technique allowed groupings of serotonergic, adrenergic, or dopaminergic neurons to be recognized in the reticular formation, a region of the brain stem so named because of its diffuse and relatively nonnuclear appearance. Many other powerful techniques

P.333

for defining the chemical or genetic composition of neuronal cell types have emerged in the last two decades. For example, in situ hybridization allows neurons to be visualized based on the genes they express.

Figure 17-13 Several nuclei can be seen in this coronal section through the right hemisphere of a Macaque monkey brain. Nissl stains mark neuronal and glial cell bodies and make up the grainy dark appearance of much of the section. In this low-magnification photograph individual neuronal cell bodies are difficult to distinguish. Several nuclei are visible. The lateral geniculate nucleus of the thalamus is subdivided into layers. Other layered neurons appear in the hippocampus and the neocortex of the temporal lobe. Other nuclei are more homogeneous, such as the caudate nucleus, putamen, and claustrum. The white regions between the cellular staining constitute the white matter where unstained axons run from one brain region to the next.

The cellular organization of the brain would be of far less functional significance if it varied greatly from individual to individual. However, the types of neurons within a particular brain nucleus and the connections they make are the end result of a stereotypical developmental program of cellular proliferation, migration, and differentiation and therefore are similar in every individual. This regularity of the position and components of brain nuclei provides support for the notion that the spatial location of neurons, their relationship to other neurons within a nucleus, and the three-dimensional distribution of their axons and dendrites within the nervous system are all crucial for normal brain function.

Modulatory Systems in the Brain Influence Motivation, Emotion, and Memory

Some areas of the brain are neither purely sensory nor purely motor but instead are modulatory. These modulatory

P.334

systems are nevertheless essential components of the neural circuitry underlying complex behaviors. Complex behaviors are often directed toward filling a primary need such as hunger, thirst, or sleep. Thus, sensory and modulatory systems in the hypothalamus determine blood glucose levels. Once blood sugar drops below a certain critical level, we feel hunger. To satisfy hunger, perceptual and modulatory processes must first be brought into play. Thus, when a predator surveys the environment for clues of prey, including sights, sounds, or odors, modulatory systems in the brain focus the sensory apparatus on stimuli that are relevant to feeding.
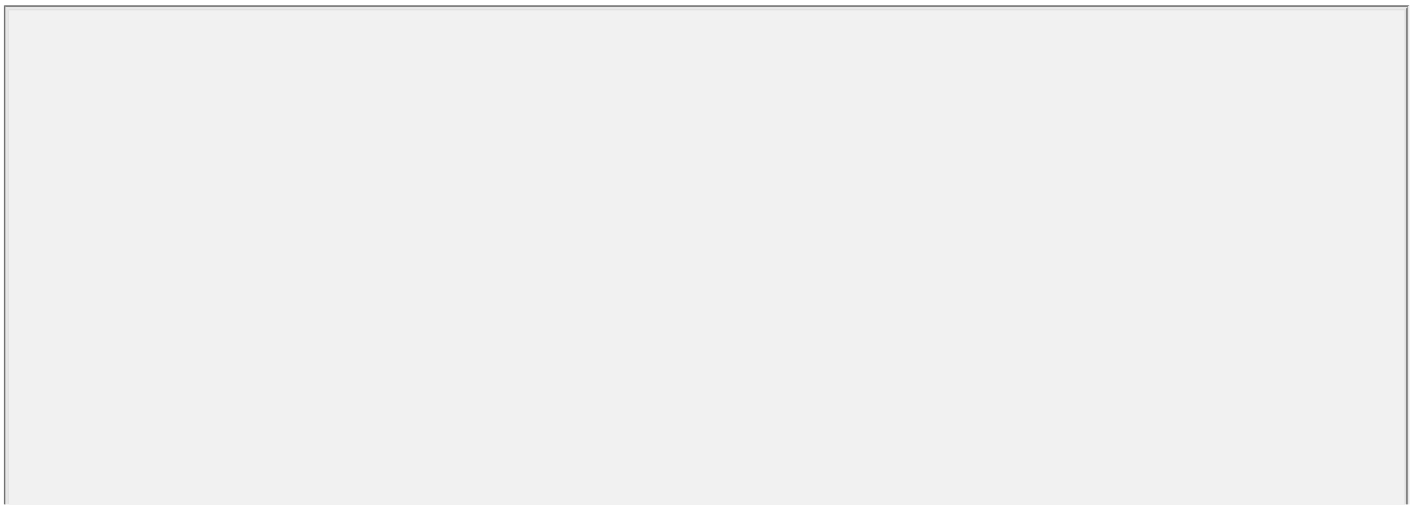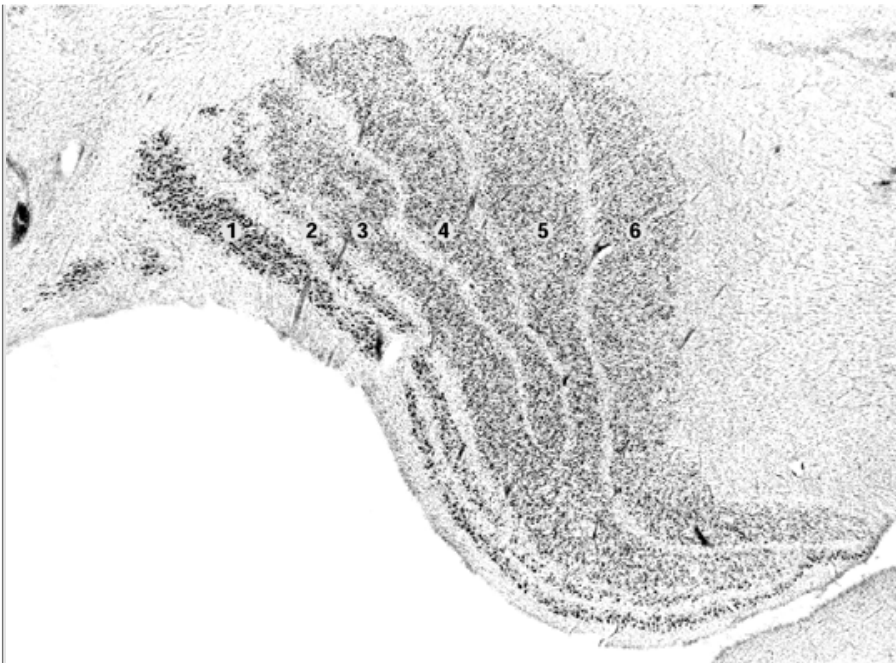
Figure 17-14 Most nuclei are not homogeneous populations of cells. The organizational complexity of the lateral geniculate nucleus can be seen in this Nissl-stained coronal section of the right hemisphere of a human brain. Axons from neurons in the retina terminate in different layers (1-6) of the nucleus. Layers 1 and 2 contain much larger neurons (magnocellular) than layers 3-6 (parvocellular), and the two types of cells have different functions. Each layer contains both projection neurons and interneurons.

The neural basis of arousal and selective attention is not well understood. We know, however, that distinct modulatory systems within the brain stem participate in these functions. Small groups of modulatory neurons in the brain stem contain noradrenaline and serotonin, and these neurotransmitters set the general arousal level of an animal through their modulatory influences on forebrain structures. Another group of modulatory neurons involved in arousal or attention is the basal nucleus of Meynert, located beneath the basal ganglia in the basal forebrain portion of the telencephalon. Cholinergic neurons in the basal nucleus send connections to essentially all portions of the neocortex, where they participate in attentional mechanisms that sharpen cognitive or perceptual processes.

If a predator finds potential prey, a variety of cortical and subcortical structures determines whether the prey is edible. Once food is recognized, other cortical and subcortical systems initiate a comprehensive volitional motor program to bring the animal into contact with the prey, capture it and place it in the mouth, and chew and swallow.

Finally, the physiological satisfaction the animal experiences in consuming food reinforces the behaviors that led to the successful predation. Modulatory systems of dopaminergic neurons in the midbrain mediate these rewarding aspects of behavior. The power of these systems has been demonstrated by experiments with rats. When electrodes were implanted into the animals' reward regions and the animals were allowed to press a lever to electrically stimulate their brains, the rats preferred self-stimulating their brains to obtaining food or water, engaging in sexual behavior, or any other naturally rewarding activity.

How the brain's modulatory systems concerned with reward, attention, and motivation interact with the sensory and motor systems remains one of the most interesting questions in neuroscience, one that is fundamental to our understanding of learning and memory storage. We take up this question in Chapters 44 and 45.

The Peripheral Nervous System Is Anatomically But Not Functionally Distinct From the Central Nervous System

In this chapter we have outlined the anatomy of the central nervous system—the brain and spinal cord—and its functional systems because the focus of this book is on how the brain mediates behavior. As we shall see

throughout the book, however, the brain processes a continuous stream of information about the environment—both the external environment and the internal environment of the body. This information is supplied by the peripheral nervous system, which, though anatomically separate from the central nervous system, is functionally intertwined with it.

The peripheral nervous system is divided into somatic and autonomic divisions. The *somatic division* includes the sensory neurons that innervate the skin, muscles, and joints. The cell bodies of these sensory neurons lie in the dorsal root ganglia and the cranial ganglia. Receptors associated with dorsal root and cranial ganglion cells provide sensory information to the central nervous system about muscle and limb position and about touch and pressure at the body surface. In Part V (Perception) we shall see how remarkably specialized the sensory receptors are in transducing the variety of physical energies (stimuli) into a code used universally throughout the nervous system. In Part VI (Movement) we shall see that sensory receptors in the muscles and joints are crucial to shaping coherent action that allows us to move about the world and exploit its resources.

The *autonomic division* of the peripheral nervous system mediates visceral sensation as well as motor control of the viscera, smooth muscles, and exocrine glands. It consists of the sympathetic, parasympathetic, and enteric systems. The sympathetic system participates in the body's response to stress, while the parasympathetic system acts to conserve body resources and restore homeostasis. The enteric nervous system controls the function of smooth muscle of the gut. The functional organization of the autonomic nervous system is described in Chapter 49 and its role in emotion and motivation in Chapters 50 and 51.

An Overall View

The nervous system obtains sensory information from the environment, evaluates the significance of the information, and generates appropriate behavioral responses. Accomplishing these tasks requires an anatomical plan of considerable complexity. The human nervous system is comprised of several hundreds of billions of neurons, each of which receives and gives rise to tens of thousands of connections. Some of these connections are located nearly a meter from the cell bodies of origin.

Despite this complexity, the structure of the nervous system is similar from individual to individual within a species. Knowledge of neuronal structure and the pathways of information flow in the brain is important not only for understanding the normal function of the brain but also for identifying specific regions that are disturbed during neurological illness.

The nervous system has two anatomically distinct components: the central nervous system, consisting of the brain and the spinal cord, and the peripheral nervous system, composed of specialized clusters of neurons (ganglia) and peripheral nerves. The peripheral nervous system relays information to the central nervous system and executes motor commands generated in the brain and spinal cord. The simplest action involves the integrated activity of multiple sensory, motor, and motivational pathways in the central nervous system. Each pathway contains a series of relay nuclei and each nucleus has several functional subdivisions. Most neurons are precisely arranged into functional pathways that have the same anatomical arrangement in every individual. Many pathways cross from one side of the nervous system to the other. These basic principles govern the organization of the nervous system from the spinal cord through the brain stem to the highest levels of the cerebral cortex.

While neuroanatomy may seem to provide only a static picture of the nervous system, it can provide profound insight into how the nervous system functions, in the same way that the detailed structure of proteins reveals important principles of protein function. Many of the prevailing ideas about the dynamic mechanisms in the nervous system were forecast a century ago by Ramón y Cajal on the basis of images of neurons in stained histological specimens. Indeed, many of the established properties of neuronal connectivity were first discovered using the methods of classical anatomy. Golgi staining first showed the existence of two major classes of nerve cells in the brain: projection neurons, whose axons connect the major regions of the nervous system, and local interneurons, which integrate information within specific nuclei of the brain. Later staining techniques demonstrated the considerable convergence and divergence of projections between brain regions.

The introduction of electron microscopic methods to neuroanatomy in the 1950s revealed the structure of synapses and illustrated that different classes of neurons form synapses with quite different features. Some synaptic terminals are located on dendrites, others on axon terminals, and still others on the soma of the postsynaptic cell. The location of synapses on the neuronal surface critically affects the function of the cell.

Today, our understanding of higher brain function depends on refined mapping of neuronal circuits using new anatomical and imaging techniques. Modern neuro-anatomical labeling techniques have revealed the topographic organization of projections from one brain region to the next.

As we shall see in later chapters, modern imaging techniques have revolutionized the study of the cognitive functions of the brain and thereby placed neurology and psychiatry on a firmer empirical footing. Positron emission tomography (PET) and magnetic resonance imaging (MRI) have made the functional organization of the human brain visible during behavioral experiments. These techniques, in addition to being important tools for diagnosing diseases of the central nervous system, have given us a much clearer idea of the brain regions involved in many complex cognitive functions.

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18

The Functional Organization of Perception and Movement

David G. Amaral

STUDIES OF ARTIFICIAL intelligence have shown that the human brain recognizes objects and carries out actions in ways no current computer can even begin to approach. Merely to see—to look onto the world and recognize a face or enjoy a landscape—entails amazing computational achievements. Indeed, all our perceptions—seeing, hearing, smelling, tasting, and touching—are analytical triumphs. Similarly all of our voluntary actions are triumphs of engineering. The brain accomplishes these computational feats because its many components—its nerve cells—are wired together in very precise ways.

In this chapter we outline the principles essential for understanding perception and action. We shall focus on touch because the somatosensory system is particularly well understood and because touch clearly illustrates the interaction of sensory and motor systems—how information from the body surface ascends through the sensory relays of the nervous system to the cerebral cortex and is transformed into motor commands that descend to the spinal cord to produce movements.

There is now a fairly complete understanding of how the physical energy of a tactile stimulus is transduced by mechanoreceptors in the skin into electrical activity, and how this activity at different relays in the brain correlates with specific aspects of the experience of touch. Since the central paths are well delineated, we now can see how this electrical information is processed at different relay points.

Trying to comprehend the functional organization of the brain might at first seem daunting. But as we saw in the last chapter, the organization of the brain is simplified by three anatomical considerations. First, there are relatively few types of neurons. Each of the many thousands of spinal motor neurons or millions of neocortical pyramidal cells has a similar structure and serves a similar function. Second, neurons in the brain and spinal cord are clustered into discrete cellular groups called nuclei, which are connected to form functional systems. Third, local regions of the cerebral cortex are specialized for sensory, motor, or associational functions. We begin by examining these three anatomical principles in the context of the perception of touch.
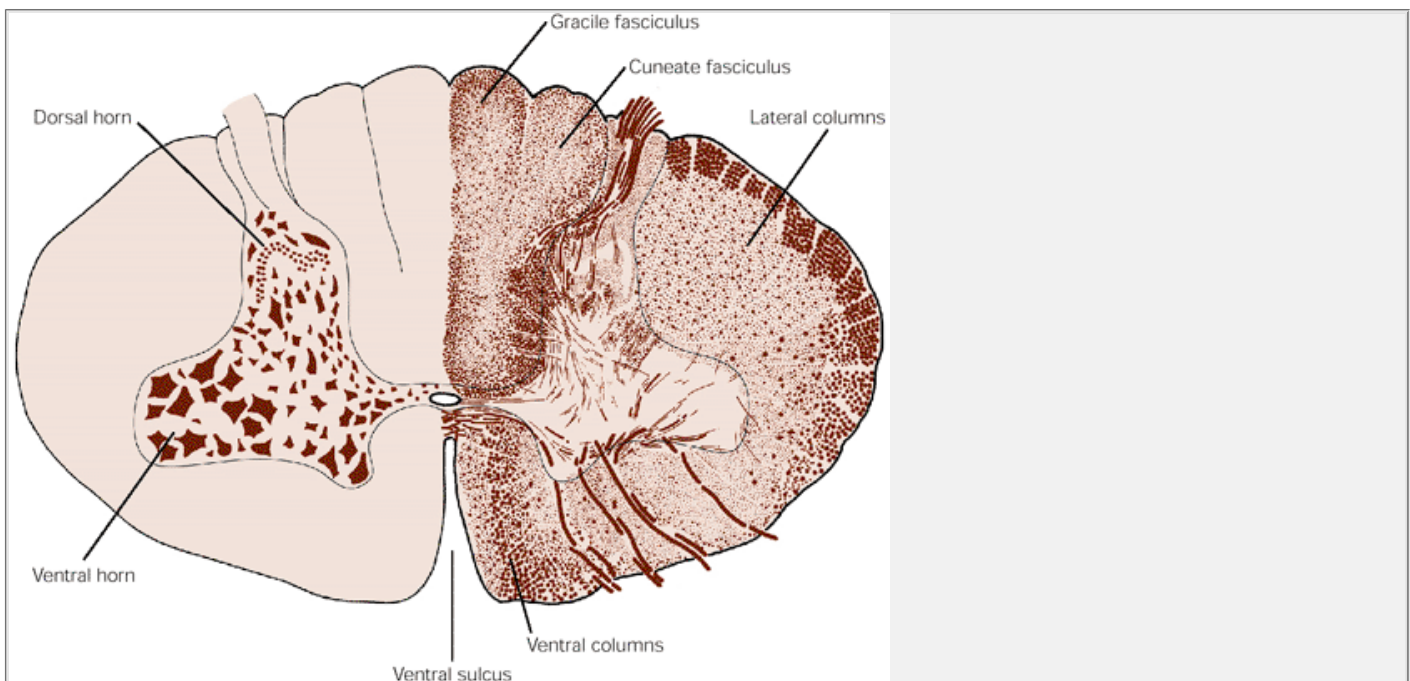

Figure 18-1 The major anatomical features of the spinal cord. The **left** side depicts a cell stain of the gray matter and the **right** side a fiber-stained section. The ventral horn contains large motor neurons, whereas the dorsal horn contains small neurons. Fibers of the gracile fasciculus carry somatosensory information from the lower limbs. Fibers of the cuneate fasciculus carry somatosensory information from the upper body. Fiber bundles of the lateral and ventral columns include both ascending and descending fiber bundles.

Sensory Information Processing Is Illustrated in the Somatosensory System

Complex behaviors such as tactile perception generally require the integrated action of several nuclei and cortical regions. A general principle of brain information processing is that it is carried out in a hierarchical fashion. Stimulus information is conveyed through a succession of subcortical and then cortical regions. To increase the computational capacity of the brain, information processing, even within a single sensory modality, is carried out simultaneously in several anatomically discrete pathways. In the somatosensory system a light touch and a painful stimulus to the same area of skin are mediated by different pathways in the brain.

Somatosensory Information From the Trunk and Limbs Is Conveyed to the Spinal Cord

Sensory information from the trunk and limbs enters the spinal cord, which is composed of a central core region of gray matter surrounded by white matter. The gray matter is shaped like the letter H, with each side subdivided into dorsal (or posterior) and ventral (or anterior) horns (Figure 18-1). In cross sections of the cord, the gray matter of the dorsal horn contains the sensory nuclei, or groups of sensory neurons, whose axons receive stimulus information from the body's surface. The ventral horn contains the motor nuclei, or groups of motor neurons, whose axons exit the spinal cord and innervate skeletal muscles. The motor cells do not actually form discrete clusters, like the sensory nuclei, but instead are arranged in columns that run along the length of the spinal cord. Interneurons of various types in the gray matter modulate information flowing from the sensory neurons toward the brain and the commands from higher centers in the brain to the motor neurons, as well as information passed between groups of motor neurons.

The white matter surrounding the gray matter is divided into dorsal, lateral, and ventral columns (Figure 18-1). Each of these columns includes a variety of

bundles of ascending or descending axons. The dorsal columns, which lie between the two dorsal horns of the gray matter, contain only ascending axons that carry somatic sensory information to the brain stem. The lateral columns include both ascending axons and axons descending from the brain stem and neocortex that innervate interneurons and motor neurons in the spinal cord. The ventral columns also include ascending and descending axons. The ascending somatic sensory axons in the lateral and ventral columns constitute parallel pathways that convey information about pain and thermal sensation to higher levels of the central nervous system. The descending motor axons control axial muscles and posture.

The spinal cord is divided into four major regions: cervical, thoracic, lumbar, and sacral (Figure 18-2).

These regions are related to the embryological somites from which muscles, bones, and other components of the body develop (Chapters 52 and 53). Axons leaving the spinal cord to innervate body structures that develop at the same segmental level join together in the intervertebral foramen with axons entering the spinal cord to form spinal nerves. Spinal nerves at the cervical level are involved with sensory perception and motor function of the back of the head, neck, and arms. Nerves at the thoracic level innervate the upper trunk, while

lumbar and sacral spinal nerves innervate the lower trunk, back, and legs.
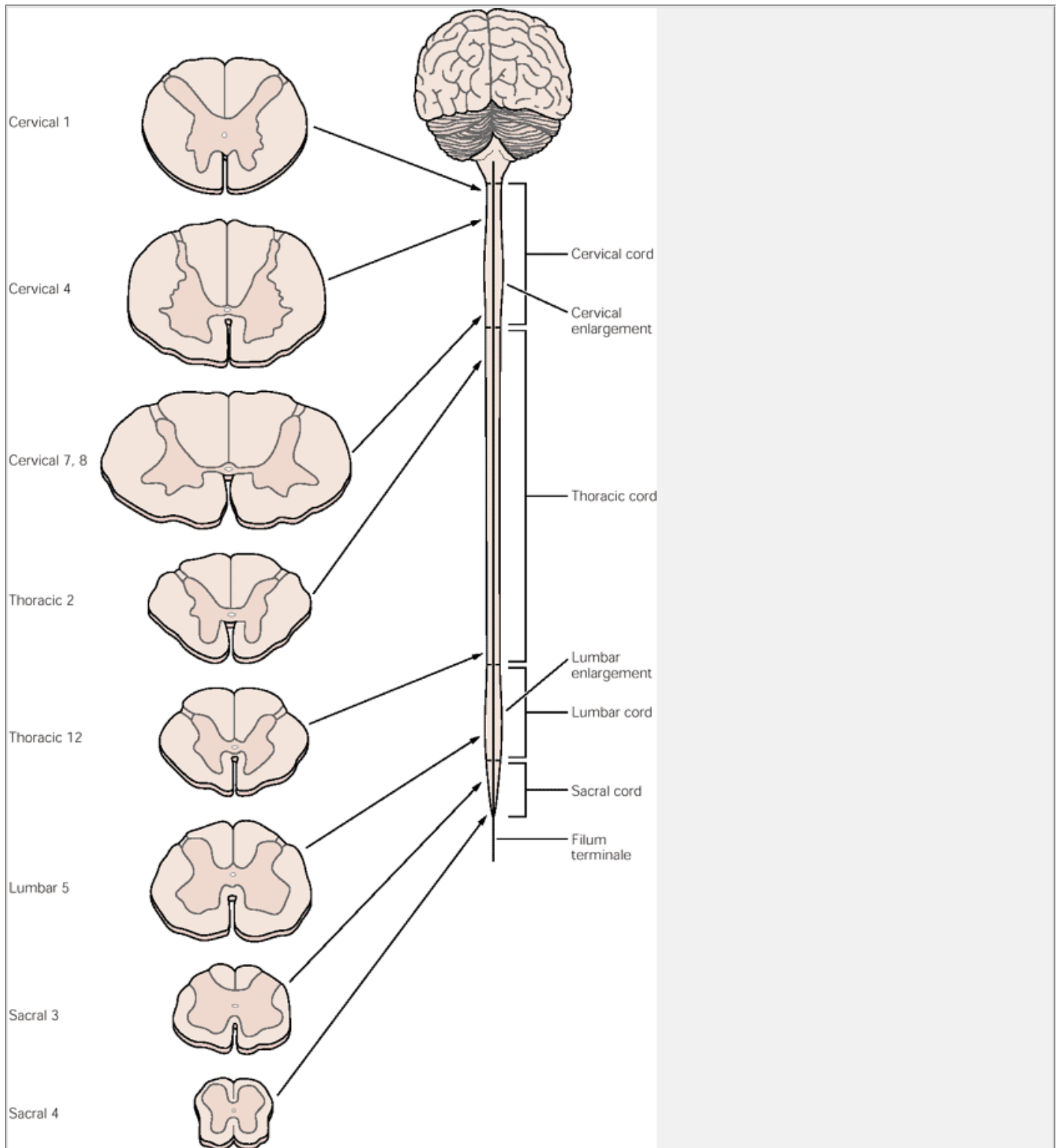

Figure 18-2 The internal and external appearances of the spinal cord vary at different levels. The proportion of gray matter to white matter is greater at sacral levels than at cervical levels. At sacral levels very few incoming sensory fibers have joined the spinal cord, whereas most of the motor fibers have already terminated at higher levels of the spinal cord. The cross-sectional area of the spinal cord shows enlargements at the lumbar and cervical levels, regions where the large number of fibers innervating the limbs enter or leave the spinal cord.
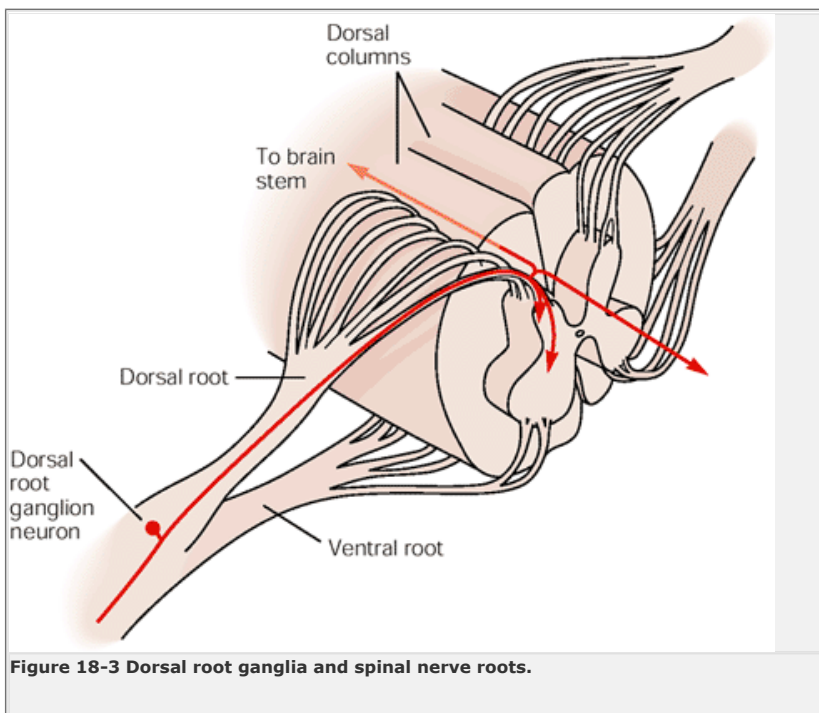
Figure 18-3 Dorsal root ganglia and spinal nerve roots.

Each of the four regions of the spinal cord contains several segments characterized by the number and location of the dorsal and ventral roots that enter or exit the cord. There are 8 cervical segments, 12 thoracic segments, 5 lumbar segments, and 5 sacral segments. Although the actual substance of the mature spinal cord does not look segmented, the spinal cord varies in size and shape along its rostrocaudal axis because of two organizational features. First, relatively few sensory axons enter the cord at the sacral level. At higher (lumbar, thoracic, and cervical) levels the number of sensory axons entering the cord increases progressively. Conversely, most descending axons from the brain terminate at cervical levels, with progressively fewer descending to lower levels of the spinal cord. Thus the number of fibers in the white matter is highest at cervical levels (where there are the highest numbers of both ascending and descending fibers) and lowest at sacral levels. As a result, sacral levels of the spinal cord have much less white matter than gray matter whereas the cervical cord has more white matter than gray matter (Figure 18-2).

The second feature that differentiates the shape of the spinal cord along its rostrocaudal axis is variation in the size of the ventral and dorsal horns. The ventral horn is larger where the motor nerves that innervate the arms and legs exit the spinal cord because of the larger number of motor neurons needed to innervate the greater number of muscles and to regulate the greater complexity of movement in the limbs as compared with the trunk. Likewise, the dorsal horn is larger where sensory nerves from the limbs enter the cord because the limbs have a greater density of sensory receptors and thus send more fibers to the cord. These regions of the cord are known as the lumbosacral and cervical *enlargements.*

The Primary Sensory Neurons of the Trunk and Limbs Are Clustered in the Dorsal Root Ganglia

The sensory neurons that convey information from the skin, muscles, and joints of the limbs and trunk to the spinal cord are clustered together in dorsal root ganglia within the vertebral column immediately adjacent to the spinal cord (Figure 18-3). These neurons are pseudo-unipolar neurons; they have a bifurcated axon with central and peripheral branches (see Figures 52-4 and 4-8). The peripheral branch terminates in skin, muscle, or other tissue as a free nerve ending or in association with specialized receptors.

The central process enters the spinal cord close to the tip of the dorsal horn. Upon entry the axon forms branches that either terminate within the spinal gray matter or ascend to nuclei located at the junction of the spinal cord with the medulla (Figure 18-3). These local and ascending branches provide two functional pathways for somatosensory information entering the spinal cord from dorsal root ganglion cells. The local branches can activate local reflex circuits while the ascending branches carry information into the brain, where this information becomes the basis of the perception of touch, position sense, or pain.

The Central Axons of Dorsal Root Ganglion Neurons Are Arranged to Produce a Map of the Body Surface

The central axons of the dorsal root ganglion cells form a neural map of the body surface when they terminate in the spinal cord. This orderly distribution of inputs from different portions of the body surface is called *somatotopy* and is maintained throughout the entire ascending somatosensory pathway.

Axons that enter the cord in the sacral region ascend in the dorsal column near the midline, while those that enter at successively higher levels ascend at progressively more lateral positions within the dorsal columns. Thus, in the cervical cord, where axons from all portions of the body have already entered the cord, sensory fibers from the lower body are carried medially in the dorsal column; fibers from the trunk, the arm and shoulder, and finally the neck occupy progressively more lateral areas. At the cervical levels of the cord the axons forming the dorsal columns are divided

P.341

into two bundles: a medially situated gracile funiculus and a more laterally situated cuneate funiculus (Figure 18-4).

Each Somatic Submodality Is Processed in a Distinct Subsystem From the Periphery to the Brain

The submodalities of somatic sensation—touch, pain, and position sense—are processed in the brain through different pathways that end in different brain regions. To illustrate the specificity of these parallel pathways, we will follow the path of information for the submodality of touch.

The primary afferent fibers that carry information about touch enter the ipsilateral dorsal column and, without crossing to the contralateral column, ascend to the medulla. Fibers from the *lower* body run in the gracile funiculus and terminate in the gracile nucleus, while fibers from the *upper* body run in the cuneate funiculus and terminate in the cuneate nucleus. Neurons in the gracile and cuneate nuclei give rise to axons that cross to the other side of the brain and ascend to the thalamus in a long fiber bundle called the medial lemniscus (Figure 18-4). As in the dorsal columns of the spinal cord, the fibers of the medial lemniscus are arranged somatotopically. Because the sensory fibers cross the midline to the other side of the brain, the right side of the brain receives sensory information from the left side of the body, and vice versa. The fibers of the medial lemniscus end in a specific subdivision of the thalamus called the ventral posterior nucleus. The fibers maintain their somatotopic organization in the thalamus; fibers from the lower body end laterally, and those from the upper body and face end medially.

The Thalamus Is an Essential Link Between Sensory Receptors and the Cerebral Cortex for All Modalities Except Olfaction

The thalamus is an oval-shaped structure that constitutes the dorsal portion of the diencephalon. It conveys sensory input to the primary sensory areas of the cerebral cortex but is more than simply a relay. It acts as a gatekeeper for information to the cerebral cortex, preventing or enhancing the passage of specific information depending on the behavioral state of the animal.

The thalamus is a good example of a brain region made up of several well-defined nuclei. As many as 50 thalamic nuclei have been identified. Some nuclei receive information specific to a sensory modality and project to a specific area of the neocortex. Thus, the axons of cells in the ventral posterior lateral nucleus (where the medial lemniscus terminates) project to the primary somatosensory cortex in the postcentral gyrus (Figure 18-4). Others participate in motor functions, transmitting information from the cerebellum and basal ganglia to the motor regions of the frontal lobe.

Axons from cells of the thalamus that project to the neocortex travel in the internal capsule, a large fiber bundle that carries most of the axons running to and from the cerebral hemisphere. Through its connections with the frontal lobe the thalamus may also play a role in cognitive functions, such as memory. Some nuclei that may play a role in attention project diffusely to large but distinctly different regions of cortex. The reticular nucleus, which forms the outer shell of the thalamus, does not project to the neocortex at all. It receives inputs from other fibers as they exit the thalamus en route to the neocortex and in turn projects to the other thalamic nuclei, thus providing feedback to the output nuclei of the thalamus.

The nuclei of the thalamus are most commonly classified into four groups—anterior, medial, ventrolateral, and posterior—with respect to the internal medullary lamina, a sheet-like bundle of fibers that runs the rostrocaudal length of the thalamus (Figure 18-5). Thus, the medial group of nuclei is located medial to the internal medullary lamina, while the ventrolateral and posterior groups are located lateral to it. At the rostral pole of the thalamus the internal medullary lamina splits and surrounds the anterior group. The caudal pole of the thalamus is occupied by the posterior nuclear group, comprised mainly of the pulvinar nucleus. Groups of neurons are also located within the fibers of the internal medullary lamina and are collectively referred to as the intralaminar nuclei.

The *anterior group* in humans consists of only one nucleus, which receives its major input from the mammillary nuclei of the hypothalamus and from the presubiculum of the hippocampal formation. The role of the anterior thalamic group is uncertain, but it is thought to participate in memory and emotion. The anterior thalamic group is also interconnected with regions of the cingulate and frontal cortices.

The *medial group* consists mainly of the mediodorsal nucleus. This large thalamic nucleus has three subdivisions, each of which is connected to a particular portion of the frontal cortex. The nucleus receives inputs from portions of the basal ganglia, the amygdala, and midbrain and has been implicated in memory.

The nuclei of the *ventral group* are named according to their position within the thalamus. The ventral anterior and ventral lateral nuclei are important for motor control and carry information from the basal ganglia and cerebellum to the motor cortex. The ventral post-erior

P.342

P.343

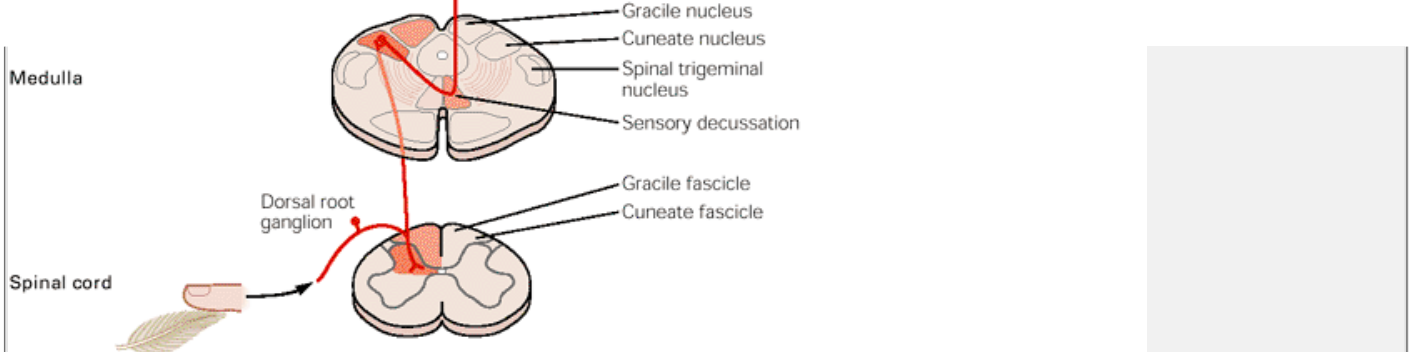lateral nucleus conveys somatosensory information to the neocortex.

Ascending dorsal column–medial lemniscal pathway to primary sensory cortex
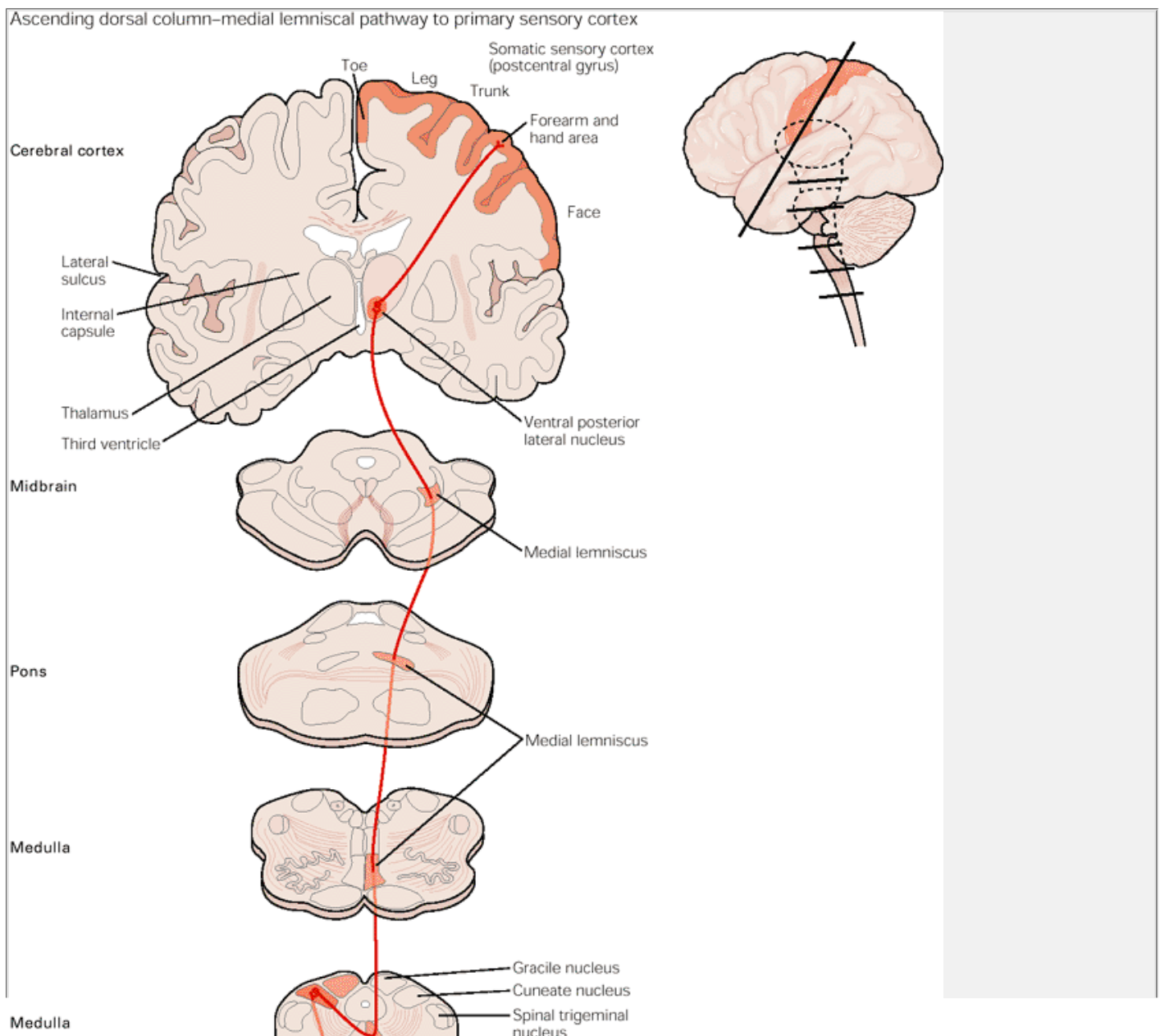
Figure 18-4 The medial lemniscus is a major afferent pathway for somatosensory information. Somatosensory information enters the nervous system through the dorsal root ganglion cells. The flow of information ultimately leads to excitation of the somatosensory cortex. Fibers representing different parts of the body maintain an orderly relationship to each other and form a neural map of the body surface that is maintained at each stage of information processing and ultimately in the neocortex.
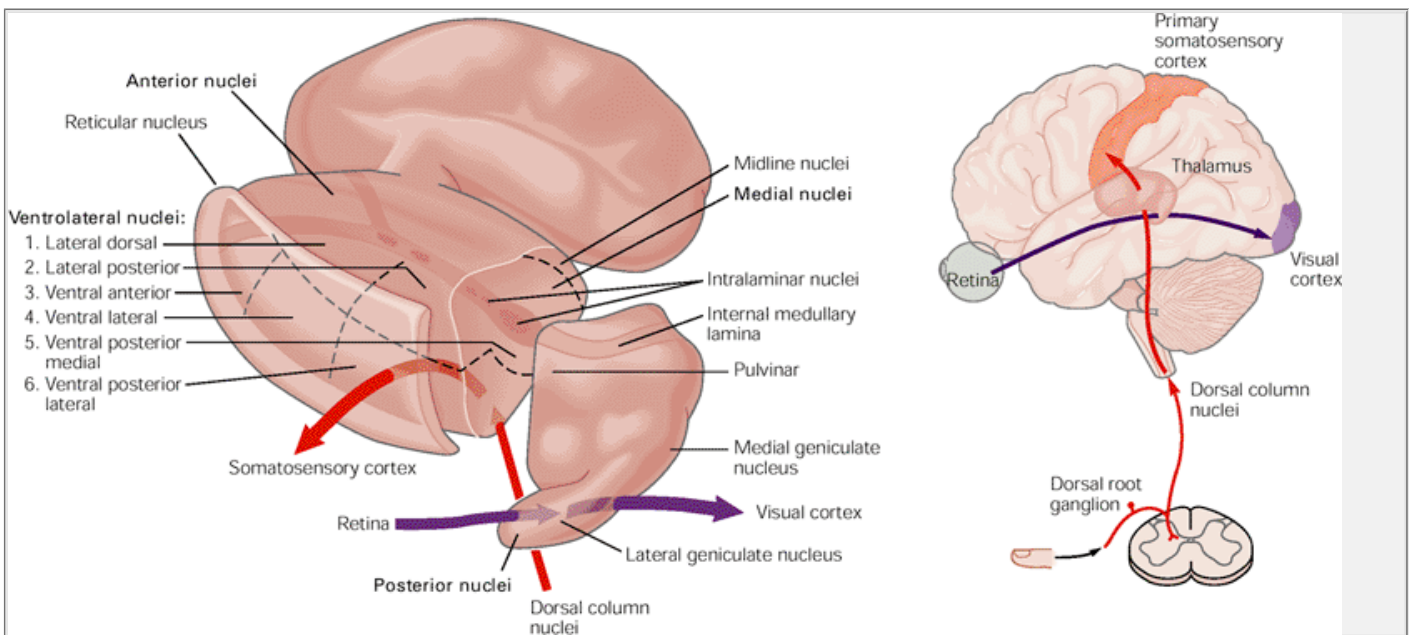

Figure 18-5 The major subdivisions of the thalamus. The thalamus is the critical relay for the flow of sensory information to the neocortex. Somatosensory information from the dorsal root ganglia reaches the ventral posterior lateral nucleus, which relays it to the primary somatosensory cortex. Visual information from the retina reaches the lateral geniculate nucleus, which conveys it to the primary visual cortex in the occipital lobe. Each of the sensory systems, except olfaction, has a similar processing step within a distinct region of the thalamus.

The *posterior group* includes the medial and lateral geniculate nucleus, lateral posterior nucleus, and the pulvinar. The medial and lateral geniculate nuclei are located near the posterior part of the thalamus. The medial geniculate nucleus is a component of the auditory system and conveys tonotopically organized auditory information to the superior temporal gyrus of the temporal lobe. The lateral geniculate nucleus receives information from the retina and conveys it to the primary visual cortex in the occipital lobe. The pulvinar is most enlarged in the primate brain, especially in the human brain, and its development seems to parallel the enlargement of the association regions of the parietal-occipital-temporal cortex (Chapter 19). It has been divided into at least three subdivisions and is extensively interconnected with widespread regions of the parietal, temporal, and occipital lobes, as well as with the superior colliculus and other nuclei of the brain stem related to vision.

The thalamus not only projects to the visual areas of the neocortex but also receives a return projection from the neocortex. The return projection from the occipital cortex actually accounts for a greater number of synapses in the lateral geniculate nucleus than does the retinal input! Most nuclei of the thalamus receive a similarly prominent return projection from the cerebral cortex

The thalamic nuclei described thus far are called the *relay* (or *specific*) *nuclei* because they have a specific and selective relationship with a particular portion of the neocortex. Other thalamic nuclei, called *diffusely projecting* (or *nonspecific*) *nuclei*, project to several cortical and subcortical regions. These nuclei are located either on the midline of the thalamus (the midline nuclei) or within the internal medullary lamina (the intralaminar nuclei). The largest of the midline nuclei are the para-ventricular, parataenial, and reuniens nuclei; the largest of the intralaminar cell groups is the centromedian nucleus. The intralaminar nuclei project to limbic structures, such as the amygdala and hippocampus, but also send projections to components of the basal ganglia. These nuclei receive inputs from a variety of sources in the spinal cord, brain stem, and cerebellum and are thought to mediate cortical arousal and perhaps to participate in the integration of sensory submodalities that we shall learn about in Chapters 20 and 28.

Finally, the outer covering of the thalamus is formed by a unique sheet-like structure, the *reticular nucleus.*

The majority of its neurons utilize the inhibitory transmitter γ-aminobutyric acid (GABA), whereas most of the neurons in the other thalamic nuclei utilize the excitatory transmitter glutamate. Moreover, the neurons of the reticular nucleus are not interconnected with the neocortex. Rather, their axons terminate on the other nuclei of the thalamus. These other nuclei also provide the input to the reticular nucleus via collaterals of their axons that exit the thalamus through the reticular nucleus. Thus, the reticular nucleus modulates activity in other thalamic nuclei based on its monitoring of the entirety of the thalamocortical stream of information.
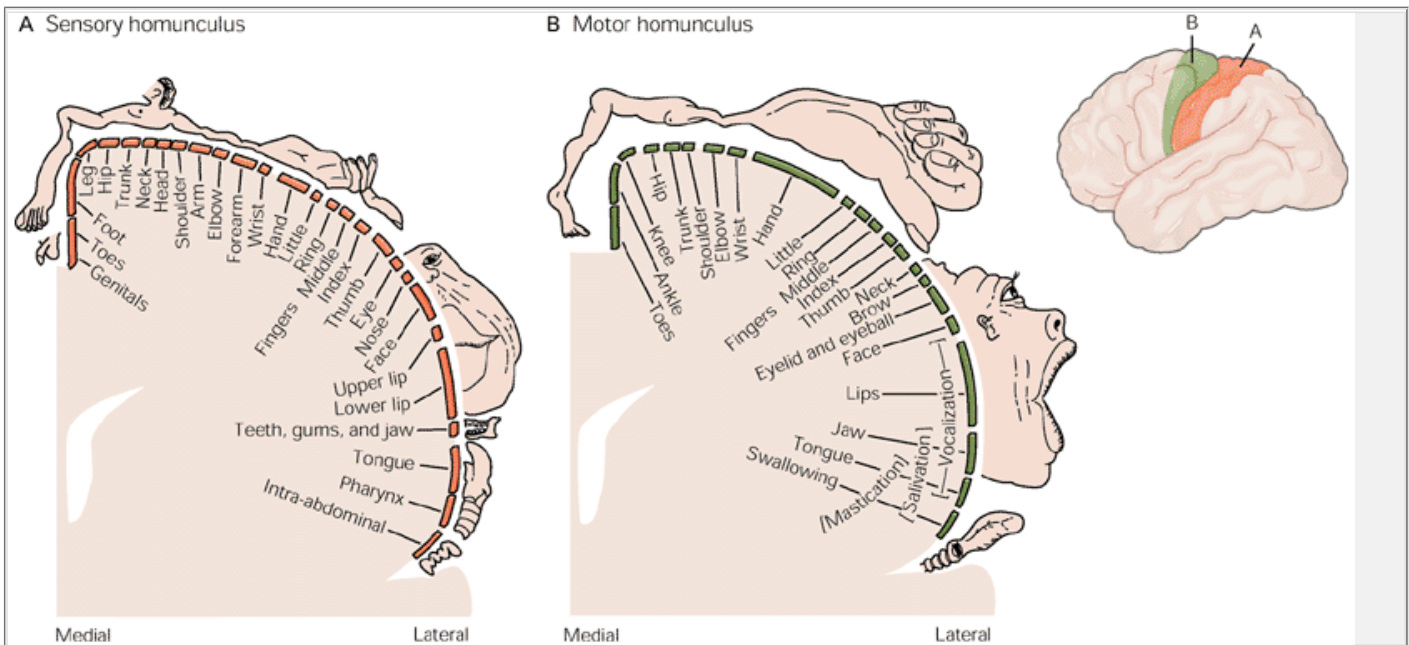
Figure 18-6 The homunculus is a way of illustrating the location and amount of cortical area dedicated to a particular function. The entire body surface is represented in an orderly array of somatosensory inputs to the cortex. The area of cortex dedicated to processing information from a particular part of the body is not proportional to the mass of the body part but instead reflects the degree of innervation of that part. Thus, sensory input from the lips and hands occupies more area of cortex than, say, that from the elbow. Output from the motor cortex is organized in a similar fashion; the amount of cortical surface dedicated to a part of the body is related to the degree of motor control exercised in that part. Thus, in humans much of the motor cortex is dedicated to moving the muscles of the fingers and the muscles related to speech. (Adapted from Penfield and Rasmussen 1950.)

We see, then, that the thalamus is not a relay station where information is simply passed on to the neocortex. Rather it is a complex brain region where substantial information processing is possible. To give but one example, the output of somatosensory information from the ventral posterior lateral nucleus is subject to four types of processing: (1) local processing within the nucleus; (2) modulation by brain stem inputs, such as the noradrenergic and serotonergic monoamine systems; (3) inhibitory feedback from the reticular nucleus; and (4) excitatory feedback from the neocortex.

Sensory Information Processing Culminates in the Cerebral Cortex

After the ventral posterior lateral nucleus of the thalamus, what is the next relay in the processing of somatic sensory information? The axons of cells in the ventral posterior lateral nucleus terminate primarily in the primary somatosensory cortex in Brodmann's area 3b. The neurons here are exquisitely sensitive to tactile stimulation of the skin surface. As in the other processing organs of the somatosensory system, the neurons in different parts of the cortex are somatotopically organized. When Wilder Penfield stimulated the surface of the somatic sensory cortex in patients undergoing brain surgery, he found that sensation from the lower limbs is mediated by neurons located near the midline of the brain, while sensations from the upper body, hands and fingers, the face, lips, and tongue are mediated by neurons located laterally.

As we shall learn in more detail in Chapter 20, Penfield and Jasper found that all portions of the body are represented in the cortex somatotopically, but not in proportion to body mass. Instead, each part of the body

is represented in the cortex in proportion to its degree of innervation. Thus the area of cortex devoted to the fingers is larger than that for the arms. Likewise, the representation of the lips and tongue occupies more cortical surface than that of the remainder of the face (Figure 18-6A). Because the cerebral cortex is organized functionally into columns of cells extending from the white matter to the surface of the cortex, the larger the area of cortex dedicated to a function, the greater the number of computational columns that are involved in that function (Chapter 17). Our highly discriminative sense of touch in the fingers is thus due to the large area of cortex dedicated to the processing of somatosensory information from this part of the body.
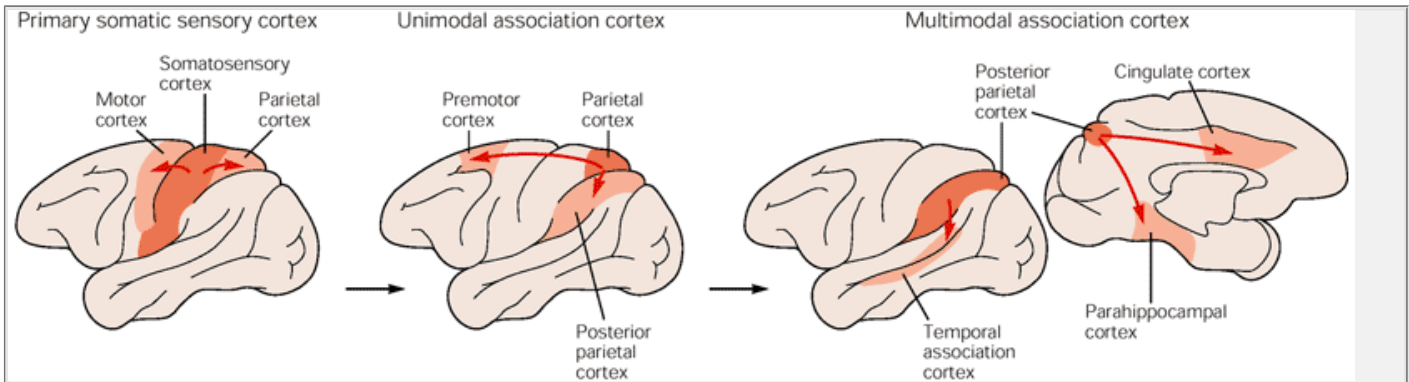

Figure 18-7 The processing of sensory information in the cerebral cortex begins with primary sensory cortices, continues in unimodal association cortices, and is completed in multimodal association areas. In each brain shown here the dark colored areas indicate the origin of a projection and the light colored areas the termination. Sensory systems also project to portions of the motor cortex. In the somatosensory system, for example, the primary somatosensory cortex projects to the motor area in addition to the somatosensory association area. The somatosensory association area, in turn, projects to higher-order somatosensory association areas and to the premotor cortex. Information from different sensory systems converges in the multimodal association areas, which include the parahippocampal, temporal association, and cingulate cortices.

A second major insight from the early electro-physiological studies was that the somatosensory cortex contains not one but several topographically organized sets of inputs from the skin and therefore several somatotopic maps of the body surface. The primary somatosensory cortex (anterior parietal cortex) has four complete

maps of the skin, one each in areas 3a, 3b, 1, and 2. Basic processing of tactile information takes place in area 3, while more complex or higher-order processing occurs in area 1. In area 2 both tactile information and information concerning limb position are combined to mediate the tactile recognition of objects. Neurons in the primary somatosensory cortex project to neurons in adjacent areas, which in turn project to other adjacent cortical regions (Figure 18-7). At higher levels of the hierarchy, somatosensory information is used in motor control, eye-hand coordination, and memory related to tactile experience and touch.

The cortical areas involved in the early stages of processing somatosensory information are concerned only (or primarily) with the processing of somatosensory information. These cortical regions are called unimodal association areas. Ultimately, however, somatosensory information from the unimodal association areas converges on multimodal association areas of the cortex concerned with combining sensory modalities. As we shall learn in the next two chapters and again in Chapter 62, these multimodal associational areas, which are heavily interconnected with the hippocampus, appear to be particularly important for two tasks: (1) the production of a unified percept and (2) the representation of the percept in memory.

Thus, from the mechanical pressure on a receptor in the skin to the perception that a finger has been touched by a friend shaking your hand, somatosensory information is processed in a series of steps as it ascends in serial and parallel pathways from the dorsal root ganglia to the somatosensory cortex, to unimodal association areas, and finally to multimodal association areas. One of the primary purposes of somatosensory information is to guide directed movement. As one might imagine, there is a close linkage between the somatosensory and motor functions of the cortex.
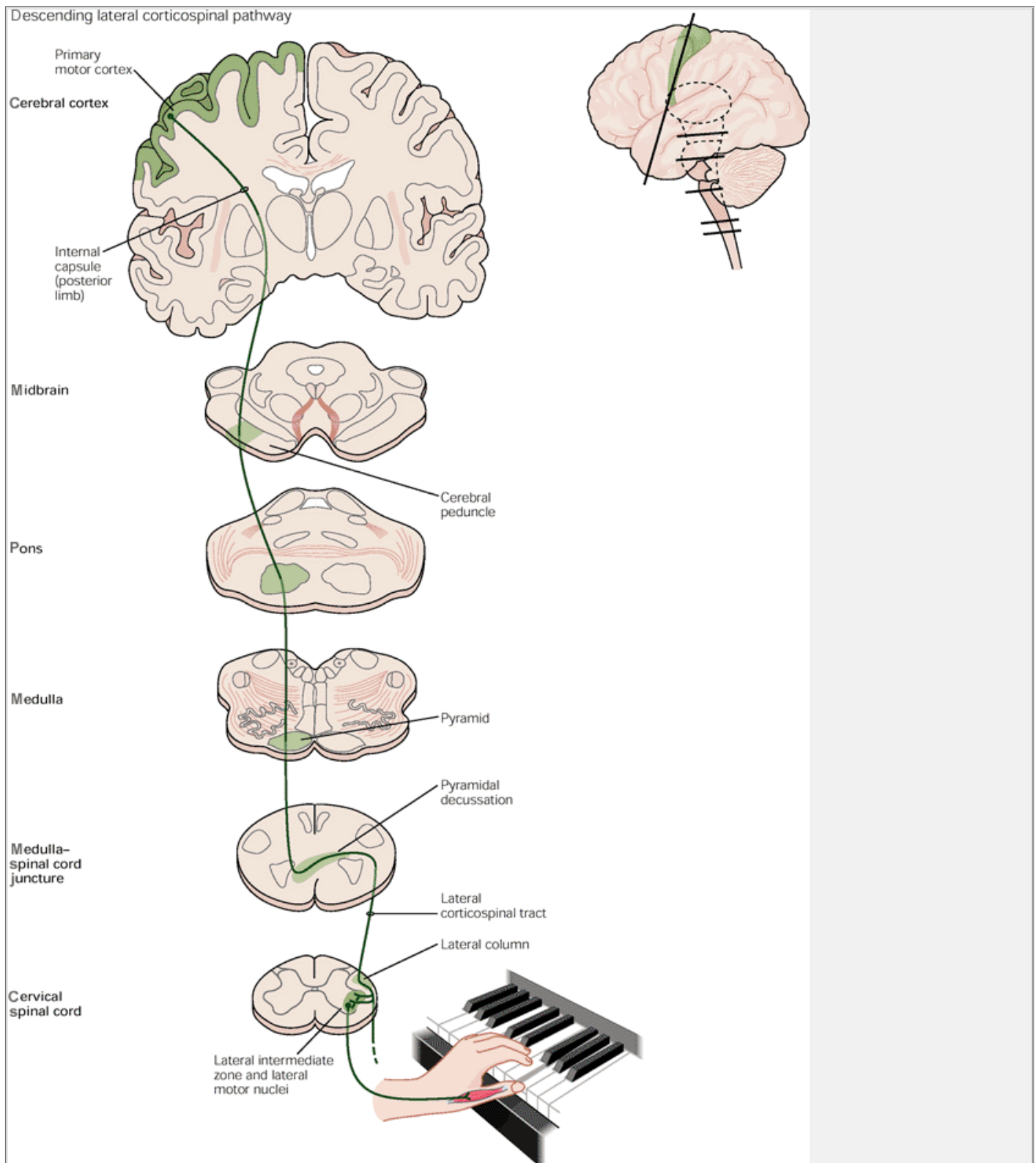

Figure 18-8 Fibers that originate in the primary motor cortex and terminate in the ventral horn of the spinal cord constitute a significant part of the corticospinal tract. The same axons are at various points in their projection part of the internal capsule, the cerebral peduncle, the medullary pyramid, and the lateral corticospinal tract.
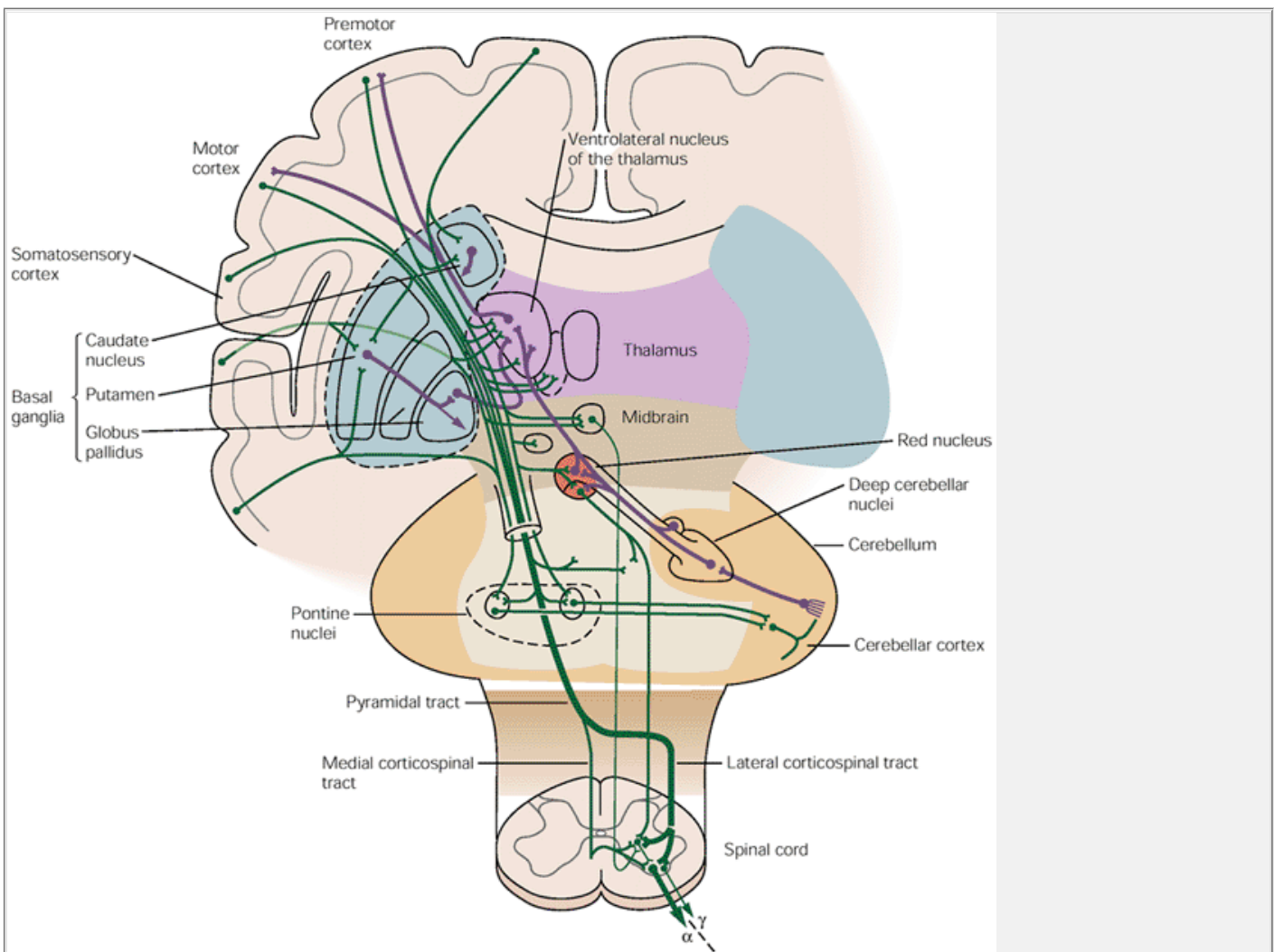
Figure 18-9 Voluntary movement requires the coordinated activity of all components of the motor system including the motor cortex, basal ganglia, thalamus, midbrain, cerebellum, and spinal cord. The principal descending projections are shown in green; the feedback projections and local connections are shown in purple. Ultimately, all of this processing converges on the motor neurons of the ventral horn of the spinal cord, the so-called "final common pathway" that innervates muscle and elicits movements.

P.346

P.347

Voluntary Movement Is Mediated by Direct Connections Between the Cortex and Spinal Cord

A major function of the perceptual systems is to provide the sensory information necessary for the actions mediated by the motor systems of the brain and spinal cord. The primary motor cortex is organized somatotopically like the somatic sensory cortex (see Figure 18-6B). Specific regions of the motor cortex influence the activity of specific muscle groups. Neurons in layer V of the primary motor cortex project their axons directly to motor neurons, or interneurons, in the ventral horn of the spinal cord via the corticospinal tract.

The human corticospinal tract consists of about one million axons, of which about 40% originate in the motor cortex. These axons descend through the subcortical white matter, the internal capsule, and the cerebral peduncle (Figure 18-8). As the fibers of the corticospinal tract descend they form the medullary pyramids, prominent protuberances on the ventral surface of the medulla, and thus the entire projection is sometimes called the pyramidal tract.

Like the ascending somatosensory system, the descending corticospinal tract crosses to the opposite side of the spinal cord. Most of the corticospinal fibers cross the midline in the medulla at a location known as the pyramidal decussation. However, about 10% of the fibers do not cross until they reach the level of the spinal cord at which they will terminate.

The corticospinal tract makes monosynaptic connections with motor neurons, connections that are particularly important for individuated finger movements. It also forms synapses with interneurons in the spinal

P.348

cord. These indirect connections are important for coordinating larger groups of muscles in behaviors such as reaching and walking.

The motor information carried in the corticospinal tract is significantly modulated by both sensory information and information from other motor regions. This includes a continuous stream of tactile, visual, and proprioceptive information needed to make voluntary movement both accurate and properly sequenced. In addition, the output of the motor cortex is under the substantial influence of other motor regions of the brain, including the cerebellum and basal ganglia, structures that are essential for smoothly executed movements.

The basal ganglia receive direct projections from much of the neocortex, which supplies it with both sensory information and information about movement, and the cerebellum receives somatosensory information directly from spinal afferents as well as from cortico-spinal axons descending from the neocortex (Figure 18-9). The cerebellum can influence posture and movement through its connection to the red nucleus, which can directly modulate descending projections to the brain stem and spinal cord. However, the major influence of the cerebellum on movement is through its connections to the ventral nuclear group of the thalamus, which connects directly to the motor cortex. Interestingly, the fibers of the medial lemniscus, basal ganglia, and cerebellum terminate in distinctly different portions of the ventral nuclear complex and ultimately influence different portions of both the somatosensory and motor regions of the cortex.

An Overall View

Sensory and motor information is processed in the brain in a variety of discrete pathways that are active simultaneously. Each pathway is formed by the serial connection of identifiable groups of neurons with each group processing progressively more complex or specific information. Thus, the sensations of touch and pain are mediated by different pathways that run through the spinal cord, brain stem, and into the cortex. All sensory and motor systems follow the pattern of hierarchical and parallel processing.

As we shall see in later chapters, contrary to an intuitive analysis of our personal experience, perceptions are not precise copies of the world around us. Sensation is an abstraction, not a replication, of the world around us. The brain constructs an internal representation of external physical events after first analyzing various features of those events. When we hold an object in the hand, the shape, movement, and texture of the object are simultaneously but separately analyzed according to the brain's own rules, and the results are integrated in a conscious experience.

As we shall see in the next two chapters, how this integration occurs—the *binding problem*—and how conscious experience emerges from the brain's *selective attention* to incoming sensory information are two of the most pressing questions in the neural and cognitive sciences and are likely to be solved only through the combined efforts of both fields.

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