

Figure 4–2 A simple behavior is mediated by many parts of the brain.

A. A tennis player watching an approaching ball uses the visual cortex to judge the size, direction, and velocity of the ball. The premotor cortex develops a motor program to return the ball. The amygdala acts in conjunction with other brain regions to adjust the heart rate, respiration, and other homeostatic mechanisms and also activates the hypothalamus to motivate the player to hit well.

B. To execute the shot, the player must use all of the structures illustrated in part **A** as well as others. The motor cortex sends signals to the spinal cord that activate and inhibit many

in the brain. The system for fine touch, pressure, and proprioception is called the epicritic system, whereas the system for pain and temperature is called the protopathic system.

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

All forms of somatosensory information from the trunk and limbs enter the spinal cord, which has a core H-shaped region of gray matter where neuronal cell bodies are located. The gray matter is surrounded by white matter formed by myelinated axons that make up both short and long connections. The gray matter on each side of the cord is divided into dorsal (or posterior) and ventral (or anterior) horns (Figure 4–3).

The dorsal horn contains groups of secondary sensory neurons (sensory nuclei) whose dendrites

muscles in the arms and legs. The basal ganglia become involved in initiating motor patterns and perhaps recalling learned movements to hit the ball properly. The cerebellum adjusts 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 space and where his racket arm is located with respect to his body. Brain stem neurons regulate heart rate, respiration, and arousal throughout the movement. The hippocampus is not involved in hitting the ball but is involved in storing the memory of the return so that the player can brag about it later.

receive stimulus information from primary sensory neurons that innervate the body's skin, muscles, and joints. The ventral horn contains groups of motor neurons (motor nuclei) whose axons exit the spinal cord and innervate skeletal muscles. The spinal cord has circuits that mediate behaviors ranging from the stretch reflex to coordination of limb movements.

As we discussed in Chapter 3, when considering the knee-jerk reflex, interneurons of various types in the gray matter regulate the output of the spinal cord motor neurons (see Figure 3–5). Some of these interneurons are excitatory, whereas others are inhibitory. These interneurons modulate both sensory information flowing toward the brain and motor commands descending from the brain to the spinal motor neurons. Motor neurons can also adjust the output of other motor neurons via the interneurons. These

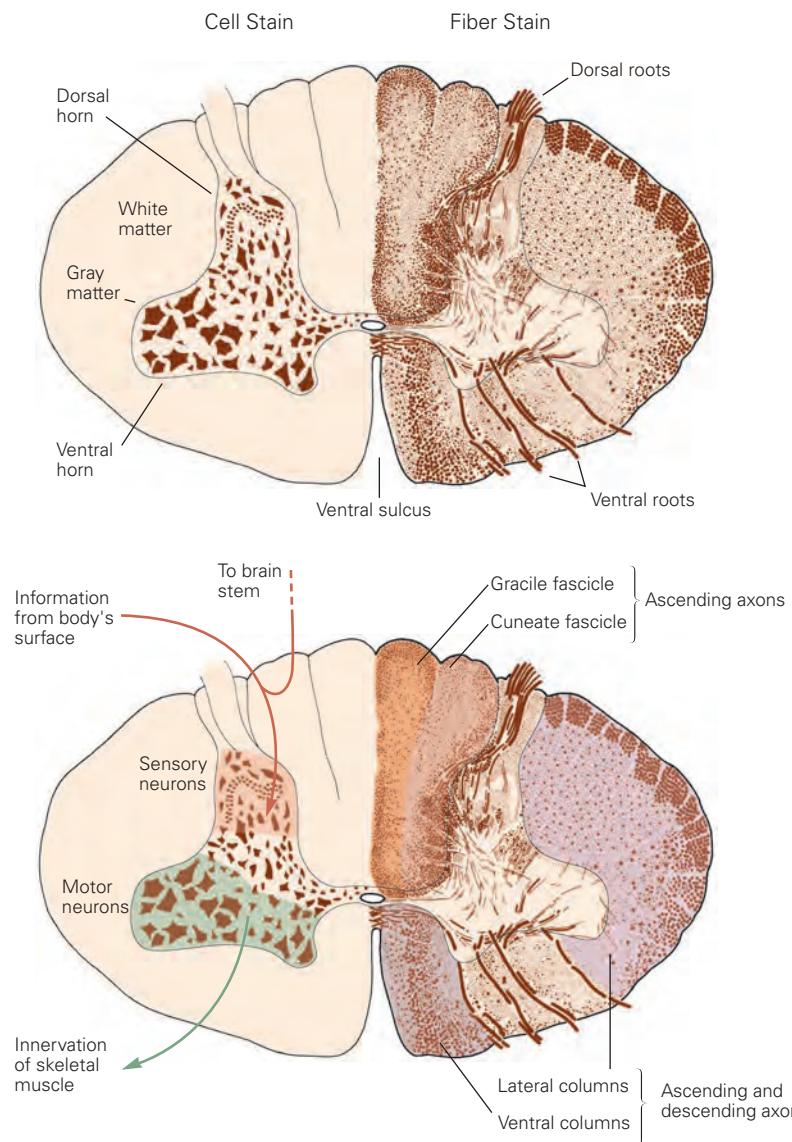


Figure 4-3 The major anatomical features of the spinal cord. The ventral horn (green) contains large motor neurons, whereas the dorsal horn (orange) contains smaller neurons. Fibers of the gracile fascicle carry somatosensory information

from the lower limbs, whereas fibers of the cuneate fascicle carry somatosensory information from the upper body. Fiber bundles of the lateral and ventral columns include both ascending and descending fiber bundles.

circuits will be considered in more detail when we discuss the spinal cord in Chapter 32.

The white matter surrounding the gray matter contains bundles of ascending and descending axons that are divided into dorsal, lateral, and ventral columns. The dorsal columns, which lie between the two dorsal horns of the gray matter, contain only ascending axons that carry somatosensory information to the brain stem (Figure 4-1). The lateral columns include both ascending and descending axons from the brain

stem and neocortex that innervate spinal interneurons and motor neurons (Figure 4-3). This demonstrates a general principle about central nervous system connections. Processing tends to be hierarchical: Projections from a lower to a higher processing region are said to be feedforward, while descending projections can modulate spinal reflexes and are considered to be feedback. The motif in which region A projects to region B and, in turn, also receives return projections from B, is recapitulated throughout the nervous

system. The ventral columns also include ascending and descending axons. The ascending somatosensory 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 axons control axial muscles and posture.

The spinal cord is divided along its length into four major regions: cervical, thoracic, lumbar, and sacral (Figure 4–4). Connections arising from these regions

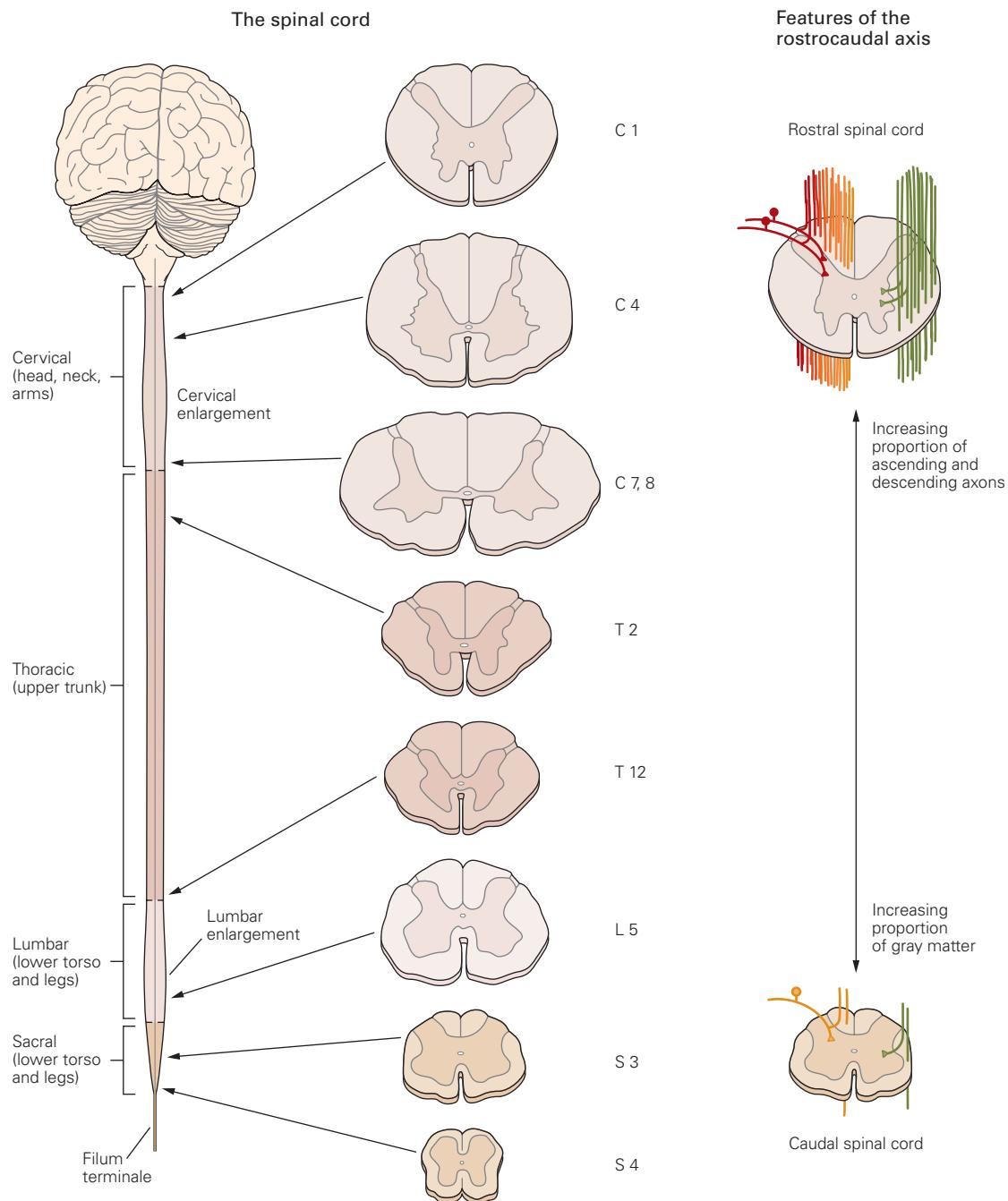


Figure 4–4 The internal and external appearances of the spinal cord vary at different levels. The proportion of gray matter (the H-shaped area within the spinal cord) to white matter is greater at sacral levels than at cervical levels. At sacral levels, very few incoming sensory axons have joined the spinal

cord, whereas most of the motor axons have already terminated at higher levels of the spinal cord. The cross-sectional enlargements at the lumbar and cervical levels are regions where the large number of fibers innervating the limbs enter or leave the spinal cord.

are segregated according to the embryological somites from which muscles, bones, and other components of the body develop (Chapter 45). Axons projecting from the spinal cord to body structures that develop at the same segmental level join with axons entering the spinal cord in the intervertebral foramen 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; lumbar and sacral spinal nerves innervate the lower trunk, back, and legs.

Each of the four regions of the spinal cord contains multiple segments corresponding approximately to the different vertebrae in each region; there are 8 cervical segments, 12 thoracic segments, 5 lumbar segments, and 5 sacral segments. The actual substance of the mature spinal cord does not look segmented, but the segments of the four spinal regions are nonetheless defined by the number and location of the dorsal and ventral roots that enter or exit the spinal cord. 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. The number of sensory axons entering the cord increases at progressively higher levels (lumbar, thoracic, and cervical). 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 4–4).

The second organizational feature is variation in the size of the ventral and dorsal horns. The ventral horn is larger at the levels where the motor nerves innervate the arms and legs. The number of ventral motor neurons dedicated to a body region roughly parallels the dexterity of movements of that region. Thus, a larger number of motor neurons is 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. Limbs have a greater density of sensory receptors to mediate finer tactile discrimination and thus send more sensory fibers to the cord. These regions of the cord are known as the lumbosacral and cervical enlargements (Figure 4–4).

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 4–5). These neurons are pseudo-unipolar in shape; they have a bifurcated axon with central and peripheral branches. The peripheral branch innervates the skin, muscle, or other tissue as a free nerve ending or in association with specialized receptors for sensing touch, proprioception (stretch receptors), pain, and temperature.

The somatosensory system and its pathways from receptors to perception are more fully described in Chapters 17 to 20. Suffice it to say at this point that there are essentially two somatosensory pathways from the periphery that carry either touch and stretch (epicritic system) or pain and temperature (protopathic system). Epicritic fibers travel in the posterior column-medial lemniscal system (Figure 4–6). The centrally directed axons from neurons in the dorsal root ganglion ascend in the dorsal (or posterior) column white matter and terminate in the gracile nucleus or cuneate nucleus of the medulla. The centrally directed axons of the pain and temperature pathway form the spinothalamic

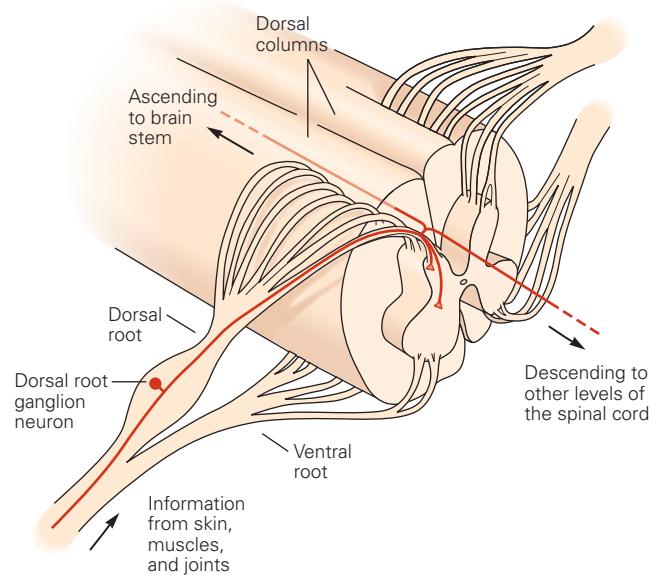
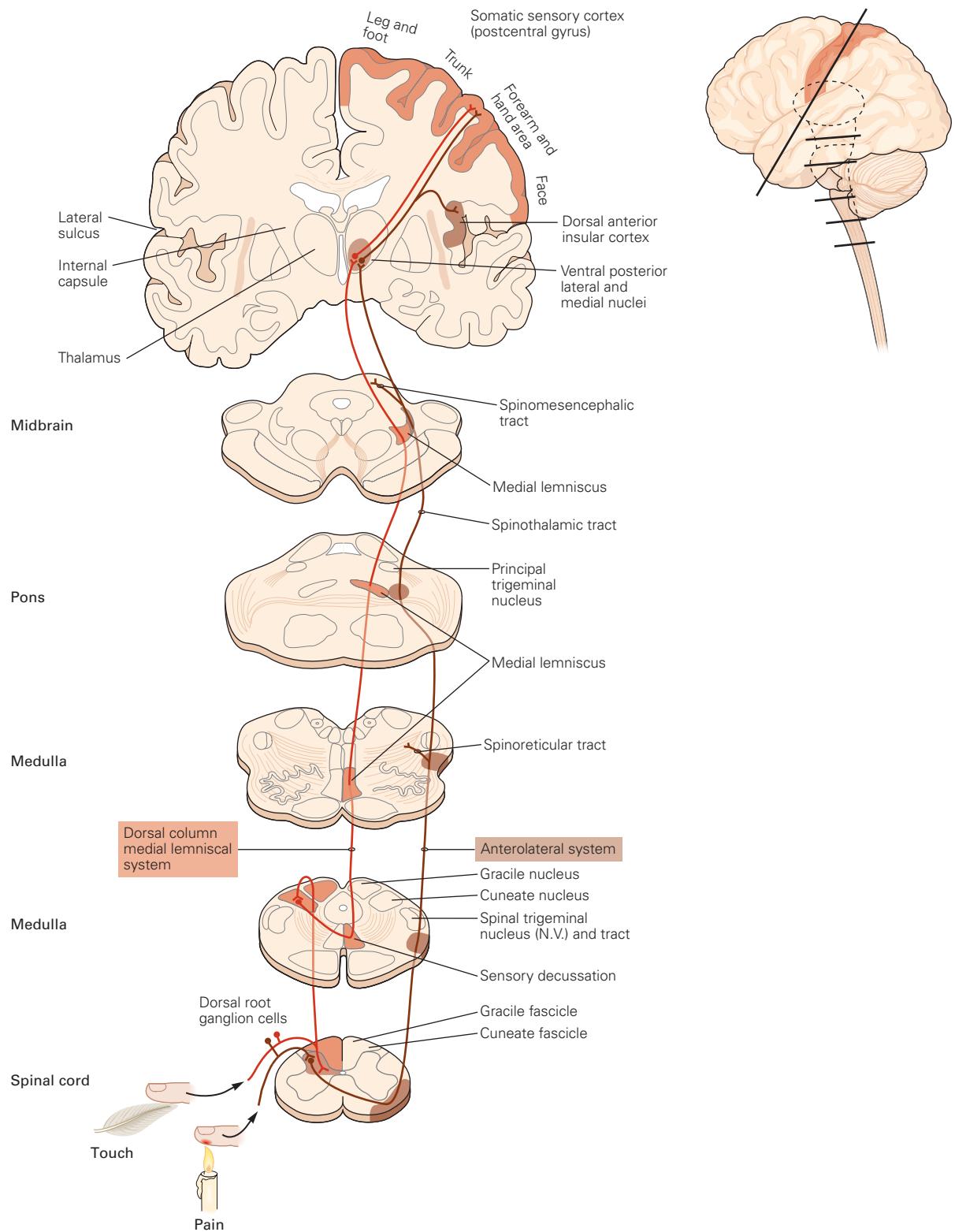


Figure 4–5 Dorsal root ganglia and spinal nerve roots. The cell bodies of neurons that bring sensory information from the skin, muscles, and joints lie in the dorsal root ganglia, clusters of cells that lie adjacent to the spinal cord. The axons of these neurons are bifurcated into peripheral and central branches. The central branch enters the dorsal portion of the spinal cord.



pathway. They terminate within the gray matter of the dorsal horn of the spinal cord. Second-order neurons cross to the other side of the spinal cord and ascend in the anterior and lateral spinothalamic tracts (Figure 4–6). Both pathways ultimately terminate in the thalamus, which sends projections to the primary somatosensory area of the cerebral cortex. In the next section, we focus on the epicritic system.

The local and ascending branches from touch and proprioceptive sensory neurons provide two functional pathways for somatosensory information entering the spinal cord from dorsal root ganglion cells. The local branches can activate local reflex circuits that modulate motor output, while the ascending branches carry information into the brain, where this information is further processed in the thalamus and cerebral cortex.

The Terminals of Central Axons of Dorsal Root Ganglion Neurons in the Spinal Cord Produce a Map of the Body Surface

The manner in which the central axons of the dorsal root ganglion cells terminate in the spinal cord forms a neural map of the body surface. This orderly somatotopic distribution of inputs from different portions of the body surface is maintained throughout the entire ascending somatosensory pathway. This arrangement illustrates another important principle of neural organization. Neurons that make up neural circuits at any particular level are often connected in a systematic fashion and appear similar from individual to individual. Similarly, fiber bundles that connect different processing regions at different levels of the nervous system are also arranged in a highly organized and stereotypical fashion.

Axons that enter the cord in the sacral region ascend in the dorsal column near the midline, whereas 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, sensory fibers from the lower body are located medially in the dorsal column, while fibers from the trunk, arm and shoulder, and finally the neck occupy progressively more lateral areas. In the cervical spinal cord, the axons forming the dorsal columns are divided into two bundles: a medially situated gracile fascicle and a more laterally situated cuneate fascicle (Figure 4–1).

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

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

The primary afferent fibers that carry information about touch enter the ipsilateral dorsal column and ascend to the medulla. Fibers from the lower body run in the gracile fascicle and terminate in the gracile nucleus, whereas fibers from the upper body run in the cuneate fascicle 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 4–1).

As in the dorsal columns of the spinal cord, the fibers of the medial lemniscus are arranged somatotopically. Because the fibers carrying sensory information

Figure 4–6 (Opposite) Somatosensory information from the limbs and trunk is conveyed to the thalamus and cerebral cortex by two ascending pathways. Brain slices along the neuraxis from the spinal cord to the cerebrum illustrate the anatomy of the two principal pathways conveying somatosensory information to the cerebral cortex. The two pathways are separated until they reach the pons, where they are juxtaposed.

Dorsal column-medial lemniscal system (orange). Touch and limb proprioception signals are conveyed to the spinal cord and brain stem by large-diameter myelinated nerve fibers and transmitted to the thalamus in this system. In the spinal cord, the fibers for touch and proprioception divide, one branch going to the ipsilateral spinal gray matter and the other ascending in the ipsilateral dorsal column to the medulla. The second-order fibers from neurons in the dorsal column nuclei cross the

midline in the medulla and ascend in the contralateral medial lemniscus toward the thalamus, where they terminate in the lateral and medial ventral posterior nuclei. Thalamic neurons in these nuclei convey tactile and proprioceptive information to the primary somatosensory cortex.

Anterolateral system (brown). Pain, itch, temperature, and visceral information is conveyed to the spinal cord by small-diameter myelinated and unmyelinated fibers that terminate in the ipsilateral dorsal horn. This information is conveyed across the midline by neurons within the spinal cord and transmitted to the brain stem and the thalamus in the contralateral anterolateral system. Anterolateral fibers terminating in the brain stem compose the spinoreticular and spinomesencephalic tracts; the remaining anterolateral fibers form the spinothalamic tract.

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 lateral nucleus (Figure 4–1). There the fibers maintain their somatotopic organization such that those carrying information from the lower body end laterally and those carrying information from the upper body end medially.

The Thalamus Is an Essential Link Between Sensory Receptors and the Cerebral Cortex

The thalamus is an egg-shaped structure that constitutes the dorsal portion of the diencephalon. It contains a class of excitatory neurons called thalamic relay cells that convey sensory input to the primary sensory areas of the cerebral cortex. However, the thalamus is not merely 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 organism.

The cerebral cortex has feedback projections that terminate, in part, in a special portion of the thalamus called the thalamic reticular nucleus. This nucleus

forms a thin sheet around the thalamus and is made up almost totally of inhibitory neurons that synapse onto the relay cells. It does not project to the neocortex at all. In addition to receiving feedback projections from the neocortex, the reticular nucleus receives input from axons leaving the thalamus en route to the neocortex, enabling the thalamus to modulate the response of its relay cells to incoming sensory information.

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 (Figure 4–7). Some nuclei receive information specific to a sensory modality and project to a specific area of the neocortex. For example, cells in the ventral posterior lateral nucleus (where the medial lemniscus terminates) process somatosensory information, and their axons project to the primary somatosensory cortex (Figures 4–1 and 4–7). Projections from the retinal ganglion cells terminate in another portion of the thalamus called the lateral geniculate nucleus (Figure 4–7). Neurons in this nucleus project in turn to the visual cortex. Other portions of the thalamus 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 corona radiata, a large

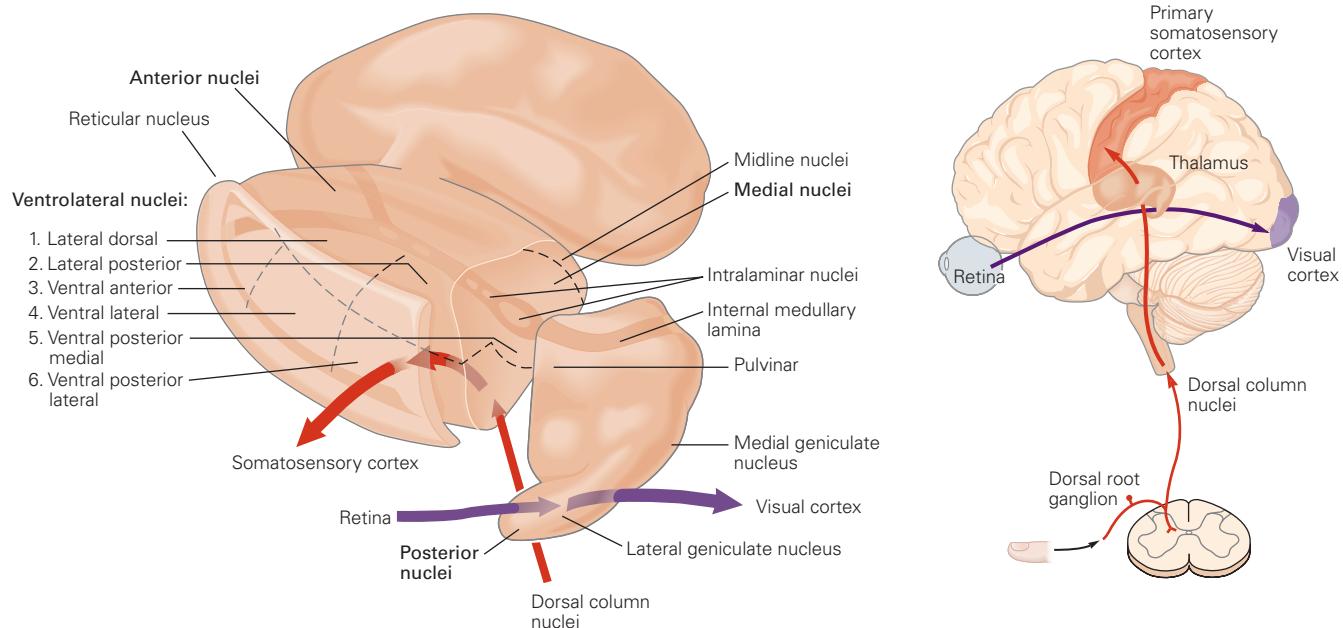


Figure 4–7 The major subdivisions of the thalamus. The thalamus is the critical relay for the flow of sensory information from peripheral receptors to the neocortex. Somatosensory information is conveyed from dorsal root ganglia to the ventral posterior lateral nucleus and from there to the primary

somatosensory cortex. Likewise, visual information from the retina reaches the lateral geniculate nucleus, from which it is conveyed 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.

fiber bundle that carries most of the axons running to and from the cerebral hemispheres. Through its connections with the frontal lobe and hippocampus, the thalamus may 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 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 4–7). Thus, the medial group of nuclei is located medial to the internal medullary lamina, whereas 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 group, dominated by 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* receives its major input from the mammillary nuclei of the hypothalamus and from the presubiculum of the hippocampal formation. The role of the anterior group is uncertain, but because of its connections, it is thought to be related to memory and emotion. The anterior group is mainly 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 and emotional processing.

The nuclei of the *ventrolateral group* are named according to their positions 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 posterior nuclei convey somatosensory information to the neocortex. The ventroposterior lateral nucleus conveys information from the spinal cord tracts, as described earlier. The ventroposterior medial nucleus conveys information from the face, which enters the brain stem mainly through the trigeminal nerve (cranial nerve V).

The *posterior group* includes the medial and lateral geniculate nuclei, the lateral posterior nucleus, and the pulvinar. The medial geniculate nucleus is a component of the auditory system and is organized tonotopically based on the sound frequency information

carried by its inputs; it conveys auditory information to the primary auditory cortex in 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. Compared to rodents, the pulvinar is enlarged disproportionately 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, and temporal cortices. 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.

As noted previously, the thalamus not only projects to the neocortex (feedforward connections) but also receives extensive return inputs back from the neocortex (feedback connections). For example, in the lateral geniculate nucleus, the number of synapses formed by axons from the feedback projection from the visual cortex is actually greater than the number of synapses that the lateral geniculate nucleus receives from the retina! This feedback is thought to play an important modulatory role in the processing of sensory information, although the exact function is not yet understood. Although this feedback is mainly from cortical neurons that are activated by both eyes, the neurons in the lateral geniculate nucleus are responsive to only one or the other eye. The implication is that they are primarily driven by input from the retina (which is from different eyes in different layers), not the feedback from the cortex, despite its numerical advantage. Most nuclei of the thalamus receive a similarly prominent return projection from the cerebral cortex, and the significance of these projections is one of the unsolved mysteries of neuroscience.

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 *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 paraventricular, paratenial, and reuniens nuclei; the largest of the intralaminar cell groups is the centromedian nucleus. The intralaminar nuclei project to medial temporal lobe structures, such as the amygdala and hippocampus, but also send projections to portions 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.

The thalamus is an important step in the hierarchy of sensory processing, not a passive relay station where information is simply passed on to the neocortex. It is a complex brain region where substantial information processing takes place (Figure 4–1). 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 from the noradrenergic and serotonergic systems; (3) inhibitory input from the reticular nucleus; and (4) modulatory feedback from the neocortex.

Sensory Information Processing Culminates in the Cerebral Cortex

Somatosensory information from the ventral posterior lateral nucleus is conveyed mainly to the primary somatosensory cortex (Figure 4–1). The neurons here are exquisitely sensitive to tactile stimulation of the skin surface. The somatosensory cortex, like earlier stages in tactile sensory processing, is somatotopically organized (Figure 4–8).

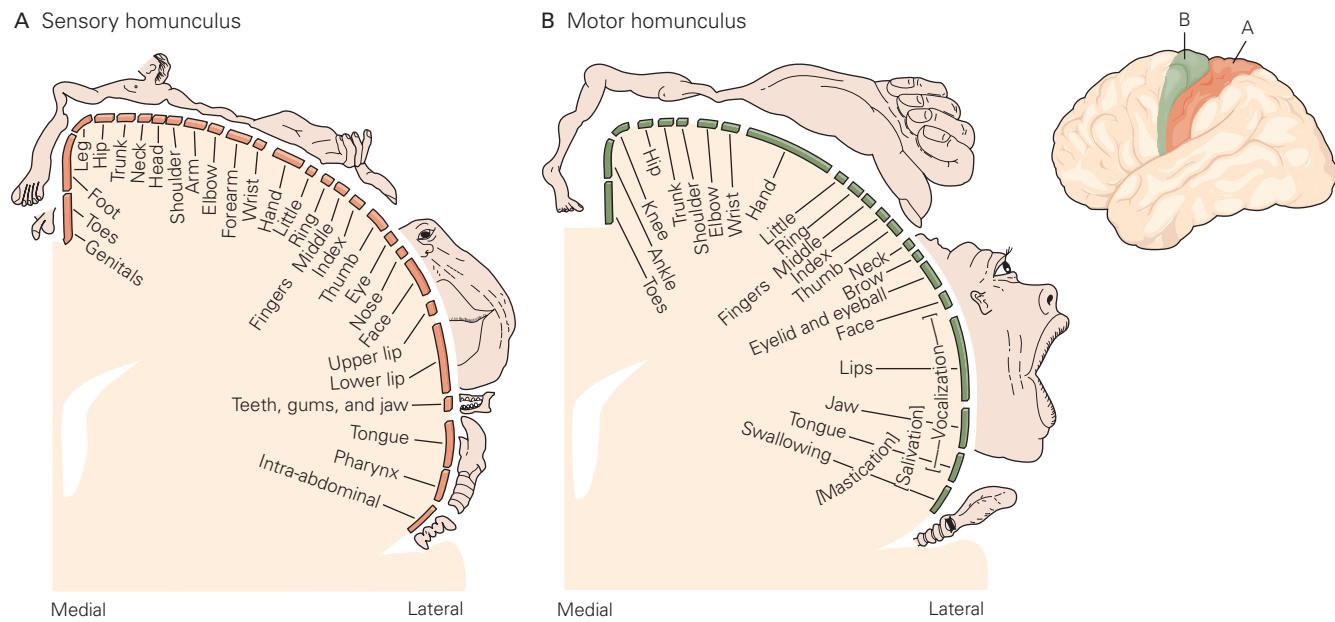


Figure 4–8 Homunculi illustrate the relative amounts of cortical area dedicated to sensory and motor innervation of individual parts of the body. The entire body surface is represented in an orderly array of somatosensory inputs in the cortex. (From Penfield and Rasmussen 1950. Reproduced by permission of the Osler Library of the History of Medicine, McGill University.)

A. The area of cortex dedicated to processing sensory information from a particular part of the body is not proportional to the mass of

When the neurosurgeon Wilder Penfield stimulated the surface of the somatosensory cortex in patients undergoing brain surgery in the late 1940s and early 1950s, he found that sensation from the lower limbs is mediated by neurons located near the midline of the brain, whereas sensations from the upper body, hands and fingers, face, lips, and tongue are mediated by neurons located laterally. Penfield found that, although all parts of the body are represented in the cortex somatotopically, the amount of surface area of cortex devoted to each body part is not proportional to its mass. Instead, it is proportional to the fineness of discrimination in the body part, which in turn is related to the density of innervation of sensory fibers (Chapter 19). 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 4–8). As we shall see in Chapter 53, the amount of cortex devoted to a particular body part is not fixed but can be modified by experience, as seen in concert violinists, where there is an expansion of the region of somatosensory cortex devoted to the fingers of the hand used to finger the strings. This illustrates

the body part but instead reflects the density of sensory receptors in that part. Thus, sensory input from the lips and hands occupies more area of cortex than, say, that from the elbow.

B. Output from the motor cortex is organized in similar fashion. The amount of cortical surface dedicated to a part of the body is related to the degree of motor control of that part. Thus, in humans, much of the motor cortex is dedicated to controlling the muscles of the fingers and the muscles related to speech.