

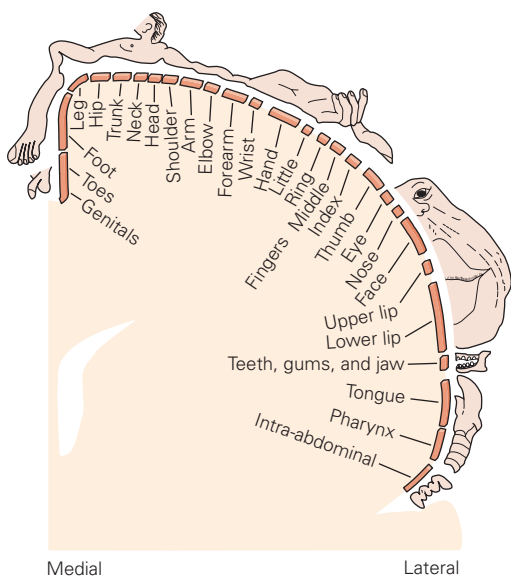
The thalamus is an important step in the hierarchy of sensory processing, not a passive relay station where information is simply passed on to the neocortex. It is a complex brain region where substantial information processing takes place (Figure 4–1). To give but one example, the output of somatosensory 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).

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

A Sensory homunculus



B Motor homunculus

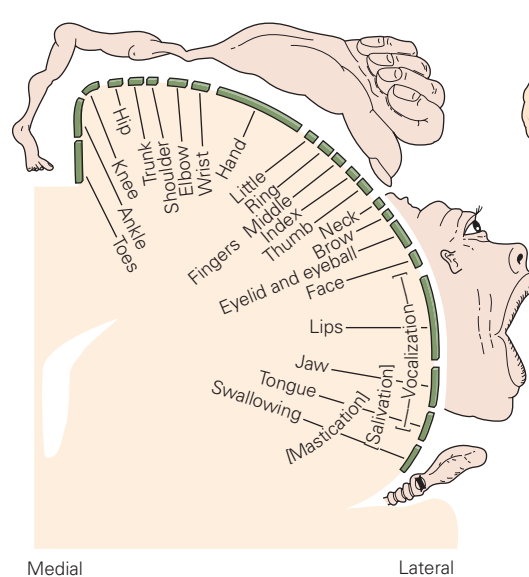


Figure 4–8 Homunculi illustrate the relative amounts of cortical area dedicated to sensory and motor innervation of individual parts of the body. The entire body surface is represented in an orderly array of somatosensory inputs in the cortex. (From Penfield and Rasmussen 1950. Reproduced by permission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

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.

an important aspect of brain circuitry: It is capable of plastic changes in response to use or disuse. Such changes are important for various forms of learning, including the ability to recover function after a stroke.

The region of cerebral cortex nearest the surface of the brain is organized in layers and columns, an arrangement that increases its computational efficiency. The cortex has undergone dramatic expansion in evolution. The more recent neocortex comprises most of the cortex of mammals. In larger brains of primates and cetaceans, the neocortical surface is a sheet that is folded with deep wrinkles, thus allowing for three times more cortical surface to be packed into an only modestly enlarged head. Indeed, approximately two-thirds of the neocortex is along the deep wrinkles of the cortex, termed sulci. The remainder of neocortex

is at the external folds of the sheet, termed gyri. The neocortex receives inputs from the thalamus, other cortical regions on both sides of the brain, and other subcortical structures. Its output is directed to other regions of the cortex, basal ganglia, thalamus, pontine nuclei, and spinal cord.

These complex input–output relationships are efficiently organized in the orderly layering of cortical neurons; each layer contains different inputs and outputs. Many regions of the neocortex, in particular the primary sensory areas, contain six layers, numbered from the outer surface of the brain to the white matter (Figure 4–9).

Layer I, the molecular layer, is occupied by the dendrites of cells located in deeper layers and axons that travel through this layer to make connections in other areas of the cortex.

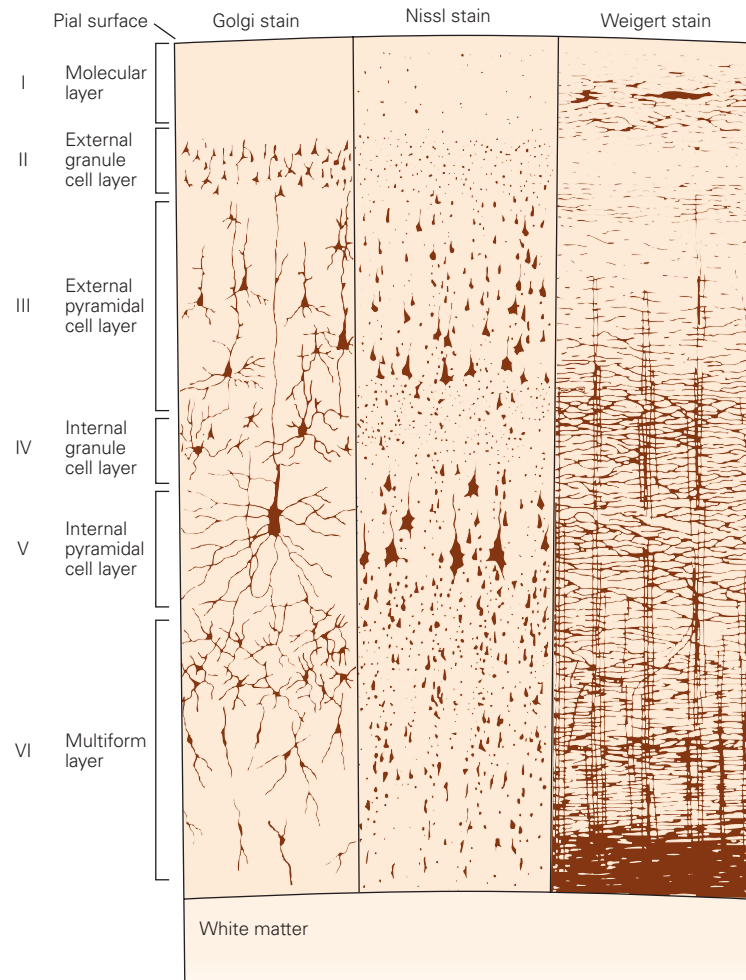


Figure 4–9 The neurons of the neocortex are arranged in distinctive layers. The appearance of the neocortex depends on what is used to stain it. The Golgi stain (*left*) reveals a subset of neuronal cell bodies, axons, and dendritic trees.

The Nissl method (*middle*) shows cell bodies and proximal dendrites. The Weigert stain (*right*) reveals the pattern of myelinated fibers. (Reproduced, with permission, from Heimer 1994.)

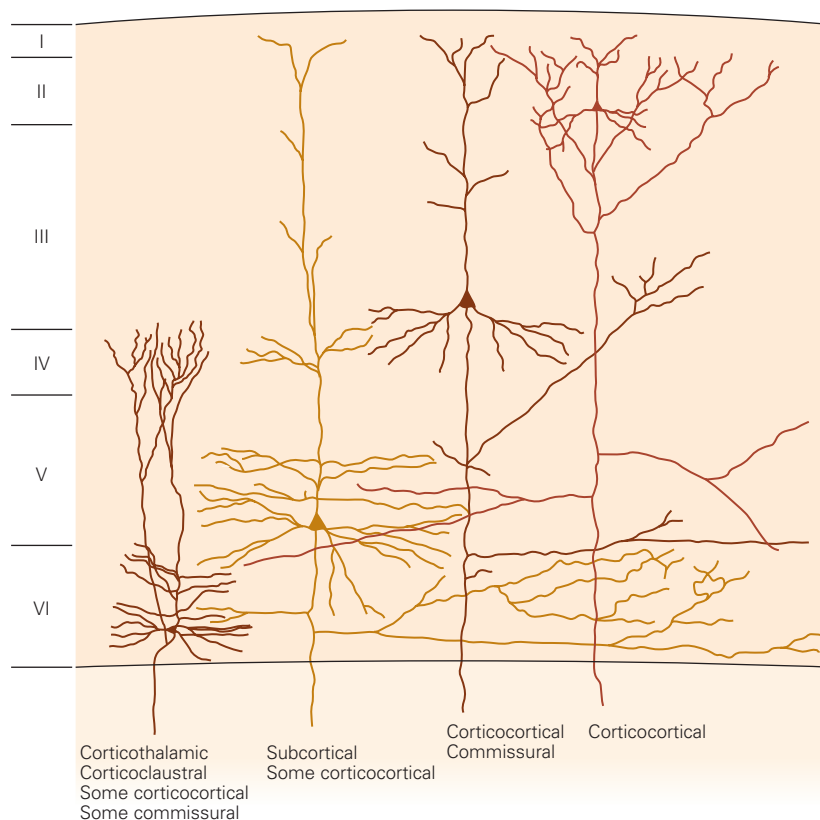


Figure 4-10 Neurons in different layers of neocortex project to different parts of the brain. Projections to all other parts of the neocortex, the so-called corticocortical or associational

connections, arise primarily from neurons in layers II and III. Projections to subcortical regions arise mainly from layers V and VI. (Reproduced, with permission, from Jones 1986.)

Layers II and III contain mainly small pyramidal shaped cells. Layer II, the external granular cell layer, is one of two layers that contain small spherical neurons. Layer III is called the external pyramidal cell layer (an internal pyramidal cell layer lies at a deeper level). The neurons located deeper in layer III are typically larger than those located more superficially. The axons of pyramidal neurons in layers II and III project locally to other neurons within the same cortical area as well as to other cortical areas, thereby mediating intracortical communication (Figure 4-10).

Layer IV contains a large number of small spherical neurons and thus is called the internal granular cell layer. It is the main recipient of sensory input from the thalamus and is most prominent in primary sensory areas. For example, the region of the occipital cortex that functions as the primary visual cortex has an extremely prominent layer IV. Layer IV in this region is so heavily populated by neurons and so complex that it is typically divided into three sublayers. Areas with a prominent layer IV are called granular cortex. In contrast, the

precentral gyrus, the site of the primary motor cortex, has essentially no layer IV and is thus part of the so-called agranular frontal cortex. These two cortical areas are among the easiest to identify in histological sections (Figure 4-11).

Layer V, the internal pyramidal cell layer, contains mainly pyramidally shaped cells that are typically larger than those in layer III. Pyramidal neurons in this layer give rise to the major output pathways of the cortex, projecting to other cortical areas and to subcortical structures (Figure 4-9).

The neurons in layer VI are fairly heterogeneous in shape, so this layer is 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 areas of cortex.

The thickness of individual layers and the details of their functional organization vary throughout the cortex. An early student of the cerebral cortex, Korbinian Brodmann, used the relative prominence of the layers above and below layer IV, cell size, and packing

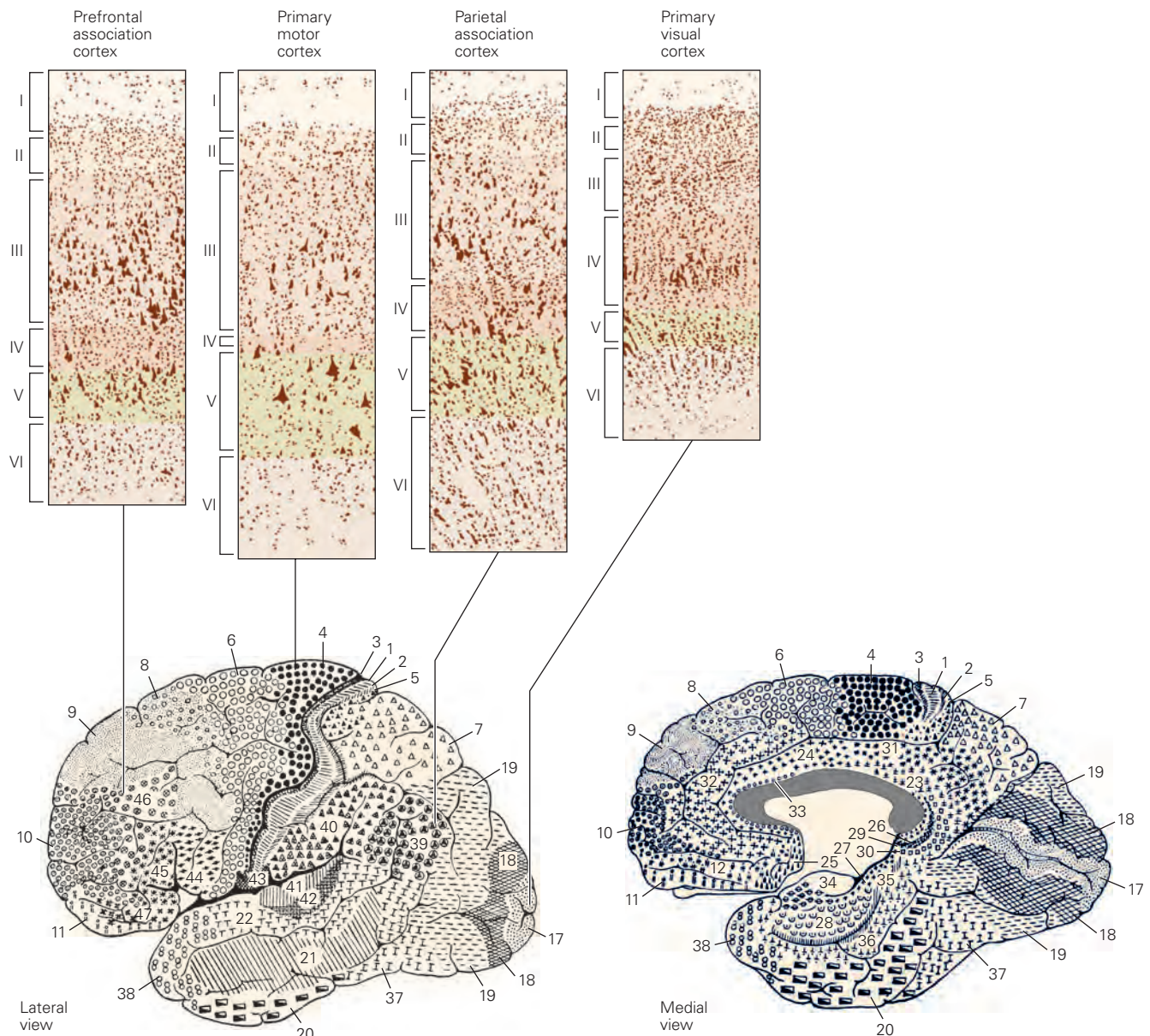


Figure 4-11 The extent of each cell layer of the neocortex varies throughout the cortex. Sensory areas of cortex, such as the primary visual cortex, tend to have a very prominent internal granular cell layer (layer IV), the site of sensory input. Motor areas of cortex, such as the primary motor cortex, have a very meager layer IV but prominent output layers, such as

layer V. These differences led Korbinian Brodmann and others working at the turn of the 20th century to divide the cortex into various cytoarchitectonic regions. Brodmann's 1909 subdivision shown here is a classic analysis but was based on a single human brain. (Reproduced, with permission, from Martin 2012.)

characteristics to distinguish different areas of the neocortex. Based on such cytoarchitectonic differences, in 1909, Brodmann divided the cerebral cortex into 47 regions (Figure 4-11).

Although Brodmann's demarcation coincides in part with information on localized functions in 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 identified five regions (areas 17–21) as being concerned with visual function in the monkey. In contrast, modern connective neuroanatomy and electrophysiology have identified more than 35 functionally distinct cortical regions within the five regions recognized by Brodmann.

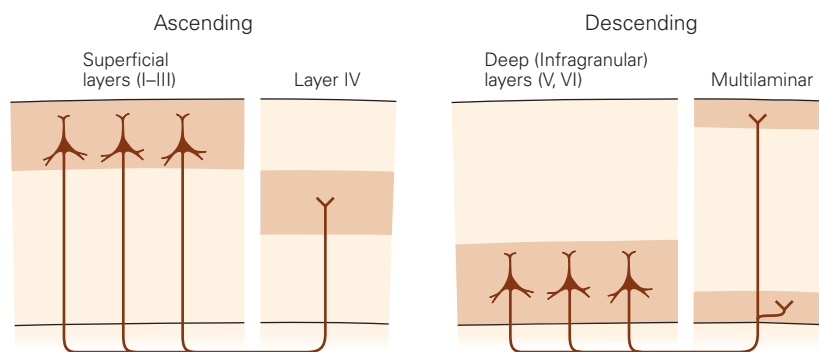


Figure 4-12 Ascending and descending cortical pathways are distinguished by the organization of their origins and terminations within the cortical layers. Ascending or feed-forward pathways generally originate in superficial layers of

the cortex and invariably terminate in layer IV. Descending or feedback pathways generally originate from deep layers and terminate in layers I and VI. (Adapted, with permission, from Felleman and Van Essen 1991.)

Within the neocortex, information passes from one synaptic relay to another using feedforward and feedback connections. In the visual system, for example, feedforward projections from the primary visual cortex to secondary and tertiary visual areas originate mainly in layer III and terminate mainly in layer IV of the target cortical area. In contrast, feedback projections to earlier stages of processing originate from cells in layers V and VI and terminate in layers I, II, and VI (Figure 4-12).

The cerebral cortex is organized functionally into columns of cells that extend from the white matter to the surface of the cortex. (This columnar organization is not particularly evident in standard histological preparations and was first discovered in electrophysiological studies.) Each column is about one-third of a millimeter in diameter. The cells in each column form a computational module with a highly specialized function. Neurons within a column tend to have very similar response properties, presumably because they form a local processing network. The larger the area of cortex dedicated to a function, the greater the number of computational columns that are dedicated to that function (Chapter 23). The highly discriminative sense of touch in the fingers is a result of many cortical columns in the large area of cortex dedicated to processing somatosensory information from the hand.

Beyond the identification of the cortical column, a second major insight from the early electrophysiological studies was that the somatosensory cortex contains not one but several somatotopic maps of the body surface. The primary somatosensory cortex (anterior parietal cortex) has four complete maps of the skin, one each in Brodmann areas 3a, 3b, 1, and 2. The thalamus sends, in parallel, a lot of deep receptor information

(eg, from muscles) to area 3a and most of its cutaneous information to areas 3b and 1. Area 2 receives input from these thalamorecipient cortical areas and may be responsible for our integrated perception of three-dimensional solid objects, termed stereognosis. Neurons in the primary somatosensory cortex project to neurons in adjacent areas, and these neurons in turn project to other adjacent cortical regions (Figure 4-13). At higher levels in the hierarchy of cortical connections, somatosensory information is used in motor control, eye-hand coordination, and memory related to touch.

The cortical areas involved in the early stages of sensory processing are concerned primarily with a single sensory modality. Such regions are called primary sensory or unimodal (sensory) association areas. Information from the unimodal association areas converges on multimodal association areas of the cortex concerned with combining sensory modalities (Figure 4-13). These multimodal association areas, which are heavily interconnected with the hippocampus, appear to be particularly important for two functions: (1) the production of a unified percept and (2) the representation of the percept in memory (we will return to this at the end of this chapter).

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 increasingly more complex circuits (networks) 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.

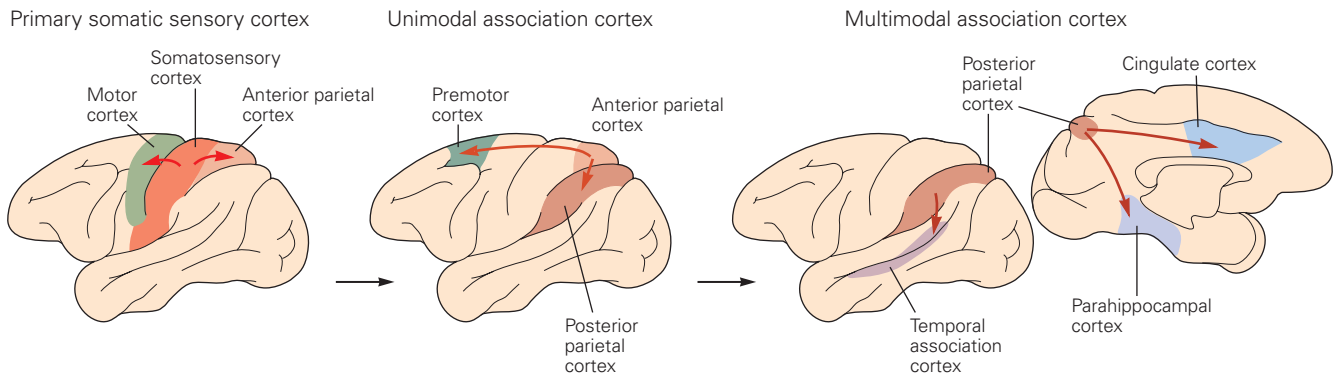


Figure 4-13 The processing of sensory information in the cerebral cortex begins with primary sensory areas, continues in unimodal association areas, and is further elaborated in multimodal association areas. Sensory systems also communicate with portions of the motor cortex. For example, the primary somatosensory cortex projects to the motor area in the

frontal lobe and to the somatosensory association area in the parietal cortex. 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.

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

As we shall see in Chapters 25 and 30, a major function of the perceptual systems is to provide the sensory information necessary for the actions mediated by the motor systems. The primary motor cortex is organized somatotopically like the somatosensory cortex (Figure 4-8B). Specific regions of the motor cortex influence the activity of specific muscle groups (Chapter 34).

The axons of neurons in layer V of the primary motor cortex provide the major output of the neocortex to control movement. Some layer V neurons influence movement directly through projections in the corticospinal tract to motor neurons in the ventral horn of the spinal cord. Others influence motor control by synapsing onto motor output nuclei in the medulla or onto striatal neurons in the basal ganglia. The human corticospinal tract consists of approximately one million axons, of which approximately 40% originate in the motor cortex. These axons descend through the subcortical white matter, the internal capsule, and the cerebral peduncle in the midbrain (Figure 4-14). In the medulla, the fibers form prominent protuberances on the ventral surface called the medullary pyramids, 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, approximately 10% of the fibers do not cross until they reach the level

of the spinal cord at which they will terminate. The corticospinal fibers make monosynaptic connections with motor neurons, connections that are particularly important for individuated finger movements. They also form synapses with both excitatory and inhibitory interneurons in the spinal cord, connections that 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. A continuous stream of tactile, visual, and proprioceptive information is 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. These two subcortical regions, which are described in detail in Chapters 37 and 38, provide feedback essential for the smooth execution of skilled movements and thus are also important for the improvement in motor skills through practice (Figure 4-15).

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

Some areas of the brain are neither purely sensory nor purely motor, but instead modulate specific sensory or motor functions. Modulatory systems are often involved in behaviors that respond to a primary need such as hunger, thirst, or sleep. For example, sensory

Descending lateral corticospinal pathway

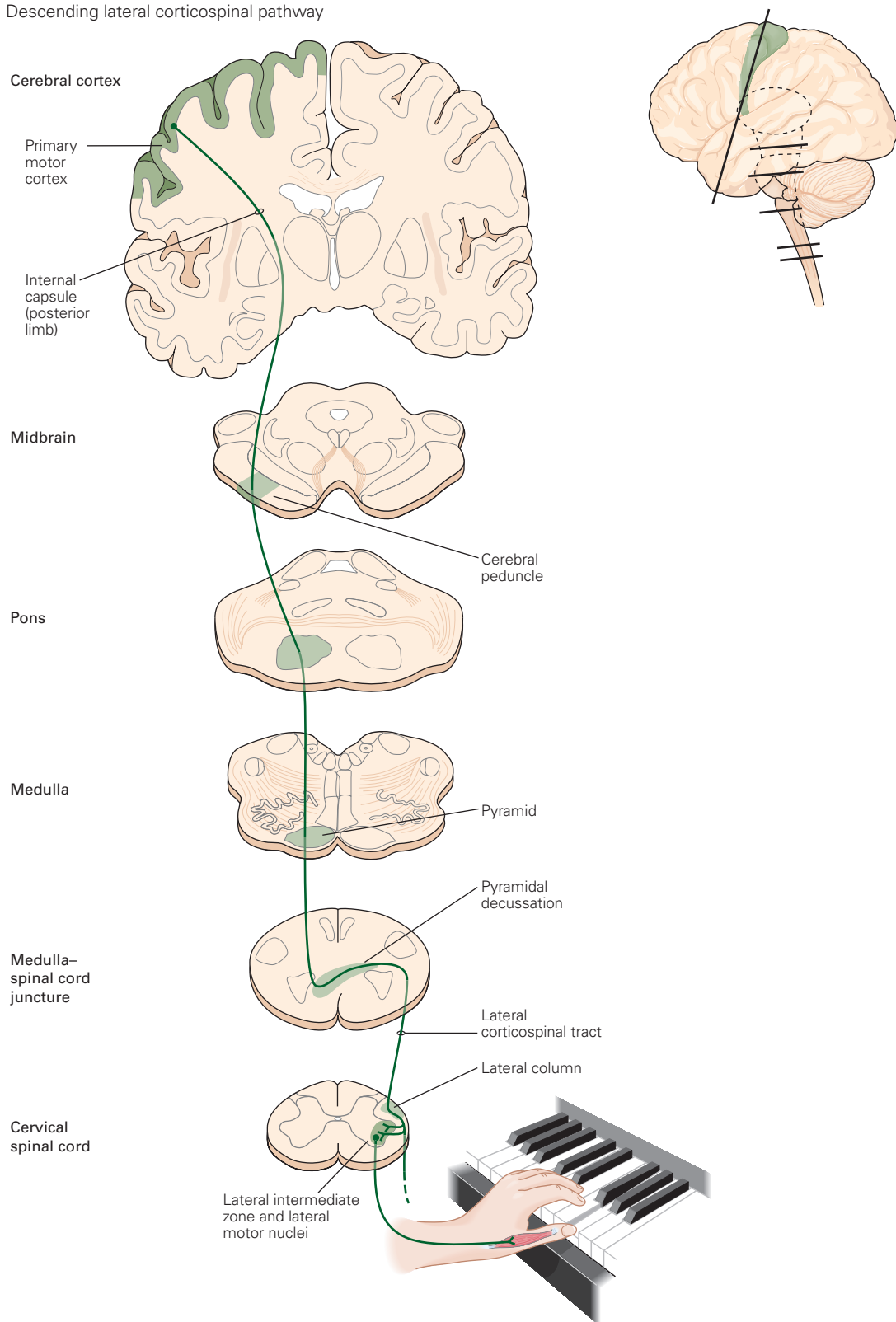


Figure 4-14 A significant number of fibers in the corticospinal tract originate in the primary motor cortex and terminate in the ventral horn of the spinal cord. The same axons

are, at various points in their projections, part of the internal capsule, the cerebral peduncle, the medullary pyramid, and the lateral corticospinal tract.

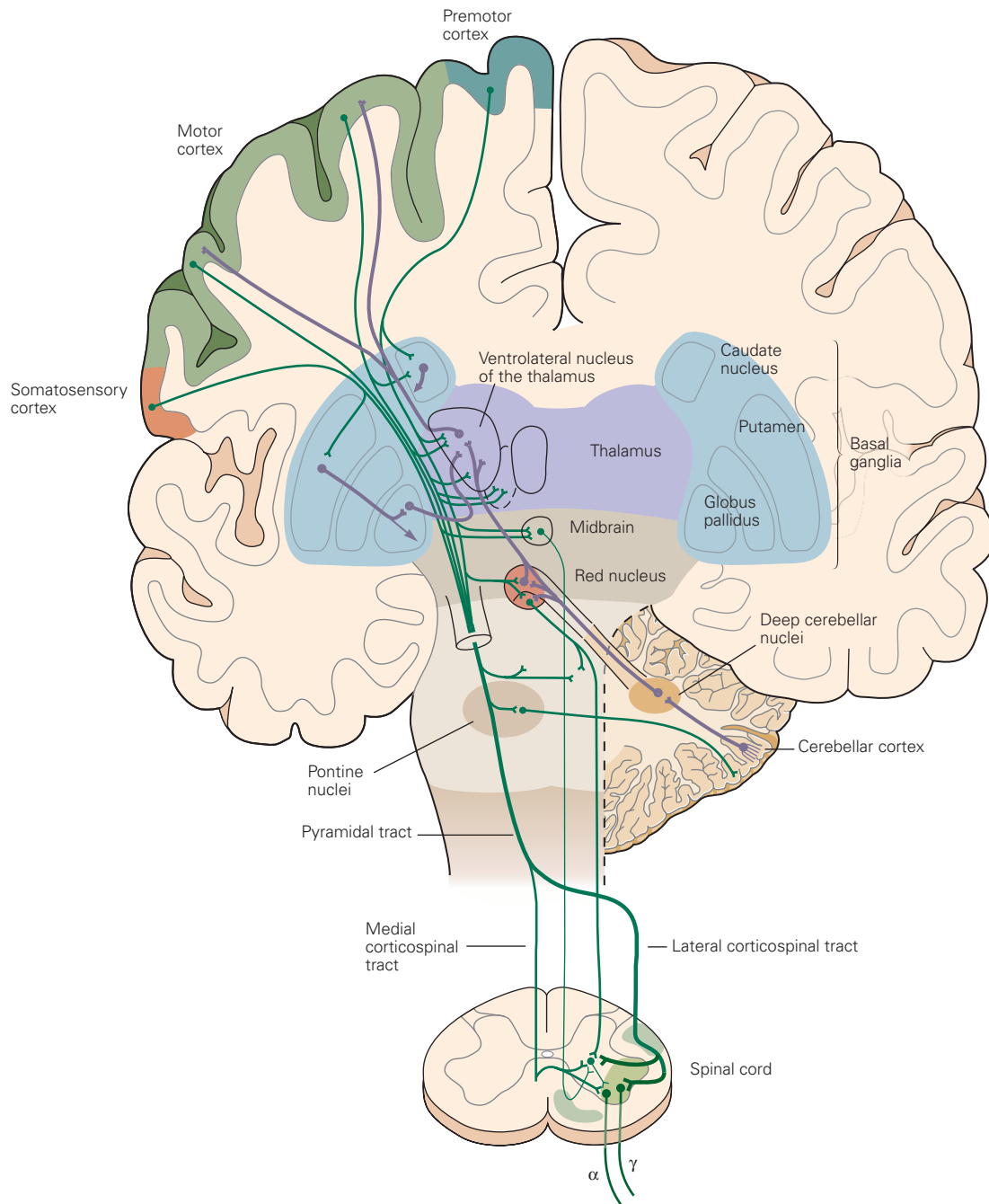


Figure 4-15 Voluntary movement requires coordination of all components of the motor system. The principal components are the motor cortex, basal ganglia, thalamus, midbrain, cerebellum, and spinal cord. The principal descending projections are shown in **green**; feedback projections and local connections

are shown in **purple**. All of this processing is incorporated in the inputs to the motor neurons of the ventral horn of the spinal cord, the so-called “final common pathway” that innervates muscle and elicits movements. (This figure is a composite view made from sections of the brain taken at different angles.)

and modulatory systems in the hypothalamus determine blood glucose levels (Chapter 41). When blood sugar drops below a certain critical level, we feel hunger. To satisfy hunger, modulatory systems in the brain

focus vision, hearing, and smell on stimuli that are relevant to feeding.

Distinct modulatory systems within the brain stem modulate attention and arousal (Chapter 40). Small

nuclei in the brain stem contain neurons that synthesize and release the modulatory neurotransmitter norepinephrine (the locus coeruleus) and serotonin (the dorsal raphe nucleus). Such neurons set the general arousal level of an animal through their widespread connections with forebrain structures. A group of cholinergic modulatory neurons, the basal nucleus of Meynert, is involved in arousal or attention (Chapter 40). This nucleus is located beneath the basal ganglia in the basal forebrain portion of the telencephalon. The axons of its neurons project to essentially all portions of the neocortex.

If a predator finds potential prey, a variety of cortical and subcortical systems determine whether the prey is edible. Once food is recognized, other cortical and subcortical systems initiate a comprehensive voluntary 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 eating reinforces the behaviors that led to the successful predation. A group of dopaminergic neurons in the midbrain are important for monitoring reinforcements and rewards. The power of the dopaminergic modulatory systems has been demonstrated by experiments in which electrodes were implanted into the reward regions of rats and the animals were freely allowed to press a lever to electrically stimulate their brains. They preferred this self-stimulation to obtaining food or water, engaging in sexual behavior, or any other naturally rewarding activity. The role of the dopaminergic modulatory system in learning through reinforcement of exploratory behavior is described in Chapter 38.

How the brain's modulatory systems, concerned with reward, attention and motivation, interact with the sensory and motor systems is one of the most interesting questions in neuroscience, one that is also fundamental to our understanding of learning and memory storage (Chapter 40).

The Peripheral Nervous System Is Anatomically Distinct From the Central Nervous System

The peripheral nervous system supplies the central nervous system with a continuous stream of information about both the external environment and the internal environment of the body. It has somatic and autonomic divisions (Figure 4–16).

The *somatic division* includes the sensory neurons that receive information from the skin, muscles, and

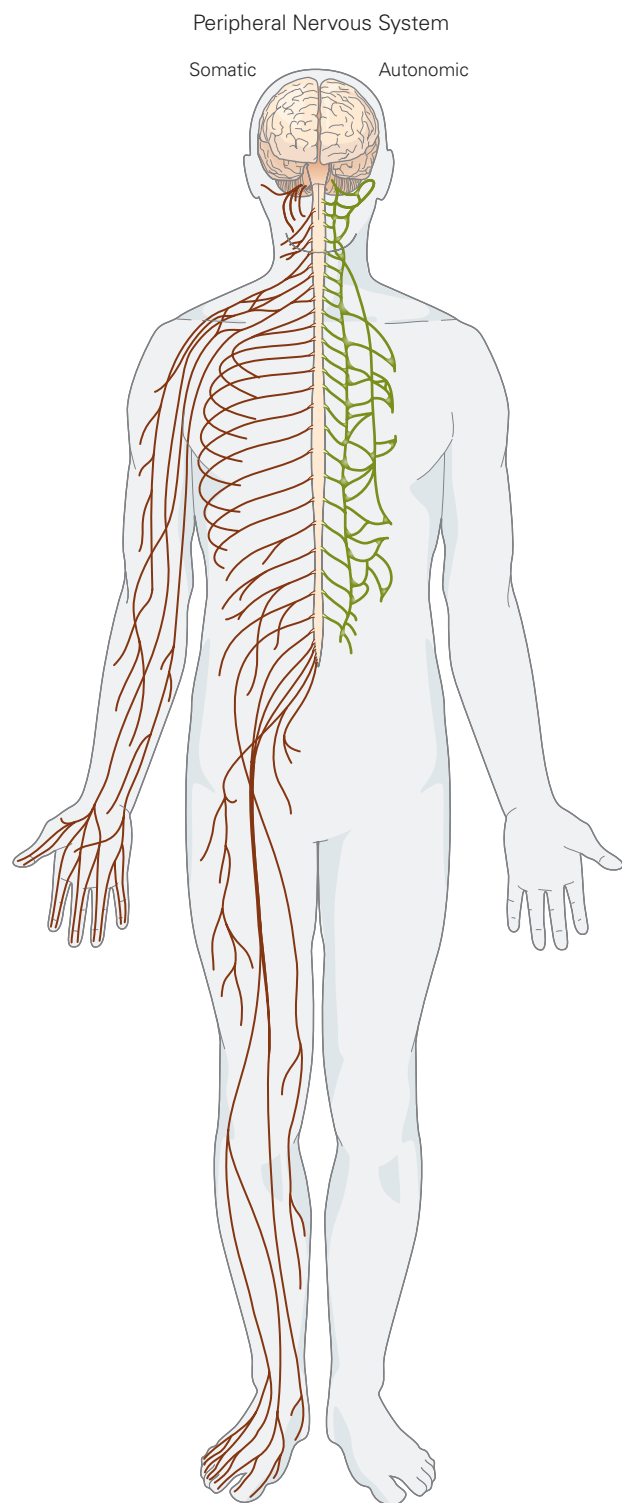


Figure 4–16 The peripheral nervous system has somatic and autonomic divisions. The somatic division carries information from the skin to the brain and from the brain to muscles. The autonomic division regulates involuntary functions, including activity of the heart and smooth muscles in the gut and glands.