

Box 1–2 Anatomical Organization of the Central Nervous System

The Central Nervous System Has Seven Main Parts

The **spinal cord**, the most caudal part of the central nervous system, receives and processes sensory information from the skin, joints, and muscles of the limbs and trunk and controls movement of the limbs and the trunk. It is subdivided into cervical, thoracic, lumbar, and sacral regions (Figure 1–3A).

The spinal cord continues rostrally as the **brain stem**, which consists of the medulla oblongata, pons, and midbrain. The brain stem receives sensory information from the skin and muscles of the head and provides the motor control for the head's musculature. It also conveys information from the spinal cord to the brain and from the brain to the spinal cord, and regulates levels of arousal and awareness through the reticular formation.

The brain stem contains several collections of cell bodies, the cranial nerve nuclei. Some of these nuclei receive information from the skin and muscles of the head; others control motor output to muscles of the face, neck, and eyes. Still others are specialized to process information from three of the special senses: hearing, balance, and taste.

The **medulla oblongata**, directly rostral to the spinal cord, includes several centers responsible for vital autonomic functions, such as digestion, breathing, and the control of heart rate.

The **pons**, rostral to the medulla, conveys information about movement from the cerebral hemispheres to the cerebellum.

The **cerebellum**, behind the pons, modulates the force and range of movement and is involved in the learning of motor skills. It is functionally connected to the three main organs of the brain stem: the medulla oblongata, the pons, and the midbrain.

The **midbrain**, rostral to the pons, controls many sensory and motor functions, including eye movement and the coordination of visual and auditory reflexes.

The **diencephalon** lies rostral to the midbrain and contains two structures. The **thalamus** processes most of the information reaching the cerebral cortex from the rest of the central nervous system. The **hypothalamus** regulates autonomic, endocrine, and visceral functions.

The **cerebrum** comprises two cerebral hemispheres, each consisting of a heavily wrinkled outer layer (the *cerebral cortex*) and three deep-lying structures (components of the *basal ganglia*, the *hippocampus*, and *amygdaloid nuclei*). The basal ganglia, which include the caudate, putamen, and globus pallidus, regulate movement execution and motor- and habit-learning, two forms of memory that are referred to as implicit memory; the hippocampus is critical for storage of memory of people, places, things, and

events, a form of memory that is referred to as explicit; and the amygdaloid nuclei coordinate the autonomic and endocrine responses of emotional states, including memory of threats, another form of implicit memory.

Each cerebral hemisphere is divided into four distinct lobes: frontal, parietal, occipital, and temporal (Figure 1–3B). These lobes are associated with distinct functions, although the cortical areas are all highly interconnected and can participate in a wide range of brain functions. The occipital lobe receives visual information and is critical for all aspects of vision. Information from the occipital lobe is then processed through two main pathways. The dorsal stream, connecting the occipital lobe to the parietal lobe, is concerned with the location and manipulation of objects in visual space. The ventral stream, connecting the occipital lobe to the temporal lobe, is concerned with object identity, including the recognition of individual faces. The temporal lobe is also important for processing auditory information (and also contains the hippocampus and amygdala buried beneath its surface). The frontal lobes are strongly interconnected with all cortical areas and are important for higher cognitive processing and motor planning.

About two-thirds of the cortex lies in the sulci, and many gyri are buried by overlying cortical lobes. The full extent of the cortex is made visible by separating the hemispheres to reveal the medial surface of the brain and by slicing the brain post mortem, for example in an autopsy (Figure 1–4). Much of this information can be visualized in the living brain through modern brain imaging (Figure 1–5; Chapter 6). These views also afford views of the white matter and subcortical gray matter.

Two important regions of cerebral cortex not visible on the surface include the cingulate cortex and insular cortex. The cingulate cortex lies dorsal to the corpus callosum and is important for regulation of emotion, pain perception, and cognition. The insular cortex, which lies buried within the overlying frontal, parietal, and temporal lobes, plays an important role in emotion, homeostasis, and taste perception. These internal views also afford examination of the *corpus callosum*, the prominent axon fiber tract that connects the two hemispheres.

The various brain regions described above are often divided into three broader regions: the *hindbrain* (comprising the medulla oblongata, pons, and cerebellum); *midbrain* (comprising the tectum, substantia nigra, reticular formation, and periaqueductal gray matter); and *forebrain* (comprising the diencephalon and cerebrum). Together the midbrain and hindbrain (minus the cerebellum) include the same structures as the brain stem. The anatomical organization of the nervous system is described in more detail in Chapter 4.

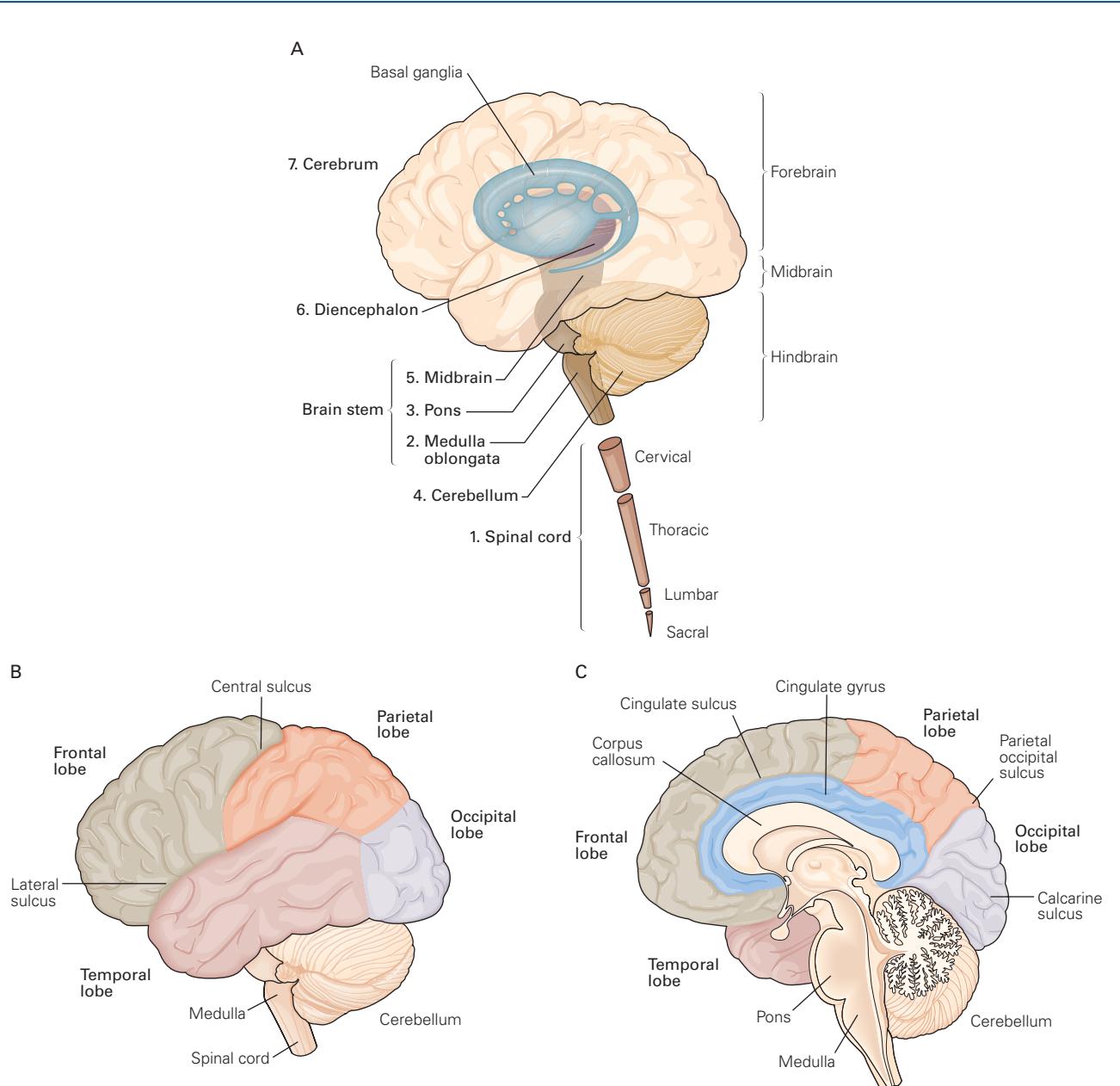


Figure 1–3 The divisions of the central nervous system.

A. The central nervous system can be divided into seven main regions, proceeding from the most caudal region, the spinal cord, to the brain stem (medulla, pons, and midbrain), to the diencephalon (containing the thalamus and hypothalamus), to the telencephalon or cerebrum (cerebral cortex, underlying white matter, subcortical nuclei, and the basal ganglia).

B. The four major lobes of the cerebrum are named for the parts of the cranium that cover them. This lateral view of the brain shows only the left cerebral hemisphere. The central

sulcus separates the frontal and parietal lobes. The lateral sulcus separates the frontal from the temporal lobes. The primary motor cortex occupies the gyrus immediately rostral to the central sulcus. The primary somatosensory cortex occupies the gyrus immediately caudal to the central sulcus.

C. Further divisions of the brain are visible when the hemispheres are separated in this medial view of the right hemisphere. The corpus callosum contains a large bundle of axons connecting the two hemispheres. The cingulate cortex is part of the cerebral cortex that surrounds the corpus callosum. The primary visual cortex occupies the calcarine sulcus.

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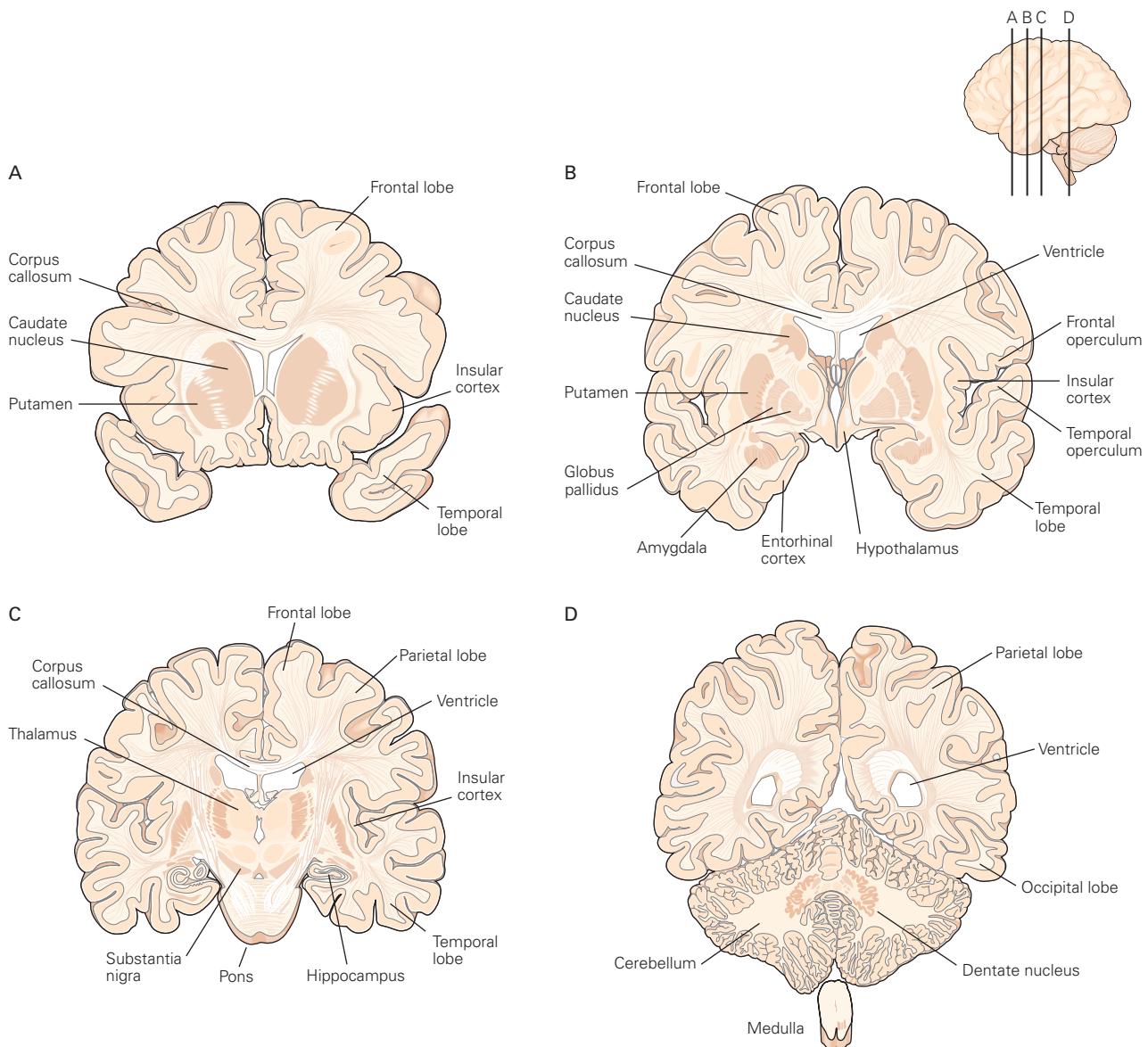
Box 1–2 Anatomical Organization of the Central Nervous System (continued)


Figure 1–4 Major subcortical and deep cortical regions of the cerebral hemispheres are visible in drawings of brain slices from postmortem tissue.

Four sequential coronal sections (A–D) were made along the rostral-caudal axis indicated on the lateral view of the brain (top right, inset). The basal ganglia comprise the caudate nucleus, putamen, globus pallidus, substantia nigra, and subthalamic nucleus (not shown). The thalamus relays sensory

information from the periphery to the cerebral cortex. The amygdala and hippocampus are regions of the cerebral cortex buried within the temporal lobe that are important for emotional responses and memory. The ventricles contain and produce the cerebrospinal fluid, which bathes the sulci, cisterns, and the spinal cord. (Adapted from Nieuwenhuys, Voogd, and van Huijzen 1988.)

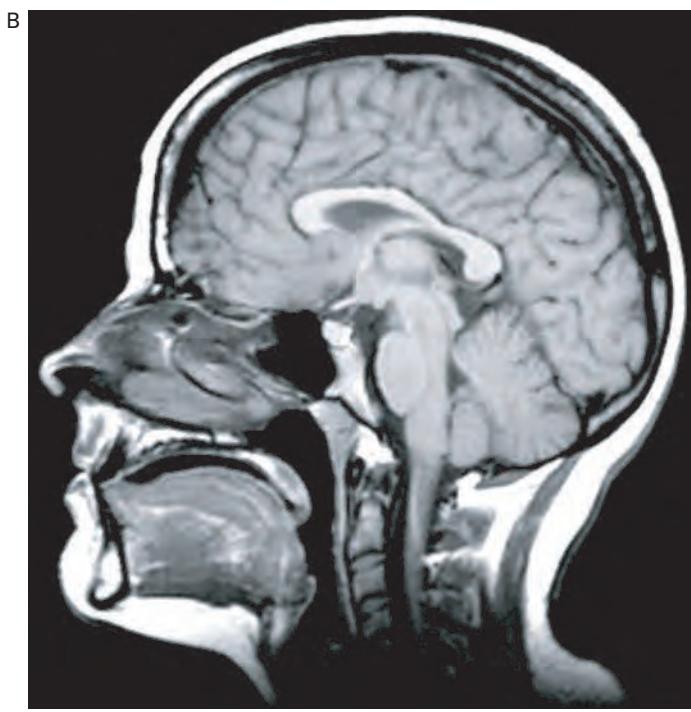
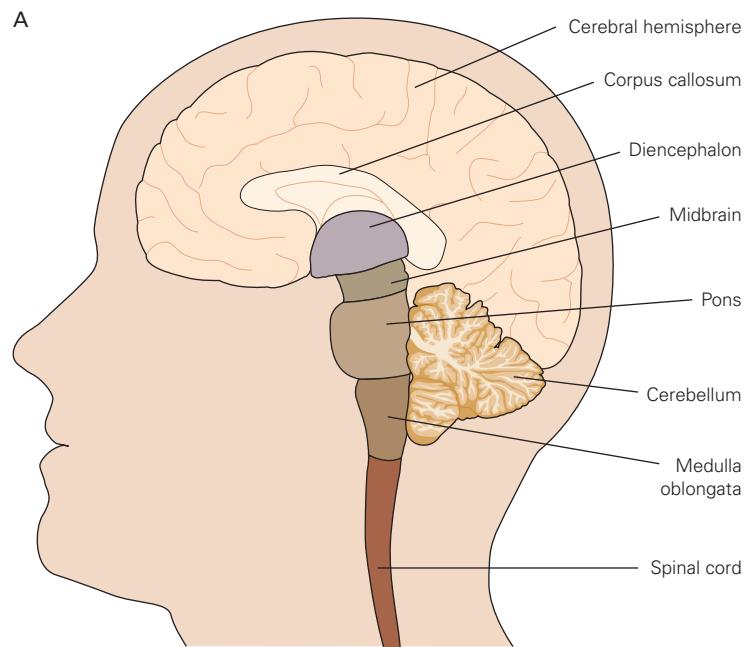


Figure 1–5 The main cortical and subcortical regions can be imaged in the brain of a living individual.

A. This schematic drawing shows, for reference, the major surface and deep regions of the brain, including the rostral end of the spinal cord.

B. The major brain divisions drawn in part A are evident in a magnetic resonance image of a living human brain.

In each of the hemispheres, the overlying cortex is divided into four lobes named for the skull bones that overlie them: *frontal*, *parietal*, *occipital*, and *temporal* (Figure 1–3B). Each lobe has several characteristic deep infoldings, an evolutionary strategy for packing a large sheet of cortex into a limited space. The crests of these convolutions are called *gyri*, and the intervening grooves are called *sulci* or *fissures*. The more prominent gyri and sulci, which are quite similar from person to person, bear specific names. For example, the central sulcus separates the precentral gyrus, an area concerned with motor function, from the postcentral gyrus, an area that deals with sensory function (Figure 1–3B). Several prominent gyri are only visible on the medial surface between the two hemispheres (Figure 1–3C), and others are deep within fissures and sulci and therefore only visible when the brain is sliced, either in postmortem tissue (Figure 1–4) or virtually, using magnetic resonance imaging (Figure 1–5), as explained in Chapter 6.

Each lobe has specialized functions. The frontal lobe is largely concerned with short-term memory, planning future actions, and control of movement; the parietal lobe mediates somatic sensation, forming a body image and relating it to extrapersonal space; the occipital lobe is concerned with vision; and the temporal lobe processes hearing, the recognition of objects and faces, and—through its deep structures, the hippocampus and amygdaloid nuclei—learning, memory, and emotion.

Two important features characterize the organization of the cerebral cortex. First, each hemisphere is concerned primarily with sensory and motor processes on the contralateral (opposite) side of the body. Thus sensory information that reaches the spinal cord from the left side of the body crosses to the right side of the nervous system on its way to the cerebral cortex. Similarly, the motor areas in the right hemisphere exert control over the movements of the left half of the body. The second feature is that the hemispheres, although similar in appearance, are not completely symmetrical in structure or function.

The First Strong Evidence for Localization of Cognitive Abilities Came From Studies of Language Disorders

The first areas of the cerebral cortex identified as important for cognition were areas concerned with language. These discoveries came from studies of *aphasia*, a language disorder that most often occurs when certain areas of brain tissue are destroyed by a stroke, the

occlusion or rupture of a blood vessel supplying a portion of a cerebral hemisphere. Many of the important discoveries in the study of aphasia occurred in rapid succession during the latter half of the 19th century. Taken together, these advances form one of the most exciting and important chapters in the neuroscientific study of human behavior.

Pierre Paul Broca, a French neurologist, was the first to identify specific areas of the brain concerned with language. Broca was influenced by Gall's efforts to map higher functions in the brain, but instead of correlating behavior with bumps on the skull, he correlated clinical evidence of aphasia with brain lesions discovered post mortem. In 1861 he wrote, "I had thought that if there were ever a phrenological science, it would be the phrenology of convolutions (*in the cortex*), and not the phrenology of bumps (*on the head*)."¹ Based on this insight, Broca founded *neuropsychology*, an empirical science of mental processes that he distinguished from the phrenology of Gall.

In 1861 Broca described a patient, Leborgne, who as a result of a stroke could not speak, although he could understand language perfectly well. This patient had no motor deficits of the tongue, mouth, or vocal cords that would affect his ability to speak. In fact, he could utter isolated words, whistle, and sing a melody without difficulty. But he could not speak grammatically or create complete sentences, nor could he express ideas in writing. Postmortem examination of this patient's brain showed a lesion in a posterior inferior region of the left frontal lobe, now called *Broca's area* (Figure 1–6). Broca studied eight similar patients, all with lesions in this region, and in each case the lesion was located in the left cerebral hemisphere. This discovery led Broca to announce in 1864: "*Nous parlons avec l'hémisphère gauche!*" (We speak with the left hemisphere!).

Broca's work stimulated a search for cortical sites associated with other specific behaviors—a search soon rewarded. In 1870 Gustav Fritsch and Eduard Hitzig galvanized the scientific community when they showed that characteristic limb movements of dogs, such as extending a paw, could be produced by electrically stimulating discrete regions of the precentral gyrus. These regions were invariably located in the contralateral motor cortex. Thus the right hand, the one most used for writing and skilled movements, is controlled by the left hemisphere, the same hemisphere that controls speech. In most people, therefore, the left hemisphere is regarded as *dominant*.

The next step was taken in 1876 by Karl Wernicke, who at age 26 published a now-classic paper,

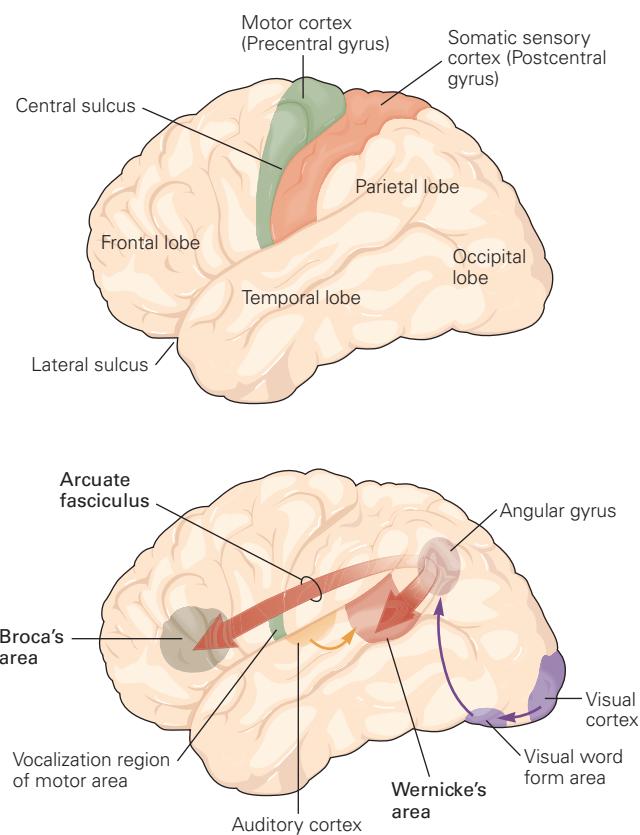


Figure 1-6 Language processing engages several regions of the left cerebral hemisphere.

Broca's area controls the production of speech. It lies near the region of the motor area that controls the mouth and tongue movements that form words. Wernicke's area processes auditory input for language and is important for understanding speech. It lies near the primary auditory cortex and the angular gyrus. The French neurologist Jules Dejerine proposed in the 1890s that a polymodal sensory area in the angular gyrus integrates information from vision and audition to represent words, but more recent studies implicate a more ventral occipitotemporal cortical area for processing of visual words. Wernicke's area communicates with Broca's area by a bidirectional pathway, part of which is made up of the arcuate fasciculus. (Adapted, with permission, from Geschwind 1979.)

"The Symptom-Complex of Aphasia: A Psychological Study on an Anatomical Basis." In it he described another type of aphasia, a failure of comprehension rather than speech: a *receptive* as opposed to an *expressive* malfunction. Whereas Broca's patients could understand language but not speak, Wernicke's patient could form words but could not understand language and produced senseless, yet grammatical, sentences. Moreover, the locus of this new type of aphasia was different from that described by Broca. The lesion occurred in the posterior part of the cerebral cortex where the temporal lobe meets the parietal lobe (Figure 1-6).

On the basis of this discovery, and the work of Broca, Fritsch, and Hitzig, Wernicke formulated a neural model of language that attempted to reconcile and extend the predominant theories of brain function at that time. Phrenologists and cellular connectionists argued that the cerebral cortex was a mosaic of functionally specific areas, whereas the holistic *aggregate-field* school claimed that every mental function involved the entire cerebral cortex. Wernicke proposed that only the most basic mental functions, those concerned with simple perceptual and motor activities, are mediated entirely by neurons in discrete local areas of the cortex. More complex cognitive functions, he argued, result from interconnections between several functional sites. By integrating the principle of localized function within a connectionist framework, Wernicke emphasized the idea that different components of a single behavior are likely to be processed in several regions of the brain. He was thus the first to advance the idea of *distributed processing*, now a central tenet of neural science.

Wernicke postulated that language involves separate motor and sensory programs, each governed by distinct regions of cortex. He proposed that the motor program that governs the mouth movements for speech is located in Broca's area, suitably situated in front of the region of the motor area that controls the mouth, tongue, palate, and vocal cords (Figure 1-6). He next assigned the sensory program that governs word perception to the temporal lobe area that he had discovered, now called *Wernicke's area*. This region is surrounded by the auditory cortex and by areas now known collectively as *association cortex*, integrating auditory, visual, and somatic sensations. According to Wernicke's model, the communication between these two language centers was mediated via a large bundle of axons known as the *arcuate fasciculus*.

Thus Wernicke formulated the first coherent neural model for language that is still useful today, with important modifications and elaborations described in Chapter 55. According to this model, the neural processing of spoken or written words begins in separate sensory areas of the cortex specialized for auditory or visual information. This information is then conveyed, via intermediate association areas that extract features suitable for recognition of spoken or written words, to Wernicke's area, where it is recognized as language and associated with meaning.

The power of Wernicke's model was not only its completeness but also its predictive utility. This model correctly predicted a third type of aphasia, one that results from disconnection. In this type, the receptive and expressive zones for speech are intact but

the neuronal fibers that connect them (arcuate fasciculus) are destroyed. This *conduction aphasia*, as it is now called, is characterized by frequent, sound-based speech errors (*phonemic paraphasias*), repetition difficulties, and severe limitation in verbal working memory. Patients with conduction aphasia understand words that they hear and read, and have no motor difficulties when they speak. Yet they cannot speak coherently; they omit parts of words or substitute incorrect sounds and experience great difficulties in verbatim repetition of a multisyllabic word, phrase, or sentence that they hear or read or recall from memory. Although painfully aware of their own errors, their successive attempts at self-correction are often unsuccessful.

Inspired in part by Wernicke's advances and led by the anatomist Korbinian Brodmann, a new school of cortical localization arose in Germany at the beginning of the 20th century, one that distinguished functional areas of the cortex based on the shapes of cells and variations in their layered arrangement. Using this *cytoarchitectonic* method, Brodmann distinguished 52 anatomically and functionally distinct areas in the human cerebral cortex (Figure 1–7).

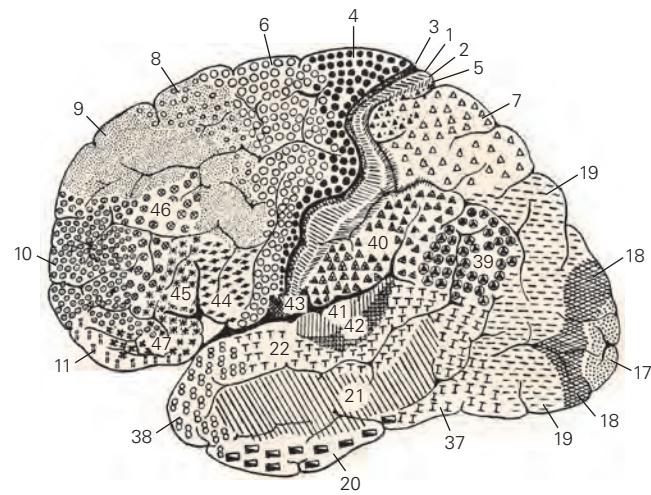


Figure 1–7 Early in the 20th century, the human cerebral cortex was classified into 52 discrete functional areas. The areas shown were identified by the anatomist Korbinian Brodmann on the basis of distinctive nerve cell structures and characteristic arrangements of cell layers. This scheme is still widely used today and is continually updated. Several areas defined by Brodmann have been found to control specific brain functions. For instance, area 4 is the motor cortex, responsible for voluntary movement. Areas 1, 2, and 3 constitute the primary somatosensory cortex, which receives sensory information primarily from the skin and joints. Area 17 is the primary visual cortex, which receives sensory signals from the eyes and relays them to other areas for further processing. Areas 41 and 42 constitute the primary auditory cortex. The drawing shows only areas visible on the outer surface of the cortex.

Even though the biological evidence for functionally discrete areas in the cortex was compelling, by the early 20th century, holistic views of the brain continued to dominate experimental thinking and clinical practice until 1950. This surprising state of affairs owed much to several prominent neural scientists who advocated the holistic view, among them the British neurologist Henry Head, the Russian behavioral physiologist Ivan Pavlov, and the American psychologist Karl Lashley.

Most influential was Lashley, who was deeply skeptical of the cytoarchitectonic approach to functional mapping of the cortex. "The 'ideal' architec-tonic map is nearly worthless," Lashley wrote. "The area subdivisions are in large part anatomically meaningless, and misleading as to the presumptive functional divisions of the cortex." His skepticism was reinforced by his studies of the effects of various brain lesions on the ability of rats to learn to run a maze. From these studies Lashley concluded that the severity of a learning defect depended on the size of the lesion, not on its precise location. Disillusioned, Lashley—and after him many other psychologists—concluded that learning and other higher mental functions have no special locus in the brain and consequently cannot be attributed to specific collections of neurons.

Based on his observations, Lashley reformulated the aggregate-field view by further minimizing the role of individual neurons, specific neuronal connections, and even specific brain regions in the production of specific behavior. According to Lashley's *theory of mass action*, it is the full mass of the brain, not its regional components, that is crucial for a function such as memory.

Lashley's experiments with rats have now been reinterpreted. A variety of studies have shown that the maze-learning used by Lashley is unsuited to the search for local cortical functions because it involves so many motor and sensory capabilities. Deprived of one sensory capability, say vision, a rat can still learn to run a maze using touch or smell. Besides, as we shall see later in the book, many mental functions are mediated by more than one region or neuronal pathway. Thus a given function may not be eliminated by a single lesion. This is especially germane when considering cognitive functions of the brain. For example, knowledge of space is supported by numerous parietal association areas that link vision to a potential shift of the gaze, turn of the head, reach of the hand, and so on. In principle, any one of these association areas can compensate for damage of another. It takes a large insult to the parietal lobe to produce obvious deficits of spatial knowledge (*spatial agnosia*) (Chapter 59). Such an

observation would have seemed to support theories of mass action, but we now recognize that it is compatible with localization of function that incorporates the idea of redundancy of function.

Soon the evidence for localization of function became overwhelming. Beginning in the late 1930s, Edgar Adrian in England and Wade Marshall and Philip Bard in the United States discovered that touching different parts of a cat's body elicits electrical activity in distinct regions of the cerebral cortex. By systematically probing the body surface, they established a precise map of the body surface in specific areas of the cerebral cortex described by Brodmann. This result showed that functionally distinct areas of cortex could be defined unambiguously according to anatomical criteria such as cell type and cell layering, connections of cells, and—most importantly—behavioral function. As we shall see in later chapters, functional specialization is a key organizing principle in the cerebral cortex, extending even to individual columns of cells within an area of cortex. Indeed, the brain is divided into many more functional regions than Brodmann envisaged.

More refined methods made it possible to learn even more about the function of different brain regions involved in language. In the late 1950s Wilder Penfield, and later George Ojemann, reinvestigated the cortical areas that are essential for producing language. While locally anesthetized during brain surgery for epilepsy, awake patients were asked to name objects (or use language in other ways) while different areas of the exposed cortex were stimulated with small electrodes. If an area of the cortex was critical for language, application of the electrical stimulus blocked the patient's ability to name objects. In this way Penfield and Ojemann were able to confirm the language areas of the cortex described by Broca and Wernicke. As we shall learn in Chapter 55, the neural networks for language are far more extensive and complex than those described by Broca and Wernicke.

Initially almost everything known about the anatomical organization of language came from studies of patients with brain lesions. Today functional magnetic resonance imaging (fMRI) and other noninvasive methods allow analyses to be conducted on healthy people engaged in reading, speaking, and thinking (Chapter 6). fMRI not only has confirmed that reading and speaking activate different brain areas but also has revealed that just *thinking* about a word's meaning in the absence of sensory inputs activates a still different area in the left frontal cortex. Indeed, even within the traditional language areas, individual subregions are recruited to different degrees, depending on the way

we think about words, express them, and resolve their meaning from the arrangement of other words (ie, syntax). The new imaging tools promise not only to teach us which areas are involved but also to expose the functional logic of their interconnection.

One of the great surprises emerging from modern methodologies is that so many areas of cortex are activated in language comprehension and production. These include the traditional language areas, identified by Broca, Wernicke, and Dejerine, in the left hemisphere; their homologs in the right hemisphere; and newly identified regions. Functional imaging tends to elucidate areas that are recruited differentially, whereas lesions from stroke, tumor, or injury distinguish brain areas that are essential for one or more functions. Thus it appears that Broca's area, once thought to be dedicated to language production, is in fact also involved in a variety of linguistic tasks including comprehension (Figure 1–6). In some cases, functional imaging invites refinement or revision of the critical areas identified by lesion studies. For example, reading is now thought to recruit specialized regions in the ventral occipitotemporal cortex in addition to the angular gyrus in the parietal cortex (shown in Figure 1–6).

Thus the processing of language in the brain exemplifies not only the principle of localized function but also the more sophisticated elaboration of this principle, that numerous distinct neural structures with specialized functions belong to systems. Perhaps this is the natural reconciliation of the controversy concerning localized and distributed processes—that is, a small number of distinct areas, each identified with a small set of functions and contributing through their interactions to the phenomenology of perception, action, and ideation. The brain may carve up a task differently than our intuition tells us. Who would have guessed that the neural analysis of the movement and color of an object would occur in different pathways rather than a single pathway mediating a unified percept of the object? Similarly, we might expect that the neural organization of language may not conform neatly to the axioms of a theory of universal grammar, yet support the very seamless functionality described by linguistic theory.

Studies of patients with brain damage continue to afford important insight into how the brain is organized for language. One of the most impressive results comes from the study of deaf people who have lost their ability to communicate through the use of a signed language (eg, British Sign Language [BSL] or American Sign Language [ASL]) after suffering cerebral damage. Signed languages use hand movements rather than

vocalizations and are perceived by sight rather than sound, but have the same structural complexity as spoken languages. Sign language processing, as with spoken language processing, localizes to the left hemisphere. Damage to the left hemisphere can have quite specific consequences for signing just as for spoken language, affecting sign comprehension (following damage in Wernicke's area), grammar, or fluency (following damage in Broca's area). These clinical observations are supported by functional neuroimaging. Not surprisingly, production and comprehension of signed and spoken languages do not involve identical brain areas, but the overlap is truly remarkable (Figure 1–8). There is even evidence that processing the constituent parts of signs (eg, handshape used) involves some of the same brain regions involved when making rhyme judgements about speech.

These observations illustrate three points. First, language processing occurs primarily in the left hemisphere, independently of pathways that process the sensory and motor modalities used in language. Second, auditory input is not necessary for the emergence and operation of language capabilities in the left hemisphere. Third, spoken language is only one of a family of language skills mediated by the left hemisphere.

Investigations of other behaviors have provided additional support for the idea that the brain has distinct cognitive systems. These studies demonstrate that complex information processing requires many interconnected cortical and subcortical areas, each concerned with processing particular aspects of sensory stimuli or motor movement and not others. For example, perceptual awareness of an object's location, size, and shape relies on activity in numerous parietal association areas that link vision to potential actions, such as moving the eyes, orienting the head, reaching, and shaping the hand to grasp. The parietal areas do not initiate these actions but evaluate sensory information as evidence bearing on these potentialities. They receive information from the dorsal visual stream—sometimes referred to as the *where pathway*, but more aptly termed a *how pathway*—to construct a state of knowing (*gnosia*) about the location and other spatial properties of objects. The ventral visual stream, or *what pathway*, is also concerned with possible actions, but these are associated with socializing and foraging. These associations establish *gnosia* about the desirability of objects, faces, foods, and potential mates. In this sense, the *what pathway* might be a *how pathway* too.

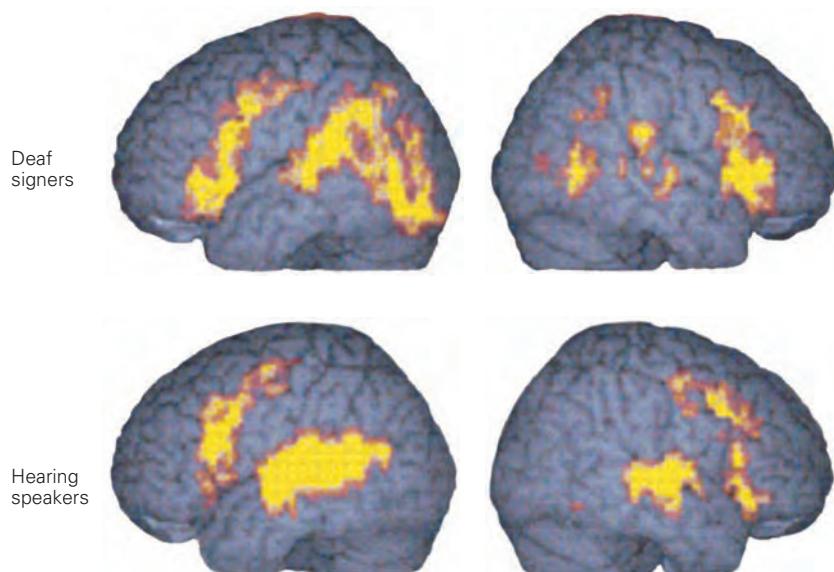


Figure 1–8 Deaf signing and hearing individuals share common language processing areas. Regions of the cortex involved in the recognition of a spoken or signed language, identified by functional magnetic resonance imaging (fMRI). Yellow highlight shows the areas of the left and right cerebral hemispheres (left and right columns, respectively) that were activated more when comprehending language than when performing a perceptual task. For the deaf signers (top row), the

highlighted regions were more active during comprehension of British Sign Language than during the detection of a visual stimulus superimposed on the same motionless signer. For the hearing speakers (bottom row), highlighted regions were more active during comprehension of audio-visual speech than during the detection of a tone while viewing a motionless (silent) speaker. (Adapted, with permission, from MacSweeney et al., 2002. Copyright © 2002 Oxford University Press.)