CHAPTER

2

The Neural Basis of Speech and Language

Introduction

This section gives the reader a brief overview of what takes place neurally when a person starts a conversation by saying, "Hello. How are you? How was your vacation trip?" to another individual whom the person meets on the street. Simply put, the steps involved would be as follows:

1. Basic vision: seeing a person on the street
2. Visual perception: recognizing the person as someone the speaker knows
3. Cognition: the desire to speak with this person about a trip that the speaker may want to take in the future
4. Language: searching for the right sounds, syllables, words, and sentences, all presented in the right order, with meaning properly related to the greeting and the subject matter, to be expressed with a positive attitude
5. Motor programming or planning: readying the speech mechanism just prior to speaking so that the production is correct
6. Motor production or execution: speaking
7. Feedback: (1) from self: hearing and feeling oneself speak and then using that information as a guide for further appropriate speaking (e.g., usually we know when something said does not sound right, and we either repeat it or put it into different words); (2) from others: looking at and listening to another person speak to help determine what to say next (e.g., responding to questions from someone who looks and sounds angry as opposed to someone who does not).

Responding to auditory feedback from oneself or from others involves the hearing of sound (basic hearing). Recognizing that sound as speech and not some other environmental noise is auditory perception. Understanding what is said is language comprehension. All of the steps mentioned above, with the exception of cognition, will be commented on in the neural outline that follows. The neural basis for cognition (thinking and behavior) probably involves bilateral cortical areas (especially the frontal lobes) as the prime movers, assisted by subcortical and brainstem systems. Because of the widespread neural activity, localization of cognitive functions is quite difficult. However, cognition and defects of cognition are noted in other parts of this manuscript (e.g., the chapters dealing with right hemisphere damage, dementia, and traumatic brain injury).

The information in the following outline has been gleaned from Bhatnagar (2008), Duffy (2005), Kent (1997), Webb and Adler (2008), Webster (1999), and Zemlin (1998); the organization of the outline mostly follows that of Webb and Adler, with

details from Bhatnagar. The reader is referred to these sources for further elaboration of any of the topics mentioned in the outline. In a number of places within the outline, examples are given of the speech and/or language problem that can occur if there is damage to certain portions of the neural system. Most of the speech and/or language problems given as examples are mentioned further in other parts of this text.

Definitions

The Neuron

The neuron, or nerve cell, consists of a cell body, dendrites, and an axon (**Figure 2.1**). The *cell body* (intracellular) contains a high concentration of potassium and low concentrations of sodium and chloride, compared to the fluids outside the cell body (extracellular). The concentrations

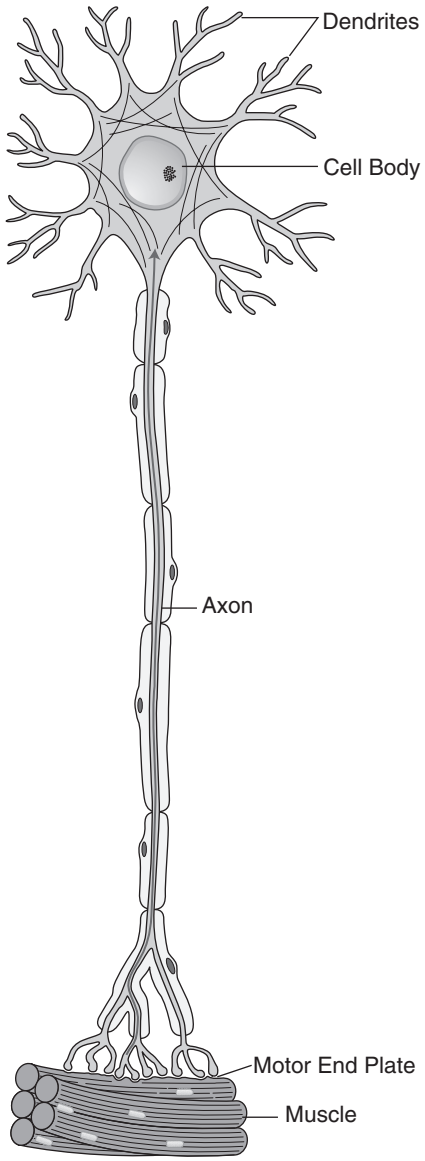

Figure 2.1 A neuron, with its cell body, dendrites, and axon, synapsing at the myoneural junction of the muscle.

are reversed in the extracellular fluids, thus creating an electrical current for transmission of neural impulses. *Dendrites* are numerous short projections that carry neural impulses to the cell body. The *axon* carries neural impulses away from the cell body. The neuron can transmit neural impulses to other neurons, glands, or muscles.

The juncture at which neural impulses are transmitted is called a *synapse*; neurochemical transmitters aid in moving the neural impulses along. *Myelin*, a fatty sheath that insulates the larger axons, is said to increase the speed of neural transmission and also to reduce interference with the neural message. There may be about 100 billion neurons in the human nervous system. Axons can produce anywhere from 1000 to 10,000 synapses, and their cell bodies and dendrites receive neural data from about 1000 other neurons. As a result, the number of synapses occurring in the brain may be about 100 trillion.

Nerve Cell Structure

Cell Body (also called *perikaryon,* or *soma*)

1. *Protoplasm* refers to the nucleus and cytoplasm.
2. *Cytoplasm* is composed of a watery substance and protein molecules, and is enclosed within the cell membrane. Microscopic structures in cytoplasmic materials include the following:
   a. *Neurofibrils* (which tend to become tangled in Alzheimer disease) serve as channels for intracellular communication.
   b. *Mitochondria* contain enzymes involved with cellular metabolic energy.
   c. *Ribosomes* are protein granules involved in the synthesis of RNA.
   d. *Lysosomes* contain enzymes that participate in intracellular digestion.
   e. *Golgi* complexes are responsible for protein secretion and transportation.

Axons and Dendrites

1. *Nerve fiber* means an axon and its covering sheath.
2. *Axons* are efferent (motor) structures that transmit information away from the cell body to other neurons. They depend on cytoplasmic proteins for survival.
3. *Axon hillock* refers to a cone-shaped region of the cell. Axons extend longer distances than dendrites. At their ends, they may branch into smaller multiple filaments, called *telodendria,* that include *synaptic knobs*, or end in a *terminal bouton (knob)*. Both types of knobs contain neurotransmitters.
4. *Dendrites* are afferent (receptive) structures that transmit information to the cell body from other cells via synaptic sites. They tend to be short and have many branches. When they have spikes or spines, this increases the surface available for synapses with other nerve cells. Many of these spines atrophy from disuse as part of typical maturation. One theory of autism is based on an excess of especially short, stubby dendritic spines, although in Fragile X syndrome, also associated with autism, dendritic spines tend to be long and thin.

Myelin Sheath

1. *Myelin* is a multilayered lipid (fatty) material that insulates and protects the nerve fiber so that electric energy cannot escape during impulse transmission and speed of nerve impulses can be regulated. Intervals between the segments of the myelin sheath are called *nodes of Ranvier*.
2. *Oligodendroglial* cells produce the myelin sheath in the central nervous system (CNS). Myelin damage of unknown origin is associated with multiple sclerosis; a rare and

slowly growing neoplastic growth (glioma) may also occur (oligodendroglioma). In the peripheral nervous system (PNS), the myelin sheath is produced by Schwann cells that lie along the axons, and is sometimes referred to as the *sheath of Schwann* (also called *neurolemma* or *neurilemma*). A schwannoma or neurofibroma is a moderately firm, benign, nonencapsulated tumor resulting from proliferation of Schwann cells in a disorderly pattern that includes portions of nerve fibers (sometimes observed as an acoustic neuroma).

Synapse

1. The *knob*, or *bouton*, contains synaptic vesicles (subdivisions of embryonic neural tubes). They are filled with neurotransmitters.
2. The *synaptic cleft* is the space between the axon of the presynaptic nerve cell and the receptive ends of the postsynaptic cell. Nerve impulses do not cross the synapse, but are communicated through the neurotransmitter released from the bouton terminals.
3. The *receptive sites* of the connecting nerve cells are chemically activated to generate the electric impulses that stimulate the nerve cell body.

Nerve Cell Types

Multipolar cells have many dendrites and one axon. Most are in the CNS. The most common examples are spinal interneurons and cerebellar Purkinje cells.

Bipolar cells have two processes, one extending from each pole of the body: a peripheral process (dendrite) and a central process (axon).

Unipolar cells are T-shaped with one process that extends from the body and divides into central (axonal) and peripheral (dendritic) portions. Unipolar cells are found in spinal dorsal roots.

Golgi Cells

1. *Golgi type I* are nerve cells whose axons leave the gray matter of which they form a part.
2. *Golgi type II* are cells with short axons which ramify in the gray matter.

Neuronal Circuits

A *divergent circuit* amplifies an impulse when an impulse from a single presynaptic cell activates several postsynaptic cells.

A *convergent circuit* has two patterns of connections. In the first neuronal circuit of convergence, the postsynaptic neuron receives impulses from several diverged fibers of the same presynaptic nerve cell. In the second pattern, impulses from different nerve cells converge on one postsynaptic nerve cell.

In *lateral inhibition*, the signal or cellular message is sharpened by inhibiting the adjacent nerve cells.

The *reverberating circuit* is a self-propagating system between cells that, if activated, can discharge the signal continuously until its operation is blocked by an external source. In the reverberating circuitry, neurons are arranged in a chain formation. The incoming impulse activates the first nerve cell, which activates the second cell, which stimulates the third, and so on. Branches from the second, third, and fourth cells send impulses back to activate the previous nerve cell, forming a closed neuronal loop.

Neuroglial Cells

Glial (meaning "glue") cells support and protect the nerve cells. Found in the gray and white matter of the brain, there are 40 to 50 times as many glial cells as nerve cells. Glial cells do not generate or transmit nerve impulses.

Astrocytes function as connective tissue, providing skeletal support for the brain cells and their processes. They contribute to the *blood–brain barrier* by contacting capillary surfaces with their end feet and using tight junctions. This restricts the movement of certain substances from the blood to the brain through selective permeability.

Oligodendroglia cells form and maintain the myelin sheath in the CNS (see the section called "Myelin Sheath").

Ependymal cells form the inner surface of the ventricles. The choroid plexus, which secretes cerebrospinal fluid, consists of vascular pia surrounded by an epithelial layer of ependymal cells.

Microglial cells are multipotential, because they act sometimes as phagocytes (which remove dead neural tissue debris) and at other times as astrocytes or oligodendrocytes. They are the scavengers of the CNS.

After an injury to the brain, astroglial cells are important in recovery. In strokes (cerebrovascular accidents, or CVAs), the astrocytes, and microglial cells proliferate and migrate to the lesion site. Microglia phagocytose (engulf) cellular debris, leaving a cavity. For large lesions, astrocytes seal the cavity, which is called a *cyst*. In smaller lesions, astrocytes fill the space with a glial scar that is called *replacement gliosis*.

Nerve Impulses

Nerve impulses have a chemical component that underlies the electric potential of the cells. An *action potential* results from charged particles (ions) moving through the cell membranes. Nerve impulses activate the release of a neurotransmitter in a presynaptic neuron. The transmitter causes the adjacent postsynaptic receptors to open an ion channel.

When nerve cells conduct an impulse (and, to a limited degree, even when they do not), positive and negative ions on each side of a cell membrane are unequal (polarized). This membrane potential is maintained by an unequal distribution of positively charged sodium and potassium ions and negative charged chloride ions and proteins across the membrane. The negative ions are highly concentrated inside the cell, and the positive ions are in higher concentration outside the cell. Opposite ions attract, and identical ions repel. This tug of war forms an electrochemical gradient along the cell membrane, which is called the cell's *resting potential*.

Nerve Excitability

Excitability is a cell's response to various stimuli and its conversion of this response into a nerve impulse or action potential. The same stimuli that affect overall homeostasis in the body (e.g., chemical or temperature change, electrical pulsing) can affect action potential or intracellular potential. When the cell interior becomes more negative, it is hyperpolarized; in the other direction (depolarization), it triggers a large spike.

A change of at least 10 mV is required to trigger an action potential and depolarize a nerve cell. The resting membrane potential is arbitrarily defined as –70 mV inside the cell membrane. So a change which brings the cell interior from –70 to –60 mV is needed to trigger a nerve impulse or message.

Impulse Conduction

Nerve impulses are conducted on the basis of polarization. For example, passive impulse conduction for a short distance occurs when sodium enters the cell membrane. This makes the interior of the axon more positive than the adjacent area; the impulse allows positively charged ions to enter the cell membrane as it moves distally along the axon.

Similarly, polarization is the basis for exciting or inhibiting an impulse in the postsynaptic neuron. *Excitatory postsynaptic potential (EPSP)* refers to a lowered membrane potential in the postsynaptic neuron, which creates an environment for a new impulse. The opposite is true for *inhibitory postsynaptic potential (IPSP)*.

Neurotransmitters

Neurotransmitters are chemical substances released at a synapse to transmit signals across neurons. They help regulate brain mechanisms that control cognition, language, speech, and hearing, among other functions. For our purposes, *small-molecule* transmitters need particular study. They include acetylcholine and the following five monoamines, which are derived from amino acids: dopamine, norepinephrine, serotonin, glutamate, and γ-aminobutyric acid (GABA). *Large-molecule* peptides produce longer-lasting effects.

Most neurotransmitters have more than one receptor type and may have different effects on different synapses. Because more than one neurotransmitter may be secreted by a single terminal bouton, it is difficult to identify a specific behavioral effect of a given neurotransmitter at all times.

Acetylcholine

Acetylcholine is the primary neurotransmitter of the PNS and is also important in the CNS. Cholinergic neurons are concentrated in the reticular formation, the basal forebrain, and the striatum. Neurons in the forebrain supply the neocortex, hippocampus, and amygdala. Cholinergic projections from the forebrain are thought to participate in regulating levels of forebrain activity; those from the reticular formation to the thalamus are critical in the cycle of sleep and wakefulness. Actions of acetylcholine are slow and diffuse in the CNS, but brief and precise in the PNS.

Antibodies that interfere with the action of acetylcholine on muscle cells at the myoneural junction are found in the myasthenia gravis. Deficient cholinergic projections in the hippocampus and orbitofrontal cortex have been implicated in Alzheimer disease, but replacing acetylcholine has not been successful in alleviating or retarding progression of the disease.

Monoamines

Dopaminergic projections are located in the mesostriatal (midbrain and striatum) and mesocortical (midbrain to cortex) systems. We are more interested in the first group. Mesostriatal projections are dopaminergic cells from the substantia nigra to the putamen and caudate nucleus of the basal ganglia. Degeneration of the substantia nigra reduces production and transmission of dopamine and is associated with Parkinson disease.

Norepinephrine-containing (noradrenergic) neurons are in the pons and medulla, with most in the reticular formation. Noradrenergic neurons project to the thalamus, hypothalamus, limbic forebrain structures, and the cerebral cortex. Descending fibers project to other parts of the brainstem, cerebellar cortex, and spinal cord. Clinically, noradrenergic neurons are thought to be involved in generating paradoxical sleep and maintaining attention and vigilance. Drugs used for treating depression act by enhancing norepinephrine transmission.

Serotonin neurons are found at most levels of the brainstem, with terminals in the reticular formation, hypothalamus, thalamus, septum, hippocampus, olfactory tubercle, cerebral cortex, basal ganglia, and amygdala. Clinically, serotonin is concerned with overall level of arousal and slow-wave sleep. It contributes to the descending pain control system. Severe depression is thought to be associated with low serotonin, and a feeling of well-being is

associated with higher levels of this neurotransmitter. Drugs such as selective serotonin reuptake inhibitors are used to control anxiety and panic disorders.

GABA, or *γ-aminobutyric acid*, is a major neurotransmitter for the CNS, just as acetylcholine is in the periphery. It serves as the inhibitory neurotransmitter from the striatum to the globus pallidus and substantia nigra, from the globus pallidus and substantia nigra to the thalamus, and from the Purkinje cells to the deep cerebellar nuclei. Clinically, GABA is implicated in Huntington disease.

The Human Nervous System

The human nervous system is made up of the central, peripheral, and autonomic nervous systems. The areas of the human nervous system that will be reviewed in the following pages are those that are vital for speech and language. The CNS contains the brain, spinal cord, meninges, ventricles, and blood supply. The PNS is composed of the spinal peripheral nerves and the cranial nerves (**Figure 2.2**). The autonomic nervous system (ANS) contains a sympathetic division and a parasympathetic division.

We have noted different myelin-forming cells: an oligodendrocyte, which myelinates many axons in the CNS; and a Schwann cell, which forms myelin exclusively for one internode of a peripheral nerve fiber. Composition of nerve fibers varies between the CNS and PNS.

Peripheral nerve fiber bundles are held together by connective tissue (*collagen fibers*, which compose connective tissue throughout the body, and in the brain form *fibroblasts* and other cells that form an *endoneurial membrane*). There is no such fibrous connective tissue in the CNS. The endoneurium wraps around a peripheral axon and merges with *neurilemma*, the most external layer of the multilayered myelin, which contains the nucleus of the Schwann cell. The neurilemma is important in the regeneration of injured axonal fibers in the PNS. Axonal shearing is discussed in the chapter on traumatic brain injury.

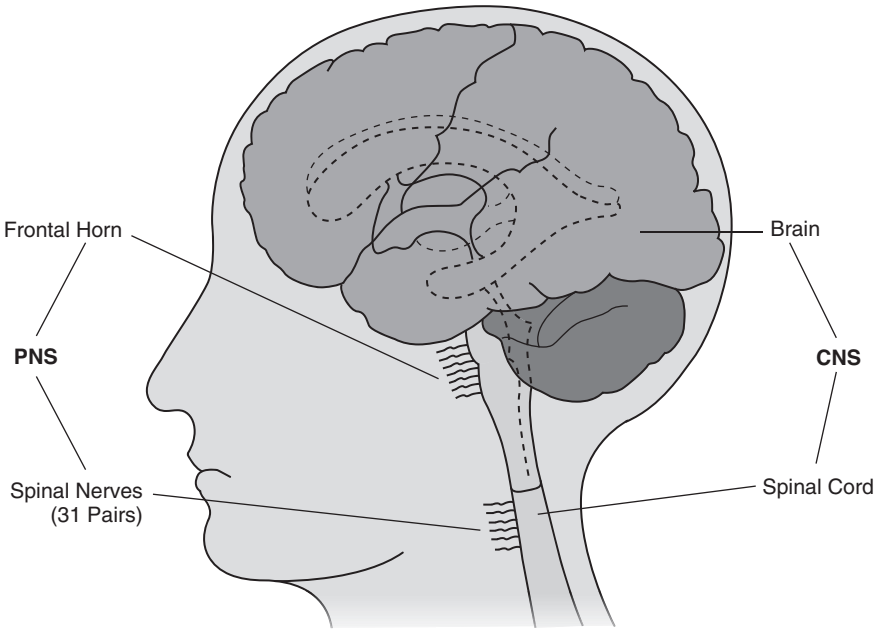

Figure 2.2 The CNS (brain and spinal cord) and PNS (12 pairs of cranial nerves and 31 pairs of spinal nerves).

The Central Nervous System

The central nervous system (CNS) consists of the brain, spinal cord, meninges, ventricles, and blood supply.

The Brain

The brain is composed of the cerebral hemispheres, the basal ganglia, the cerebellum, and the brainstem. The largest part of the brain is called the cerebrum and is made up of the two cerebral hemispheres and the basal ganglia. The cerebral cortex covers the cerebrum and is composed of many prominent sulci or fissures (grooves on the surface of the brain or spinal cord) and gyri (elevations or ridges on the surface of the cerebrum). Korbinian Brodmann (1868–1918), a German neurologist, established the numbering system for 52 areas of the cerebral cortex, which remains the universal standard (called *Brodmann areas*) used today.

Cerebral Hemispheres

The cerebral hemispheres are composed of a left and a right hemisphere and are connected by a mass of white matter called the *corpus callosum*. The purpose of the corpus callosum is to pass neuronal information from one hemisphere to the other. Medically directed severance of the corpus callosum has led to a good deal of "split brain" research. Included in the findings of this research is the observation that the left hemisphere serves a different purpose than the right hemisphere. Some of the functions of the left hemisphere are involvement in language and analytical and logical aspects, whereas the right hemisphere is involved with perceptual, spatial, intuitive, and holistic aspects (e.g., a lesion in a language area of the left hemisphere can result in aphasia, whereas a lesion in the right hemisphere can result in the patient's inability to draw information through inference that is arrived at by taking a holistic and intuitive approach).

The *longitudinal cerebral fissure*, which runs from the front to the back of the brain, separates the two hemispheres (**Figure 2.3**). The cerebral cortex in each hemisphere is partitioned

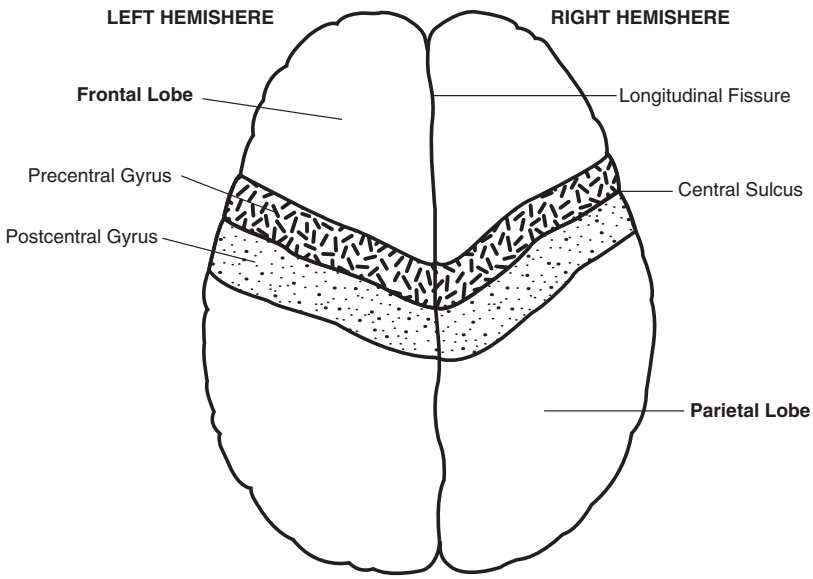

Figure 2.3 A superior view of the cerebral hemispheres.

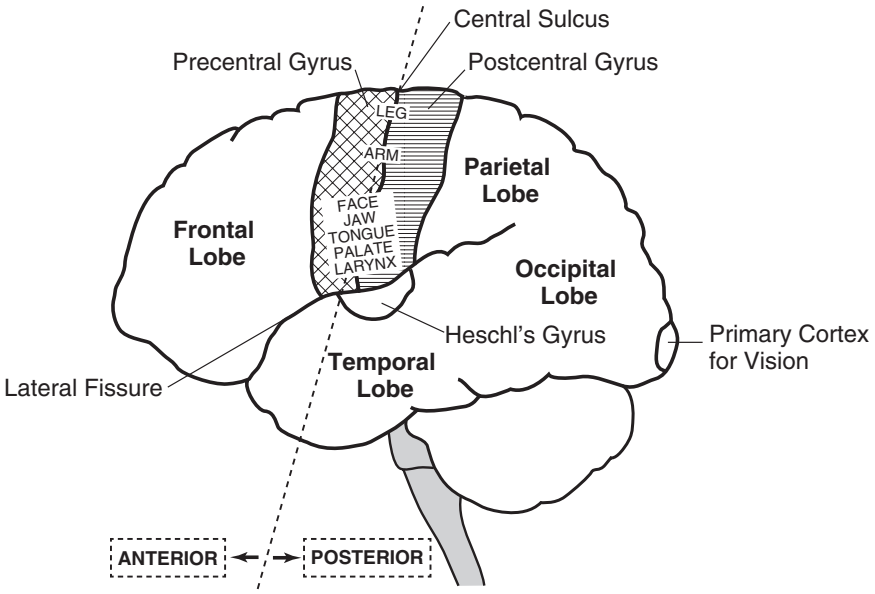

Figure 2.4 Lateral view showing the location of the four lobes of the brain.

into the frontal, parietal, temporal, and occipital lobes (**Figure 2.4**). Lying beneath the outer surface of the cerebral cortex is a fifth lobe called the *limbic lobe*.

The frontal lobe. The frontal lobe is bounded in the back by the central sulcus and below by the lateral fissure. The brain is divided into anterior and posterior regions by the central sulcus. Within the frontal lobe is the precentral gyrus, which lies immediately anterior to the central sulcus. The precentral gyrus is also known as the *primary motor cortex*, or "motor strip" area, and it controls voluntary muscular movement on the opposite side of the body (Figure 2.4).

The neurons within the primary motor cortex are organized in a pattern of a person ("homunculus," or "little man") standing upside down. Neurons devoted to motor movements in the face and neck area are closest to the lateral fissure, and neurons devoted to motor movements of the toes and leg are closest to the longitudinal cerebral fissure (Figure 2.4). Some parts of the body require fine motor movement, whereas other parts require less precise motor movement. There is a greater array of neurons devoted to the small muscles of the larynx, palate, tongue, jaw, and face than to the arm or leg. The number of neurons allocated for voluntary movement of a body part is typically not commensurate with its size. A lesion in the primary motor cortex within areas involving movements of the lips, tongue, or larynx can result in certain types of dysarthria.

Located in front of the precentral gyrus are the premotor and supplementary motor areas (**Figure 2.5**). These areas receive information from other regions of the brain, and their purpose is to integrate, refine, and plan or program motor speech output (e.g., a lesion in the premotor areas can result in certain types of dysarthria, or if in the dominant hemisphere, an apraxia of speech). Broca's area is in the third frontal gyrus of the dominant hemisphere (Figure 2.5). This important area plays a main role in motor speech programming and also connects to other parts of the brain involved with speech and language (e.g., a lesion in Broca's area can result in apraxia of speech in addition to the more commonly seen nonfluent aphasia).

The parietal lobe. The parietal lobe is bounded in the front by the central sulcus and below by the back end of the lateral fissure. Within the parietal lobe is the postcentral gyrus,

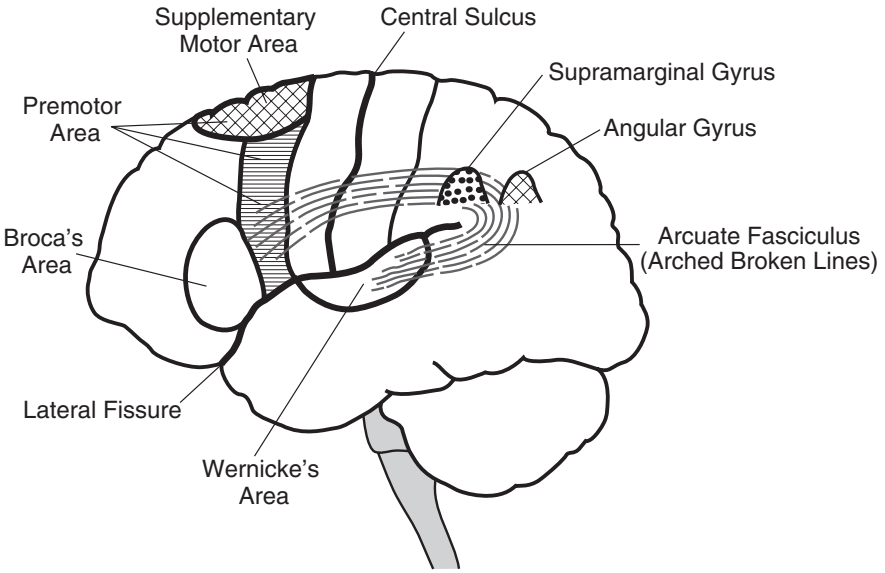

Figure 2.5 Lateral view of the left (dominant) hemisphere, showing the location of the language and motor speech programming (or planning) areas.

which is located in back of the central sulcus (Figure 2.4). The postcentral gyrus is a mirror image to the "motor strip" area of the frontal lobe and is a primary sensory cortical area ("sensory strip") having to do with temperature, pain, touch, and proprioception.

Proprioception (which includes the senses of movement, vibration, pressure, position, equilibrium, and deep pain) enables one to realize exactly where the individual parts of the body are in space, and the relationship of one body part to another (e.g., tongue in relation to the alveolar ridge in the production of lingua-alveolar sounds). This somatosensory cortex in the dominant hemisphere appears to play a part in motor speech programming, especially in the integration of sensory information in preparation for motor activity (e.g., a lesion in this area can result in apraxia of speech). In addition, Damasio (1994) has noted that the somatosensory cortex in the right hemisphere helps maintain reasoning and decision making, emotion, and feelings, with a special emphasis in the social and personal domain (see the chapter on communication disorders associated with right hemisphere damage for further discussion).

The parietal lobe in the dominant hemisphere also contains the supramarginal gyrus and the angular gyrus (Figure 2.5). The supramarginal gyrus curves around the back end of the lateral fissure and is responsible for the formulation of written language and possibly for phonological storage (e.g., a lesion in this area can result in aphasia). The angular gyrus lies directly behind the supramarginal gyrus and plays a major role in reading comprehension (e.g., a lesion in this area can result in aphasia with deep dyslexia).

The temporal lobe. The temporal lobe is bounded on top by the lateral fissure and in the back by the front border of the occipital lobe. Three important areas in the temporal lobe of the dominant hemisphere are Heschl's gyrus, Wernicke's area, and the insula (or the Island of Reil). Heschl's gyrus (or primary auditory cortex) is located on the lateral fissure, two-thirds of the way back on the upper surface of the temporal lobe (Figure 2.4). It is the cortical center for hearing, responsible for appreciating the meaning of sound (e.g., a lesion in this area can result in auditory processing problems, which can lead to an auditory comprehension deficit). Wernicke's area (an auditory association area) is located on the back part of the

superior temporal gyrus (Figure 2.5) and plays a major role in auditory comprehension and other language abilities (e.g., a lesion in this area can result in aphasia). The insula, which can be seen if the two borders of the lateral fissure are pulled apart, is in the paralimbic area. The function of the insula is not clearly defined, but a lesion there can result in aphasia or apraxia of speech.

The occipital lobe. The occipital lobe is located at the back of the cerebral hemisphere. It is bounded in the front by the parietal and temporal lobes and in back by the longitudinal fissure. The primary visual cortex and visual association areas are situated in the occipital lobe. The primary visual cortex (Figure 2.4) is responsible for basic vision (e.g., a lesion in this area can produce degrees of blindness). The visual association area is needed for integrating and organizing incoming visual stimuli (e.g., a lesion here can result in visual perception problems, which in turn can influence reading comprehension).

The limbic lobe. The limbic lobe is situated on the medial surface of the cortex and contains the orbital frontal region, the cingulate gyrus, and the medial portions of the temporal lobe. The limbic system regulates emotions and behavior. For example, a lesion in this system can affect prosody, or possibly pragmatic abilities (see "Limbic System" in this chapter for further discussion).

The association areas. As mentioned previously, there are primary centers for motor, sensory, hearing, and visual functioning. These centers are connected to one another and to other parts of the brain by association areas. The association areas are responsible for higher mental functioning, including language, and are located in the lobes of each hemisphere.

The *frontal association* area is responsible for initiation and integration of purposeful behavior and for planning and carrying out sequences of volitional movement. The parietal association area, or somesthetic area, is responsible for the discrimination and integration of tactile information. The temporal or auditory association area is needed for the discrimination and integration of auditory information. The visual association area is responsible for the discrimination and integration of visual information. A lesion in an association area of the dominant hemisphere can result in aphasia, as can a lesion in a pathway connecting one association area with another, as in the case of the arcuate fasciculus (Figure 2.5), which connects the association area of the temporal lobe with that of the frontal lobe.

The Basal Ganglia (or Basal Nuclei)

In another part of the brain are subcortical structures called the *basal ganglia*. They are a mass of gray matter that lies deep within the cerebrum and below the cerebral cortex. The basal ganglia consist of the caudate nucleus, the globus pallidus, and the putamen; grouped together, these are called the *corpus striatum* (**Figure 2.6**). The globus pallidus and putamen are sometimes named together as the *lentiform nucleus*. The basal ganglia are responsible for controlling and stabilizing motor functions and for interpreting sensory information so as to guide and influence motor behavior (e.g., a lesion in the basal ganglia can result in dysarthria).

The Cerebellum

The cerebellum is located just behind the pons and the medulla at the base of the occipital lobe (Figure 2.6). The cerebellum contains right and left hemispheres that are connected by the vermis between them (**Figure 2.7**). These are the areas most involved in speech control. The cerebellum does not initiate motor movements, but through its connections to the spinal cord, cerebrum, pons, and medulla, it helps in coordinating the skilled, voluntary muscle activity produced elsewhere (e.g., a lesion in the cerebellum can result in dysarthria).

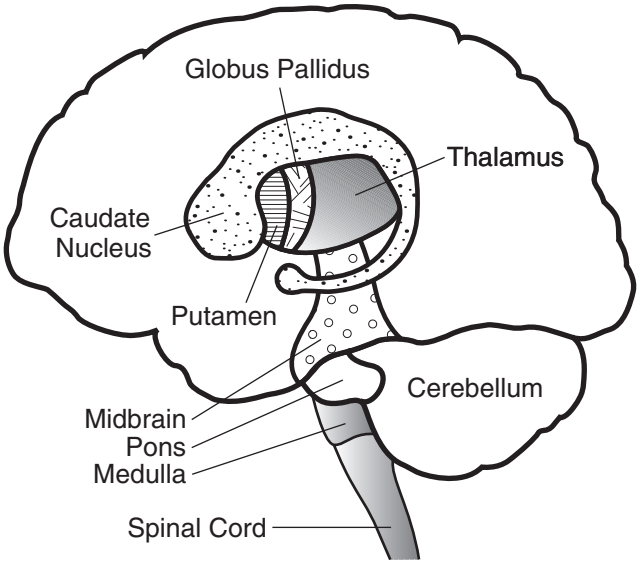

Figure 2.6 A sagittal section of the brain that shows the location of the spinal cord, brainstem, (medulla, pons, midbrain), thalamus, basal ganglia (caudate nucleus, globus pallidus, putamen), and cerebellum. A sagittal section is a vertical cut or slice which divides the body into right and left halves, producing two equal, mirror-image parts.

The Brainstem

The brain also contains the brainstem, which appears as an upward extension of the spinal cord and thrusts upward into the brain between the cerebral hemispheres. In ascending order, once the spinal cord enters the foramen magnum of the brain case, the brainstem consists of the medulla oblongata, the pons, the midbrain (mesencephalon), and two structures (diencephalon) called the *thalamus* and *hypothalamus* (Figure 2.6). Some authors include the thalamus and hypothalamus as part of the cerebrum.

The medulla and pons. The medulla contains nuclei for several of the cranial nerves, and ascending and descending tracts to and from the cortex that are important for the control of speech production. The pons contains nuclei for several of the cranial nerves, has major connections to the cerebellum, and has other connections to the cortex that are important for speech production (e.g., a lesion in a cranial nerve important for speech can result in dysarthria).

The midbrain, thalamus, and hypothalamus. The midbrain, or mesencephalon, serves as a way station in the auditory and visual nervous systems, and contains the corpora

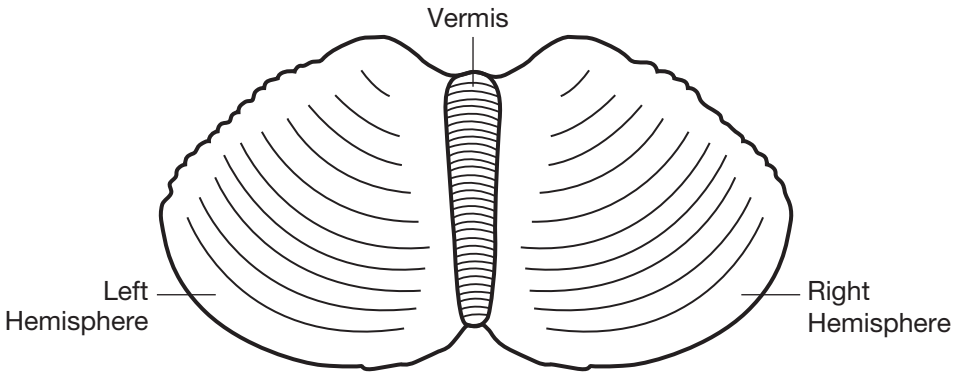

Figure 2.7 A superior view of the cerebellum showing the two hemispheres and the vermis.

quadrigemina (which means "the body of four parts"). There are synapses here for vision (two superior colliculi) and hearing (two inferior colliculi). The midbrain also contains the *substantia nigra*. The substantia nigra is responsible for the production of a chemical neurotransmitter called *dopamine*, which aids in motor control and muscle tone (e.g., a lesion in the substantia nigra can result in dysarthria).

The thalamus serves as a relay station for sensory information going to and from the sensory areas of the cortex, and has direct ties to cortical language and motor speech systems (Figure 2.6) (e.g., a lesion in the thalamus can result in aphasia). The hypothalamus controls aspects of emotional behavior (rage and aggression) and aids in the regulation of body temperature, food and water intake, and sexual and sleep behavior.

The Spinal Cord

In addition to the brain, the CNS also contains the spinal cord. The spinal cord extends from the skull through a large opening called the foramen magnum down to the lower back. The foramen magnum is the boundary between the medulla and the spinal cord. The spinal cord is encased in the vertebral column. A cross section of the spinal cord shows an H-shaped area of gray matter in the core of the spinal segment. The gray matter of the H shape contains motor and sensory neurons. The ventral or anterior portion of the cord conducts motor neurons, and the dorsal or posterior portion of the cord conducts sensory neurons.

The Spinal Nerves

Thirty-one pairs of spinal nerves (which along with the cranial nerves are part of the PNS) are attached to the spinal cord (Figure 2.2). The spinal cord, through these 31 pairs of nerves, relays sensory information from the receptor (e.g., skin) to the cortex for evaluation of the sensations of pain, temperature, touch, and vibration. The spinal nerves relay motor information from the CNS to the effector (e.g., muscles).

As with the cortex, the spinal cord contains gray and white matter. The gray matter contains the nerve cell bodies, and the white matter contains the ascending and descending nerve axon fibers. Ascending tracts carry sensory or afferent information, while descending tracts carry motor or efferent information.

The Reflex Arc

Occasionally, a motor response can avoid going through the higher centers of the cortex for interpretation; this shortcut is known as the *reflex arc* (**Figure 2.8**). For example, a receptor (e.g., skin) responds to pain or temperature and sends this information through an afferent

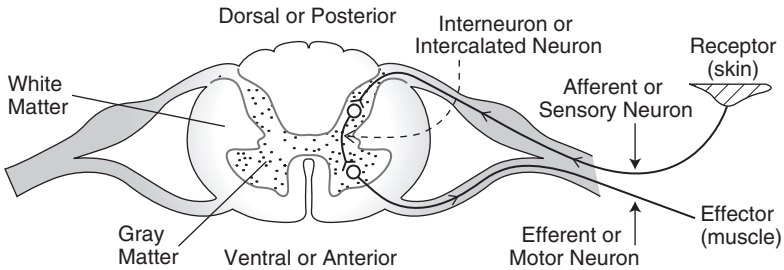

Figure 2.8 Cross section of the spinal cord showing the reflex arc.

(or sensory) neuron, which sends it to the dorsal (or posterior) horn (within the H shape) within the spinal cord. At this point, instead of ascending to higher centers of the cortex, the impulse travels through an interneuron (or intercalated neuron) within the spinal cord to the ventral (or anterior) horn (within the H shape). From there, the impulse descends through an efferent (or motor) neuron and into the effector (e.g., muscles), whose action will cause a hand to be removed instantaneously and without thinking from water that is too hot. This is a simplified version of a reflex arc taking place at the spinal cord level. There are different types of reflexes that can take place at different levels within the nervous system.

The Meninges

The brain and the spinal cord are protected and nourished by a system involving the meninges, ventricles, and blood supply. Protection of the brain and spinal cord starts with the hard bone of the cranium and the bony vertebral column of the spinal cord. Below the bone are three membranes called the *meninges* (**Figure 2.9**). In descending order the meninges are composed of the *dura mater* ("tough mother"), arachnoid mater ("spider mother"), and pia mater ("delicate mother").

There are several spaces that separate the meninges and provide a cushioning effect. Located between the outer bone and the dura mater is the extradural space. Located beneath the dura mater is the subdural space. Situated between the arachnoid mater and the pia mater is the subarachnoid space, which contains cerebrospinal fluid. (Physical trauma to the brain that tears or lacerates the meninges is identified as an open head injury, and can affect speech, language, or cognition.)

The Ventricles

There is a network of cavities within the brain called *ventricles* that are connected to one another by small canals and ducts (**Figure 2.10**). Cerebrospinal fluid, which is produced by the choroid plexus within each ventricle, fills all the ventricles. Through small openings in particular ventricles, cerebrospinal fluid fills the subarachnoid space of the meninges. The cerebrospinal fluid aids in the nourishment of nerve tissues, regulates intracranial pressure, removes waste products, and along with the meninges, cushions and protects the brain and spinal cord from physical trauma.

The ventricles involved are the two lateral ventricles, the third ventricle, and the fourth ventricle. Ventricular enlargement in babies not yet born is associated with in-utero stroke (Arroyo, Goldfarb, Cahill, & Schoepflin, 2010), a condition that occurs in about 1 in 4000 births. The lateral ventricle, which is paired (one in each hemisphere), is connected to the

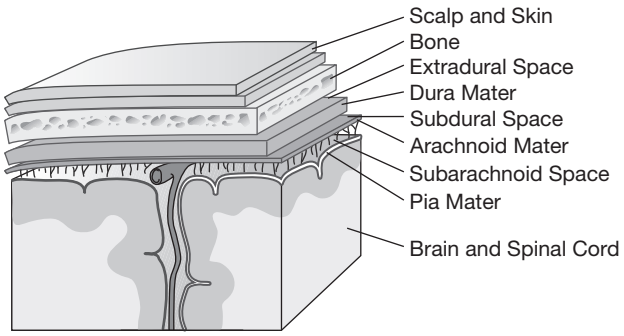

Figure 2.9 The meninges that cover the brain and the spinal cord.

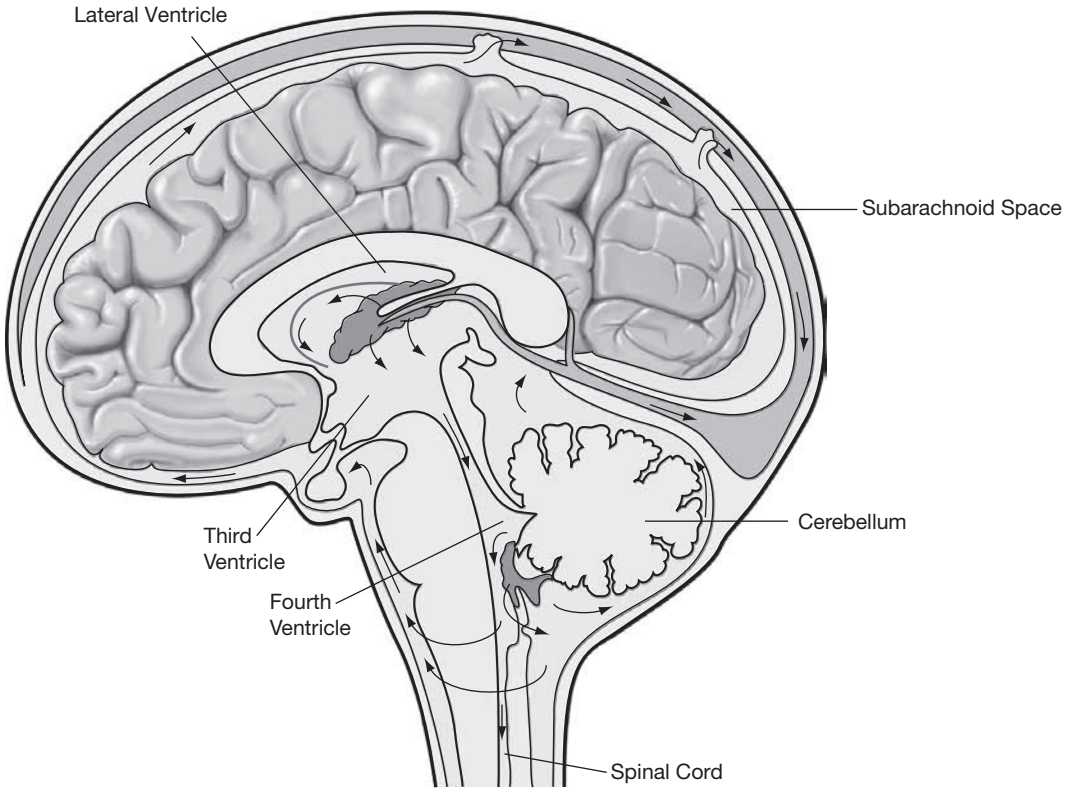

Figure 2.10 The ventricular system.

third ventricle through an opening called the *intraventricular foramen* (or the foramen of Monro). The third ventricle is connected to the fourth ventricle through the cerebral aqueduct (or the aqueduct of Sylvius). Congenital blockage of the cerebral aqueduct is associated with hydrocephalus in babies. The fourth ventricle leads into the subarachnoid space through the foramen of Luschka and the foramen of Magendi. Through this ventricular route, the cerebrospinal fluid flows into the brain and the spinal cord, and ultimately drains into the venous system for excretion.

The Blood Supply

Blood is composed of a liquid component called *plasma*, and solid components made up primarily of red corpuscles, white corpuscles, and platelets. Red corpuscles, which are produced in the bone marrow, are the cells that carry oxygen from the lungs to other parts of the body. For its proper nutrition and functioning, the brain needs oxygen and other elements carried by the blood. If the blood supply to the brain is stopped for five minutes or longer, cell death can occur.

Arteries carry blood away from the heart, veins carry blood toward the heart, and capillaries connect the arteries to the veins. The blood supply to the brain is as follows (**Figure 2.11**): The heart pumps blood into the aorta (major artery), which then branches off into four main arteries called the *two common carotid arteries* (one for the left side and one for the right side) and the two common subclavian arteries (one for each side). The two common carotid arteries ascend into the brain, where they divide into an internal carotid artery and an external

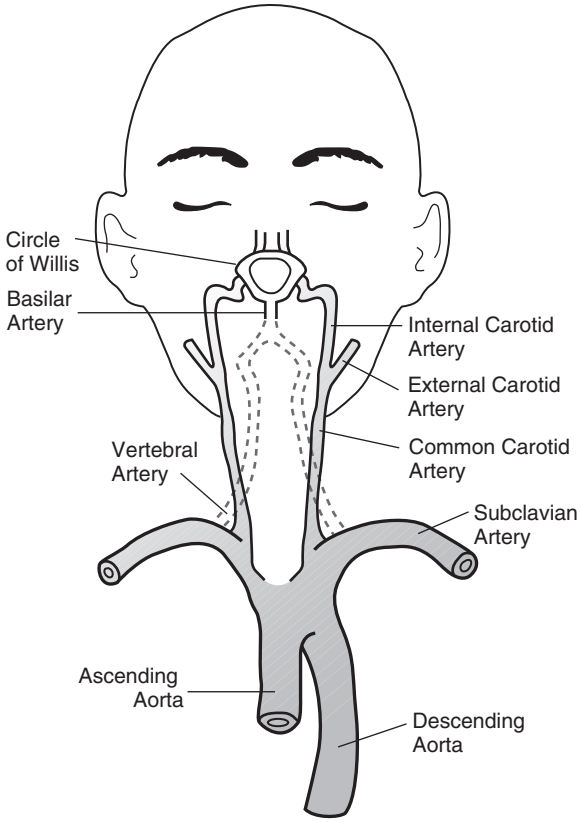

Figure 2.11 The major arteries supplying blood to the brain.

carotid artery on each side. The external carotid branch feeds the face area and is relatively unimportant for this review. The internal carotid branch further divides into the anterior and middle cerebral arteries (**Figure 2.12**). The anterior cerebral artery supplies the superior and anterior frontal lobes, corpus callosum, the medial surfaces of the hemispheres, and portions

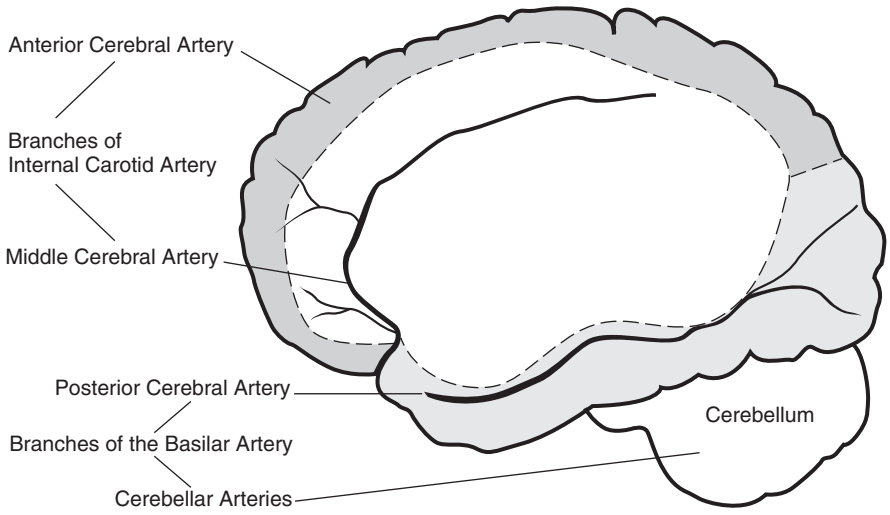

Figure 2.12 Lateral view of the left hemisphere showing the location of the anterior, middle, and posterior cerebral arteries.

of the subcortical areas. The middle cerebral artery supplies most of the lateral surfaces of the hemispheres and portions of the subcortical areas.

The two *common subclavian arteries* have branches called the *vertebral arteries*, which ascend into the brain. The vertebral artery branches (one from each side) join together to form the *basilar artery*. The basilar artery then ascends and divides into two *posterior cerebral arteries* (one for each hemisphere) (Figure 2.12), which supply the inferior lateral surface of the temporal lobe, and the lateral and medial surfaces of the occipital lobe. Through its branches, the basilar artery also supplies portions of the spinal cord, medulla, pons, midbrain, and cerebellum.

The circle of Willis (Figure 2.11) is formed in the brainstem by the joining together of the two internal carotid arteries and the two vertebral arteries. An interruption of the blood supply below the circle of Willis may not cause as much brain damage as lesions above the circle. The reason is that other undamaged blood channels can be utilized to feed all of the arteries below the circle. If an interruption occurs above the circle, alternative blood channels are not as readily available, and this can lead to more severe problems (e.g., a cerebrovascular accident above the circle of Willis in the middle cerebral artery can result in aphasia). Collateral circulation via the circle of Willis seems to work more efficiently in men than in women.

The Motor System for Speech

The neural motor pathways for the control of speech reside at all levels of the human nervous system and consist of the pyramidal system and the extrapyramidal system. The pyramidal system (or direct motor system) contains the corticospinal tract and the corticobulbar tract; both tracts are responsible for skilled voluntary motor movement (**Figure 2.13**). The function of the pyramidal system is primarily facilitative.

The Corticospinal Tract

The corticospinal tract, which controls skilled voluntary movements of the limbs and trunk, begins in the motor cortex or in the premotor cortex, which is a depository for information coming from various cortical and subcortical locations. The area primarily involved is the precentral gyrus (motor strip area) of the frontal lobe (Figure 2.4), and to a lesser degree, the premotor area of the frontal lobe (Figure 2.5) and the postcentral gyrus (sensory strip area) of the parietal lobe (Figure 2.4). The bilateral corticospinal tracts (Figure 2.13) descend from the cortex to a subcortical structure called the *internal capsule*, where they all converge. From the internal capsule, the tracts descend through the midbrain, the pons, and the medulla, and then to various levels of the spinal cord, where they synapse with the spinal nerves of the peripheral nervous system.

Before reaching the spinal nerves, about 85–90% of the corticospinal tracts cross over (decussate) to the other side of the body in a structure called the *upper medullary pyramids* (hence the name *pyramidal system*). (A lesion above the crossover decussation point of the medullary pyramids can result in paralysis of a limb that is contralateral [opposite side] to the site of the lesion. A lesion below the crossover point can result in paralysis of a limb ipsilateral [same side] to the site of the lesion.) The 85–90% of the corticospinal tracts that do cross over are called the *lateral corticospinal tracts*, and the 10–15% that do not cross over are called the *anterior corticospinal tracts*.

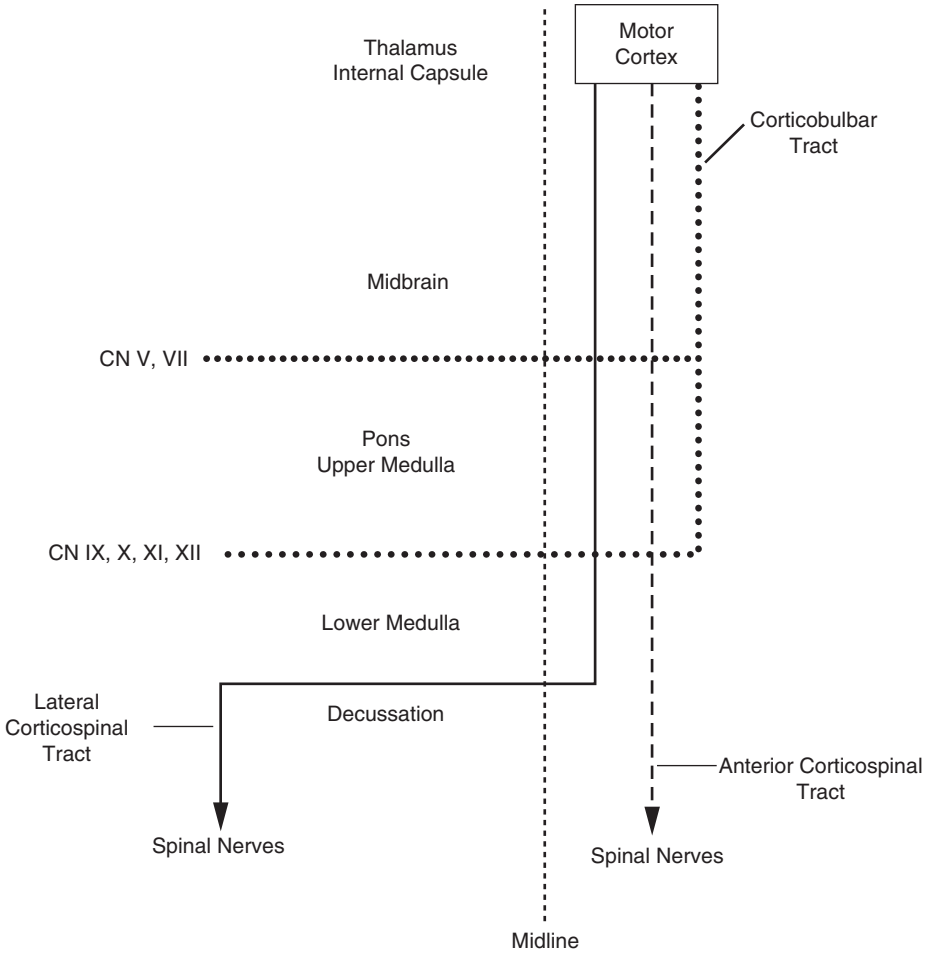

Figure 2.13 A schematic drawing of the pyramidal system in speech production, and the concept of the upper motor neuron (UMN) and the lower motor neuron (LMN). The pyramidal system (corticospinal and corticobulbar tracts) makes up the UMN. The cranial nerves (responsible for the innervation of the muscles used in phonation, resonance, and articulation) and the spinal nerves (responsible for the innervation of the muscles used in respiration) make up the LMN. CN = cranial nerve.

The Corticobulbar Tract

The corticobulbar tract ("bulbar," meaning "shaped like a bulb," is the old name for the medulla) controls the skilled voluntary movements of the speech muscles (except those used for respiration). The tract begins in the same area as the corticospinal tract and descends to the motor nuclei of the cranial nerves, which are located in the pons and the medulla (Figure 2.13). The corticobulbar tract has many ipsilateral and contralateral fibers, with crossover taking place at various levels of the brainstem. Because of the bilateral innervation that the corticobulbar tract produces, the majority of the midline structures work in bilateral symmetry (e.g., a unilateral lesion to the corticobulbar tract can result in a mild dysarthria because of help from the intact muscles of the other side).

The Extrapyramidal System

The extrapyramidal system (or indirect motor system) is made up of two major components—the indirect activation pathway and the control circuit areas.

The Indirect Activation Pathway

The indirect activation pathway (Duffy, 2005) consists of several short pathways that begin in the cerebral cortex and, through its connections, end in the spinal cord and in the cranial nerves. The indirect activation pathway is influenced by the basal ganglia and cerebellar control circuits, and through much of its journey it intermingles with the corticospinal and corticobulbar tracts of the pyramidal system. Its influence on the spinal nerves is more certain than its influence on the cranial nerves.

The function of the indirect activation pathway (Duffy, 2005) is that it helps regulate reflexes and maintain posture, tone, and other associated activities. This helps the direct motor system in accomplishing the appropriate speed, range, and direction of specific muscular movements (e.g., a unilateral lesion in the indirect activation pathway can result in a unilateral upper motor neuron dysarthria; bilateral lesions can result in a spastic dysarthria). The indirect activation pathway contains many tracts that are inhibitive in function.

The Control Circuits

The control circuits consist of the basal ganglia control circuit and the cerebellar control circuit (Figure 2.6). These control circuits do not have direct contact with the cranial nerve nuclei and the spinal cord, but rather have contact with the cortex, with portions of the pyramidal system and indirect activation pathways, and with themselves. The function of the control circuits is to provide information and sensory feedback to the pyramidal system and indirect activation pathways about the posture, orientation in space, tone, and physical environment in which timed and coordinated muscular movement will take place.

Motor disturbances associated with the basal ganglia control circuit are typically called *dyskinesias*, which means involuntary movement disorders. Within the dyskinesias are hypokinesia, which means too little movement (e.g., symptoms shown in hypokinetic dysarthria, associated with Parkinson disease), and hyperkinesia, which means too much movement (e.g., symptoms shown in hyperkinetic dysarthria, associated with Huntington disease).

Motor disturbances associated with the cerebellar control circuit are incoordination and hypotonia (a decrease in resistance when passive movement is performed) of muscular movements (e.g., a lesion in the cerebellar control circuit can result in ataxic dysarthria).

The Upper and Lower Motor Neurons

The Upper Motor Neuron

The upper motor neuron (UMN) pathways consist of the pyramidal system (or direct motor system), and a portion of the extrapyramidal system (or indirect motor system).

The pyramidal system contains the corticospinal tracts, which send motor impulses from the cortex to the spinal cord, and the corticobulbar tracts, which send motor impulses from the cortex to the cranial nerves located in the pons and the medulla (Figure 2.13). The portion of the extrapyramidal system that is a part of the UMN is the indirect activation pathway. The indirect activation pathway sends motor impulses from the cortex to the spinal cord, from the cortex to the cranial nerves, and from the cortex to the corticospinal and corticobulbar tracts.

The indirect activation pathway (Duffy, 2005) as part of the UMN (tracts that have direct input to the spinal nerves and the cranial nerves) is debatable because its anatomy and function are difficult to separate from the basal ganglia and cerebellar control circuits, and its input to the cranial nerves used for speech production is poorly understood. The control

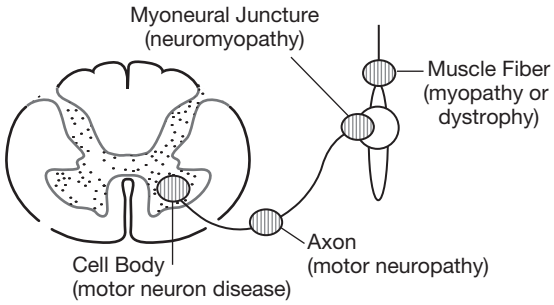

Figure 2.14 Lesion sites in the motor unit of the lower motor neuron: Site 1, cell body (motor neuron disease); site 2, axon (motor neuropathy); site 3, myoneural juncture (neuromyopathy); and site 4, muscle fiber (myopathy or dystrophy).

circuits do not have direct input to the spinal and cranial nerves, whereas the corticospinal, corticobulbar, and indirect activation tracts do have direct input.

The UMN pathways are contained in the CNS, and their function is to activate the lower motor neuron (LMN). Damage to the UMN can result in a spastic paralysis, which is primarily characterized by hypertonia (extreme tension of the muscles), hyperreflexia (an exaggeration of deep tendon reflexes), little or no atrophy (loss of bulk) of the musculature, and no fasciculations (fine muscle twitches). These characteristics can lead to decreased skilled movements, weakness, slowness, and reduced range of movement of the speech musculature (e.g., bilateral UMN damage can result in a spastic dysarthria).

The Lower Motor Neuron

The lower motor neuron (LMN) consists of the 31 pairs of spinal nerves and the 12 pairs of cranial nerves (Figure 2.2). The LMN pathways are activated by the UMN pathways, and then send motor impulses to the muscles for movement. The spinal nerves send motor impulses to the limbs, trunk, and the muscles used for respiration. The cranial nerves send motor impulses to the muscles of the speech mechanism (except those used for respiration).

Another name for the LMN is the *final common pathway* (FCP) because all motor activity must pass through it en route to the musculature. Damage to the LMN can result in a flaccid paralysis, which is primarily characterized by hypotonia, hyporeflexia, atrophy of the musculature, and fasciculations. Those characteristics can lead to weakness of the speech musculature. Lesions to the motor unit (**Figure 2.14**) of the LMN (spinal and cranial nerves) can occur in the cell body, in the axon leading to the muscle, at the neuromuscular junction, or in the muscle itself (e.g., bilateral damage to any portion of the motor unit can result in a flaccid dysarthria).

The Peripheral Nervous System

The peripheral nervous system (PNS) is composed of 31 pairs of spinal nerves and 12 pairs of cranial nerves (Figure 2.2).

The Spinal Nerves

The 31 pairs of spinal nerves leave the spinal cord and conduct sensory and motor impulses (functions) to and from other parts of the body (viscera, blood vessels, glands, and muscles). Each pair of spinal nerves contains a dorsal (posterior) root, which carries sensory messages

through afferent fibers to the CNS, and a ventral (anterior) root, which carries motor messages through efferent fibers from the CNS.

The sensory messages (e.g., pain, touch, temperature) are passed to the thalamus, which in turn sends the messages to the sensory cortex (postcentral gyrus) for evaluation. The motor messages are sent from the CNS (corticospinal tracts) to the spinal nerves of the PNS, which in turn send the message to the muscles of the limbs and the trunk.

In descending order, the 31 pairs of spinal nerves consist of 8 pairs of cervical nerves, 12 pairs of thoracic nerves, 5 pairs of lumbar nerves, 5 pairs of sacral nerves, and 1 pair of coccygeal nerves. Portions of the thoracic division are responsible for the abdominal and intercostal muscles, and portions of the cervical division form the phrenic nerves, which are responsible for the very important diaphragm muscle. All of these muscles are involved in the respiratory component of speech production (e.g., bilateral lesions that produce significant weakness of the respiratory muscles can result in reduced loudness and reduced pitch variability, and can indirectly affect phonation [compensatory strained voice] and prosody [short phrases]).

The Cranial Nerves

There are 12 pairs of cranial nerves (one nerve of each pair on each side), although only the 7 pairs of cranial nerves most relevant for speech and hearing will be detailed here. The 7 cranial nerves involved leave the pons or the medulla and conduct sensory and/or motor impulses to and from the periphery and the CNS. Motor messages are sent from the CNS (corticobulbar tracts) to the cranial nerve nuclei located in the pons and the medulla, and then out to the musculature of the speech mechanism and other portions of the head, neck, shoulders, and the abdominal and thoracic viscera.

Sensory messages come from the periphery and go to the cranial nerve nuclei located in the pons and the medulla, from where they are forwarded to the thalamus. In turn, the thalamus sends the messages to the sensory cortex (postcentral gyrus) for evaluation. Of the seven cranial nerves most relevant for speech and hearing, only the cranial nerve responsible for hearing and balance does not follow this sensory route. The route for hearing and balance will be mentioned in another section.

Most of the cranial nerves receive bilateral neural innervation, some receive unilateral neural innervation, and some receive a mixture of bilateral and unilateral neural innervation (depending upon the branches of the cranial nerve) from the corticobulbar tract of the CNS.

A unilateral lesion affecting a cranial nerve receiving bilateral neural innervation will cause less severe speech problems than one receiving unilateral neural innervation. With bilateral tracts, the undamaged tract can compensate for the damaged one. Bilateral damage to bilateral tracts, and unilateral damage to unilateral tracts, will produce more severe speech problems.

Below is a brief outline of the cranial nerves (CNs), with expanded descriptions of those most relevant to speech production and hearing. Unless specified otherwise, sensory refers to the sensation of pain, touch, temperature, or vibration.

1. *Olfactory* (CN I; Special Sensory) functions in the special sense of smell (olfaction).
2. *Optic* (CN II; Special Sensory) functions to control visual information from the retina.
3. *Oculomotor* (CN III; Somatic Motor and Visceral Motor) functions to control muscles responsible for visual tracking or fixating on an object (somatic), and in reflexes associated with pupillary light (visceral).
4. *Trochlear* (CN IV; Somatic Motor) innervates the superior oblique muscle of the contralateral orbit, which helps in the precise movement of the eye for visual tracking or fixation.

5. *Trigeminal* (CN V; Sensory and Motor) receives sensory impulses from the jaw, lips, face, and tongue, and sends motor impulses to the jaw. Bilateral damage to the sensory function and/or the motor function can affect articulation and prosody (slow rate).
   a. *Ophthalmic nerve* carries sensory fibers from the cornea, conjunctiva, iris, lacrimal gland, upper eyelid, brow and front of the scalp, nasal mucosa, and vessels.
   b. *Maxillary nerve* conveys sensation from the lower eyelid, side of nose, upper lip, palate, upper jaw and teeth, part of buccal mucosa, nasal sinuses, nasopharynx, and from vessels and glands in its area of supply.
   c. *Mandibular nerve* carries sensory fibers from the lower jaw, teeth and overlying skin and mucosa, part of the skin and mucosa of the cheek; from the auricle and part of the external auditory meatus; from the temporal region, temporomandibular joint and masticatory muscles; from salivary glands from vessels in its area of supply; and from the anterior two-thirds of the tongue. Its *motor component* supplies muscles of mastication and tensors of the soft palate and tympanic membrane.
6. *Abducens* (CN VI; Somatic Motor) innervates the lateral rectus muscle of the ipsilateral orbit, which helps in the precise movement of the eye for visual tracking or fixation.
7. *Facial* (CN VII; Motor, Sensory, and Special Sensory) receives sensory impulses from the anterior two-thirds of the tongue (taste), soft palate (taste), and nasopharynx (taste), and sends motor impulses to the face, lips, and the stapedius muscle of the middle ear. Unilateral damage to the motor function can affect articulation (mild), and bilateral damage to the motor function can affect articulation (moderate to severe), prosody (slow rate), and facial expression (pragmatics).
   a. *Motor supply* to muscles of the face, scalp, auricle, buccinator, stapedius, stylohyoid, and posterior belly of the digastric; controls facial expression and assists in regulating movements required in speech and mastication.
   b. *Secretomotor* to the submandibular and sublingual salivary glands, to lacrimal glands, and to glands of the nasal and palatine mucosa.
   c. *Special sensory* taste fibers from the anterior two-thirds of tongue (via the chorda tympani) and soft palate (via the greater petrosal nerve).
8. *Vestibulocochlear* (CN VIII) contains a vestibular branch and a cochlear branch. The vestibular branch receives sensory impulses from the vestibular apparatus of the inner ear (responsible for equilibrium or balance) and forwards those impulses to the cerebellum and other areas to help maintain balance. The cochlear branch of this nerve receives sensory impulses from the cochlea of the inner ear (responsible for sound sensitivity) and forwards those impulses to the cochlear nuclear complex in the CNS.

After leaving the cochlear nuclear complex, most fibers then decussate and move to the superior olivary complex, which in turn sends the fibers to the medial geniculate body in the thalamus. The thalamus then sends the fibers to Heschl's gyrus (primary hearing center) in the temporal lobe of the cortex.

Unilateral damage that completely destroys the cochlea, auditory nerve, or cochlear nuclei will typically result in total deafness in that ear. Unilateral damage in the ascending auditory pathways and in the auditory cortex can result in impaired hearing but not total deafness because of bilateral auditory pathways. Hearing acuity problems can indirectly affect the speaker's loudness modulation, articulation, and prosody.

Unilateral or bilateral damage in Heschl's gyrus can result in auditory agnosia, a perceptual problem where the individual has difficulty recognizing and identifying sounds in the

environment, including speech. Auditory agnosia is not due to hearing loss (hearing acuity is normal), nor aphasia (reading comprehension and oral and written expression are normal).

9. *Glossopharyngeal* (CN IX; Motor, Secretomotor, Special Sensory, and Sensory) receives sensory impulses from the posterior third of the tongue (taste and sensation) and from the pharynx, and sends motor impulses to the pharynx for dilation, contributing to the elevation and closure of the pharynx and larynx during the act of swallowing. CN IX works along with CN X, which has predominant control over laryngeal and pharyngeal sensory and motor function. Therefore, information concerning the effect on the speech mechanism is indicated under CN X.
   a. *Motor supply* to stylopharyngeus; may help innervate pharyngeal muscles.
   b. *Secretomotor* fibers promote parotid secretion and activity of mucous glands in territory of supply.
   c. *Special sensory* is the nerve of taste for posterior third of the tongue, including numerous taste buds in vallate papillae.
   d. *Sensory* fibers convey ordinary sensation from pharynx, pharyngeal part of tongue, fauces, tonsil, tympanic cavity, auditory tube, and mastoid cells. Chief nerve supply of carotid body and sinus.
10. *Vagus* (CN X; Motor, Sensory, and Special Sensory) receives sensory impulses from the larynx, pharynx, soft palate, and thoracic and abdominal viscera, and sends motor impulses to the larynx, pharynx, soft palate, and visceral organs. Unilateral damage to the motor function can affect phonation (reduced loudness, short phrases, breathiness, reduced pitch range, hoarseness, diplophonia), resonance (mild hypernasality, nasal emission), and prosody (short phrases). Bilateral damage can affect phonation (short phrases, reduced loudness, breathiness, aphonia, inhalatory stridor, hoarseness, reduced pitch range), resonance (moderate to severe hypernasality, nasal emission), articulation (weak pressure consonants), and prosody (short phrases, slow rate).
   a. *Motor* fibers innervate intrinsic laryngeal muscles and help to supply pharyngeal constrictors. Provide parasympathetic supply to heart and its vessels, to trachea and bronchi, to alimentary canal from pharynx almost to left colic (splenic) flexure and to its associated glands.
   b. *Somatic sensory* fibers supply meninges of posterior cranial fossa and parts of auricle, external acoustic meatus, and tympanic membrane.
   c. *Special sensory* fibers carry some taste impulses from epiglottis and valleculae.

The vagus is sometimes called a *vagabond*, because of its travels from the brainstem around the thoracic cavity. The anatomy of the vagus falsifies the neurochronaxic theory of phonation, introduced in 1950 by Raoul Husson (Weiss, 1959). According to this theory, a vibratory cycle is initiated by a separate nerve impulse to the vocalis muscle via the recurrent laryngeal branch of the vagus nerve. The frequency of one's voice would depend upon the rate of impulses delivered. Because the recurrent laryngeal branch has to loop around the aorta, it is longer on the left side, so bilateral innervation to the left and right portions of the vocalis muscle would be out of phase.

11. *Spinal accessory* (CN XI) contains a spinal and cranial root. The spinal portion sends motor impulses to the neck and the shoulder. Unilateral or bilateral damage to the motor function can cause neck turning and shoulder elevation problems, which may indirectly affect respiration, phonation, and resonance. The cranial portion sends motor impulses to the soft palate, pharynx, and larynx. CN XI works along with CN X, which has predominant control over palatal, pharyngeal, and laryngeal motor

function. Therefore, information concerning the effect on the speech mechanism is indicated under CN X.

12. *Hypoglossal* (CN XII) receives sensory and taste impulses from the tongue, and sends motor impulses to the tongue. Unilateral damage to the motor function can affect articulation (mild). Bilateral damage can affect articulation (mild to severe) and prosody (slow rate). Descending branch (not connected to hypoglossal nucleus) consists of fibers from C1, which join fibers from C2 and C3 to form ansa cervicalis; ansa supplies twigs to sternohyoid, sternothyroid, and omohyoid muscles.

The 12 cranial nerves, their general function, and, if damaged, their effects on the respiration, phonation, resonance, articulation, and prosody components of speech production are listed in **Table 2.1**. An old jingle to help remember the cranial nerves is "On old Olympus'

TABLE 2.1

The 12 Cranial Nerves and, If Damaged, Their Effect on Speech Production

Cranial Nerve		Function	Effect on Speech Production
I	Olfactory	s: smell	____
		m: ____	____
II	Optic	s: vision	____
		m: ____	____
III	Oculomotor	s: ____	____
		m: eye movement	____
IV	Trochlear	s: ____	____
		m: eye movement	____
V	Trigeminal	s: jaw, lips, face, tongue	Indirect—articulation
		m: jaw	Articulation, prosody
VI	Abducens	s: ____	____
		m: eye movement	____
VII	Facial	s: tongue, soft palate, nasopharynx	____
		m: face, lips, stapedius (middle ear)	Articulation, prosody, facial expression
VIII	Vestibulocochlear	s: vestibular—balance	____
		s: cochlear—hearing	Indirect—loudness, modulation, Articulation, prosody
		m: ____	____
IX	Glossopharyngeal	s: tongue, pharynx	____
		m: pharynx[a], larynx[a]	Phonation, resonance
X	Vagus	s: larynx, pharynx, soft palate, thoracic and abdominal viscera	____
		m: larynx, pharynx, soft palate	Phonation, resonance, articulation, prosody
XI	Spinal accessory	s: ____	____
		m: spinal—neck, shoulder	Indirect—respiration, phonation, resonance
		m: cranial—soft palate[a], pharynx[a], larynx[a]	phonation, resonance
XII	Hypoglossal	s: tongue	____
		m: tongue	Articulation, prosody

Note: s = sensory, m= motor.

[a]Along with cranial nerve X.

towering tops, a Finn and German viewed some hops." The first letter of each word represents the first letter of each name of the cranial nerves. Actually, the name change of CN VIII (from "acoustic" to "vestibulocochlear") means that the word "and" in the jingle above needs to be changed to a word beginning with "v." There is also a much racier version, which we will not print here.

The Neurosensory System

The neurosensory system is found in all the major levels of the human nervous system. Of vital importance for speech and hearing are the sensory pathways of general somatic functioning, the cranial nerves, vision and hearing, and the control circuits.

The General Somatic Pathways

The general somatic (pain, touch, temperature, and proprioception) sensory pathways dealing with the limbs and the trunk employ the spinal cord and spinal nerves. The somatic sensory pathways involved with the head and speech mechanism employ the cranial nerves (except for the process of respiration, which employs the spinal nerves). The sensory impulse from the periphery (e.g., skin of the arm or leg) is mediated and passed to the spinal nerves through the dorsal (posterior) portion of the cell body. From there, the sensory impulse moves through spinothalamic tracts to the thalamus, then through thalamocortical tracts to the internal capsule, and then onto the somatosensory area of the parietal lobe (postcentral gyrus, or "sensory strip" area). Sensory information about proprioception is needed so that adjustments and compensations can take place when necessary (e.g., speaking immediately after dental work, talking with food in your mouth, talking after biting your tongue or cheek, etc.).

The Vision and Hearing Pathways

The neurosensory system also contains special pathways used for vision and hearing. The visual system, under the mediation of the optic nerve (CN II), starts with the eye's absorbing light from an image, then sends the image through to the pupil. The image is then inverted and reversed as it travels into the lens. The lens focuses and projects the light onto the retina, which is a formation of nerve cells lining the inside of the eyeball. The retina sends the visual impulse to the optic nerve (this can be seen with an ophthalmoscope), which then sends it to the optic chiasma (a junction of the right and left optic nerves). At the optic chiasma, many of the fibers decussate and then move on to the lateral geniculate body of the thalamus, which then sends the fibers through the internal capsule. From there, the visual impulse is sent to the primary center for vision and the visual association areas of the occipital lobe. (Lesions of the optic nerve and the primary visual cortex can result in blindness. Lesions in the visual association cortex can result in visual perceptual problems [visual agnosia], and play a role in reading comprehension deficit [alexia].)

The neurosensory pathway used for hearing has already been noted in the section dealing with cranial nerves (under CN VIII). It is apparent that auditory and visual information is vital for the production of speech and language. The auditory system is crucial, and the visual system is quite important, in the acquisition of speech and language. The auditory system helps maintain these faculties throughout life.

The Control Circuits

The neural information that the basal ganglia and cerebellar control circuits give to the direct and indirect activation systems for their functioning rely on the masses of constant and instantaneous sensory information received from the periphery (e.g., proprioception).

The Autonomic Nervous System

The autonomic nervous system (ANS), which controls involuntary activity of the body, consists of a sympathetic and a parasympathetic division. The ANS is self-regulating and is present throughout the CNS and the PNS.

The sympathetic division is responsible for such activities as speeding up the heart rate, constricting the peripheral blood vessels, elevating blood pressure, raising the eyelids, redistributing blood, dilating the pupils, and decreasing contractions of the intestines. This division makes internal adjustments and alerts the body to cope with stress and crises (e.g., dilates the pupils of the eyes to allow more light to enter for better sight, distributes blood from the intestines to the skeletal muscles for strength, etc.).

The parasympathetic division is responsible for such activities as slowing down the heart rate, increasing contractions of the intestines, increasing salivation, and increasing secretions of the glands in the gastrointestines. This division is responsible for reducing internal activity and calming down the body (e.g., for digestion and bowel movement, sexual activity, etc.).

The ANS works along with the endocrine system (glands and other structures that release internal secretions called hormones) to maintain homeostasis (stability of the body's internal environment). All activity to maintain homeostasis is regulated by the hypothalamus in the CNS.

The ANS has an indirect effect upon speech and language, such as the nervousness (blushing, blanching, heart pounding, sweating, dry mouth, or jittery stomach) that one may feel before, during, or after certain speaking situations (e.g., speaking before an audience, a marriage proposal, playacting in a speaking role, social conversation during a blind date, etc.).

The Triune Brain

The triune brain is an integration–elaboration concept of neuroevolution. The brain, according to McLean (1978), is composed of *three* brains, only one of which, the neocortex, is responsible for human walking and talking behaviors. Each brain represents a major evolutionary stage and may be differentiated neuroanatomically and functionally.

The *neural chassis*, the foundation for the three brains, is the oldest part. It is composed of the spinal cord, medulla, and pons (hindbrain), and the midbrain. Basic neural mechanisms for reproduction and self-preservation, including regulation of the heart, circulation, and respiration, are contained here. The neural chassis represents almost all of the brain in a fish or amphibian.

According to McLean, this neural chassis has three drivers:

R-Complex: This is composed of the olfactostriatum, corpus striatum, and globus pallidus. It is important in aggressive behavior, territoriality, ritual, and in the establishment of social hierarchies.

Limbic System: This includes the olfactory cortex, thalamus, hypothalamus, amygdala, pituitary gland, and hippocampus. It is involved in generating strong emotions (as opposed to the reptilian mind). Rage, fear, or sentimentality have been observed in malfunctions of the limbic system. The beginnings of altruistic behavior may be here. Emotional aspects of smell (olfactory cortex), remembering and recall (hippocampus), oral and gustatory functions, and sexual functions are also related to the limbic system.

Bhatnagar (2008) has noted that the major structures of the limbic system are the amygdale, the hippocampus, the septal nuclei, and the cingulated gyrus. The only structure not involved in memory and learning is the cingulated gyrus. The limbic system regulates emotion, motivation, learning, and memory. Limbic projections to the forebrain contribute to emotions and provide motivation for behaviors that are fundamental to survival (feeding,

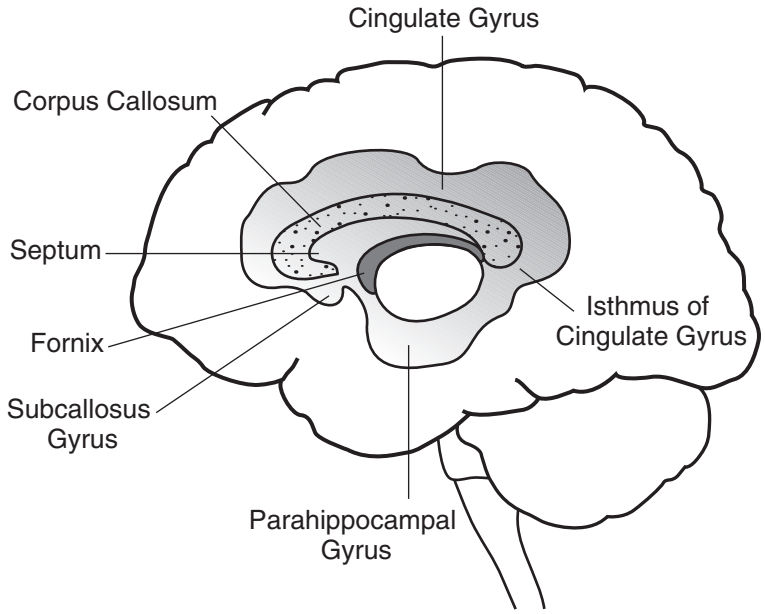

Figure 2.15 Midsaggital view showing the limbic structures.

mating, aggression, and flight). With connections into the prefrontal lobe and hippocampus, the limbic structures also participate in memory and learning (see **Figures 2.15** and **2.16**).

Neocortex: This includes the frontal, parietal, temporal, and occipital lobes. It mediates characteristically human cognitive functions. The various subdivisions may have different functions and some may share functions.

a. *Frontal lobes*: deliberation and regulation of action.
b. *Parietal lobes*: spatial perception and the exchange of information between the brain and the rest of the body.

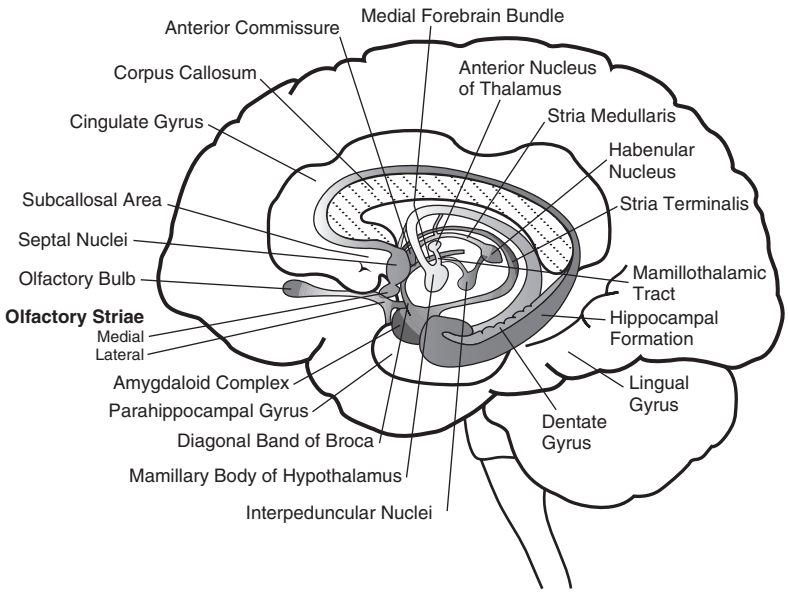

Figure 2.16 Medial view of the major limbic structures and their connections.

c. *Temporal lobes*: complex perceptual tasks.
d. *Occipital lobes*: vision, the dominant sense in humans and other primates. Frontal lobes may have been responsible for the human bipedal posture, which, in turn, freed our hands and mouths. Sections of the frontal lobes and the temporoparietal region in conjunction with various thalamic nuclei are responsible for spoken language.

Integration–Elaboration Concept

The triune brain model suggests the progressive incorporation of lower brains by higher ones and the subsequent control, modification, and elaboration of all behaviors associated with earlier or lower brains by the highest or latest-to-evolve brain.

Reflexization of Movement

Reflexes form the basis of voluntary movements. Basic respiratory activities of coughing, sobbing, sighing, and yawning; the laryngeal or glottic closing reflex; the rooting reflex; the lip reflex; the mouth-opening reflex; basic biting, suckling, chewing patterns; and suckling, swallowing, pharyngeal, palatal, and yawn reflexes may all be viewed as precursory patterns to prelinguistic phonatory and articulatory patterns, and, finally, to skilled speech movements.

That is, from these basic reflexive movements emerge, respectively, skilled movements necessary for speech breathing; speech voicing; speaker-listener postural attitudes; labial sounds; mandibular sounds; linguadental, lingua-aleolar, linguapalatal, and linguavelar sounds; and for producing nasal/non-nasal sound distinctions.

Phylogenesis of Humans and Speech

Speech phylogenesis is related to the development of the bipedal posture, manual dexterity, the liberation of the mouth from use in crude grasping and manipulative activities, and the development of the communisphere. The ontogenetic reflection of this phyletic heritage is noted when observing the development of true speech in the infant. True speech development in the infant approximately co-occurs with the development of bipedal head, neck, and trunk balance; the use of a preferred hand; the integration of various cranio-oropharyngeal reflexes such as protective, feeding, and emotional reflexes; and the growing need to communicate.

Advanced Study

Translational research refers to original investigations in the broad fields of laboratory, clinical, and public health research, and is interdisciplinary and cross disciplinary in scope. The goal is to expedite the translation of scientific discovery into new or improved standards of care. Some medical journals devoted to translational research began publishing articles in this field more than 10 years ago.

Our profession is somewhat behind the curve with regard to translational research, although there certainly have been efforts in this direction by individuals. The term "aphasiologist" may refer to a physician (usually a neurologist), neurolinguist, neuropsychologist, speech-language pathologist, or other professional. They may have different perspectives on aphasia, but may work together to test hypotheses. For example, localizing brain functions has been typically supported by evidence of shared areas of brain damage in individuals with a similar language deficit, and is sometimes called the "lesion overlap" approach. That is, if there is a functional deficit, then the area of the brain damaged in most of these individuals must have been responsible for that function. When the reciprocal association (the probability that the lesion caused the deficit) is evaluated, then the relationship may not be supported.

Hypoperfusion (reduced blood flow) does not necessarily specify the area of infarct. For example, structural damage or low blood flow in the left posterior inferior frontal gyrus may result in poor drainage into the anterior insula. Reperfusion of the anterior insula will not relieve symptoms of apraxia of speech, a motor programming speech disorder associated with left frontal lobe damage (Hillis et al., 2004).

A recent paper (Goldfarb & Davis, 2010) proposes oceanographic models for measuring regional cerebral blood flow (rCBF). It may be possible to measure blood flow in the middle cerebral artery by applying the acoustic Doppler profiler technique used to measure ocean currents. Accommodations for dune troughs that complicate measurement of ocean currents may provide a model for measuring arterial blood flow, complicated by arteriosclerotic disease.

Clinical Description

One of the authors established a stroke club at a Veterans Administration Extended Care Center. The purpose of the club was to provide communication and recreational opportunities for a group of people with aphasia and dysarthria who were no longer eligible for traditional speech-language therapy. About 20–30 men (very few women were patients in the facility) attended a 2-hour meeting each week, while their caretakers were invited to attend a support group led by an SLP and a clinical psychologist.

Accommodating a large group of wheelchair-borne individuals threatened to become a demolition derby. Even though all furniture was cleared out of the waiting room, the men with left-hemisphere CVA (and right-homonymous hemianopsia) often bumped their wheelchairs into those of the men with right-hemisphere CVA (and left visual field neglect). Seating was arranged in several small circles, with chairs set at about 45-degree angles from each other. (See the following chapter for a transcript and analysis of a conversation between one stroke club member with fluent aphasia and another with nonfluent aphasia.)

Food and drinks had to be sugar-free (for those with Type II diabetes) and salt-free (for those with hypertension), and closely monitored for those individuals with dysphagia. Many of the individuals with difficulty or pain/discomfort when swallowing did not cough when fluids escaped into the trachea, nor did they exhibit a gurgly voice when food or fluids escaped into the valleculae. These "silent aspirators" in particular needed supervision for each swallow.

Among the humbling experiences the authors can report in their many years of clinical intervention, one remains crystal clear. The wife of one of the veterans asked to speak to the author privately, as she did not want to raise this issue in the communication support group for caretakers. The conversation went something like this (W is the wife and A is the author):

W: This is uncomfortable for me to say, but I'm having problems with marital relations with my husband.

A: That's not at all unusual. Let me refer you to the urologist in the hospital.

W: No, no, he's functioning fine.

A: It's not at all unusual for there to be anxiety. Would you like to talk to Dr. P., the psychologist in our support group?

W: No, no, it's about communication.

A: (Realizing there is no longer any way he can pass this along) OK, I'm listening.

W: When we had relations before, he always used to say the most wonderful things to me, but now that he can't talk, it feels so different.

A: There are many ways to communicate. Sometimes a gesture or a facial expression can be as meaningful as a word.

W: But I can't see any of that when it's completely dark in the room.

Sometimes the job of the SLP is to help the patient and communicative partner turn on the light of communication, either figuratively or, as in the present example, literally.

Discussion Questions: Theory

1. What is involved in responding to auditory feedback from oneself or from others?
2. How is information transmitted to and away from a brain cell body?
3. What are some multipotential functions of glial cells?
4. How does the anatomy of the vagus nerve (CN X) falsify the neurochronaxic theory of phonation?
5. Use the triune brain model to explain how an infantile suckle reflex may be integrated and elaborated to become /w/ and /u/ sounds in healthy speakers, but released following brain trauma.

Discussion Questions: Therapy

1. How does language improvement in spontaneous recovery from stroke occur?
2. How does language therapy for aphasia facilitate rewiring of brain connections which have been "stunned" following a stroke?
3. A major goal of Lee Silverman Voice Therapy (LSVT) is to have the individual with Parkinson disease think about speaking loudly. How is the brain involved in achieving this goal?
4. Speech therapy for individuals with dysarthria often focuses on improving precision of articulation by developing procedural or muscle memory. What is the neural mechanism underlying this therapy?
5. Augmentative/alternative communication devices using eye tracking may be effective when used with an individual with "locked-in syndrome" following a brainstem stroke. These devices may have been helpful for the late Jean-Dominique Bauby, whose case of locked-in syndrome was described in *The Diving Bell and the Butterfly*. Explain how cranial nerves involved in moving the eyeballs may still function following brainstem stroke.

Assignment: Write a multiple-choice question with five options. Explain why the key option is correct, and why the distractors or decoys are incorrect. Avoid using forms such as, "All of the following are (in)correct *except*" in the stem, and "All (or none) of the above" in the options.

Example: After a CVA (stroke), some cells, not seriously damaged, may respond to natural recovery processes and survive: organelles resume their normal appearance (swelling recedes), and the nucleus assumes a central location. This process follows:

a. Wallerian degeneration
b. Neuroglial responses
c. Stenosis
d. Stunning
e. Axonal reaction

The correct answer is *d*: stunning is associated with spontaneous recovery; *a* is incorrect because, in a Wallerian reaction, there is degeneration of the axonal part that is separate from its cell body; *b* is incorrect because glial cells displace presynaptic and postsynaptic terminals and cell bodies, impairing transmission between neurons; *c* is incorrect because stenosis relates to narrowing of arteries; *e* is incorrect because damaged neurons do not reconnect to the distal axonal segments to reinnervate their target structures.

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