Chapter 2
Functional Neuroanatomy

The way structures in the developing brain are related to changes in psychological and cognitive development is of interest to child neuropsychologists. There are several ways that this relationship can be explored, including: (1) correlating structural changes in the developing brain with behavioral changes, (2) investigating behavioral changes and making inferences about structural maturation of the brain, and (3) studying brain dysfunction and its relationship to behavioral disorders (Kolb & Fantie, 1989).

Although these approaches can yield useful information about the developing brain, they are not without shortcomings. For example, because of the plasticity of the developing brain following damage, injury in a specific brain region may produce behavioral losses that vary greatly depending on the age of the child. Environmental factors, such as enrichment opportunities and social-cultural experiences, also influence the developing brain and the manner in which behaviors are expressed (Baron, 2004). Thus, the study of the brain-behavior relationship is particularly complex in children, and these factors must enter the equation when drawing conclusions about this relationship. Some have criticized neuropsychological approaches because of the level of inferences made when relating behavior to brain structure and function, and because of the correlational nature of the research (Fletcher & Taylor, 1984). There are now medical technologies and new research protocols that avoid some of these shortcomings. These technologies make it possible to explore the brain during craniotomies under local anesthesia (McDermott, Watson, & Ojemann, 2005), to investigate dendritic morphology with electron microscopic techniques (Scheibel, 1990), to measure sequential brain processing during cognitive tasks using visual evoked potentials (Liotti et al., 2007), and to image the brain while a person is completing a task through functional magnetic resonance imaging (Pliszka et al. 2006).

Our basic understanding of the brain and its relationship to complex human behaviors has been greatly facilitated by technological advances in modern neuroimaging techniques, including computed tomography (CT), magnetic resonance imaging (MRI), regional blood flow (rCBF), and positron-emission tomography (PET). Neuroimaging techniques allow researchers to gather direct evidence linking cognitive, behavioral, and psychosocial disorders to anatomical, physiological, and biochemical processes in the brain (Semrud-Clikeman, 2007). Research findings about the developing brain from these various approaches and methodologies will be used throughout this chapter in an effort to explore the biological basis of childhood disorders. These techniques will be further discussed in Chapter 3. To fully appreciate the brain-behavior relationship in children, an overview of the structure and function of the brain is necessary. This chapter reviews the structures and functions of the neuron and the sub-cortical and cortical regions from a neurodevelopmental perspective. This review serves as a foundation for exploring the complex interaction between anatomical development of the brain and the emergence of childhood behaviors and disorders.

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Structure and Function of the Neuron

The neuron, the basic cellular structure of the nervous system, transmits nerve impulses throughout a complex network of interconnecting brain cells. The brain contains approximately 180 billion cells, 50 billion of which transmit and receive sensory-motor signals in the central nervous system (CNS) via 15,000 direct physical connections (Carlson, 2007). Investigation of the structure and function of neurons and their synaptic connections provides insight into basic psychopharmacology at the molecular level and may provide a method for describing how various neuropsychiatric disorders emerge and progress (Pliszka, 2003).

The CNS is comprised of two major cell types, neurons and neuroglia (Carlson, 2007). While neurons conduct nerve impulses, the neuroglia ("nerve glue") provide structural support and insulate synapses (the connections between neurons). Glial cells make up about 50 percent of the total volume of the CNS. Glial cells serve various functions, including transmission of signals across neurons, structural support for neurons, repair of injured neurons, and production of CNS fluid (Carlson, 2007). Neuroglia infiltrate or invade surrounding tissue in both the gray and white matter, and in rare instances these cells replicate uncontrollably during tumor activity (Nortz, Hemme-Phillips, & Ris, 2007). Though still relatively infrequent, pediatric brain tumors are the second most common neoplasm in children under 15 years of age, and as many as 1,000–1,500 cases are estimated to occur each year (Sklar, 2002).

Gray matter is located in the core of the CNS, the corpus striata at the base of the right and left hemispheres, the cortex that covers each hemisphere, and the cerebellum (Carlson, 2007). The cell bodies, the neuroglia, and the blood vessels that enervate the CNS are gray-brown in color and constitute the gray matter. White matter covers the gray matter and long axons extending out from the neuron. Axons are generally covered by a myelin sheath, which contains considerable amounts of neuroglia and appears white upon inspection. White matter has fewer capillaries than gray matter (Carlson, 2007).

As the basic functional unit of the CNS, the neuron transmits impulses in aggregated communities or nuclei that have special behavioral functions. Neurons can be modified through experience, and they are said to learn, to remember, and to forget as a result of experiences (Hinton, 1993). Pathological changes in neurons can occur as a result of early abnormal experiences. Although these alterations are thought to have a profound effect on the mature organism, the exact nature of these changes is still under investigation. Genetic aberrations also play a role in the way neurons develop and function (Cody et al. 2005). Damage to or destruction of neurons is also of concern because neurons typically do not regenerate (Swaiman, Ashwal, & Ferriero, 2006). Neurodevelopmental disorders and issues related to recovery of function following brain trauma will be discussed in detail in later chapters (see Chapter 10).

Anatomy of the Neuron

The neuron contains four well-defined cellular parts, including the cell body, dendrites, axons, and axon terminals. The cell body, or soma, is the trophic or life center of the neuron (see Fig. 2.1). Cell bodies vary in size and shape and contain the ribonucleic acid (RNA) and deoxyribonucleic acid (DNA) of the neuron. RNA, the site of protein synthesis, transmits instructions from DNA directing the metabolic functions of the neuron. Biochemical processes of the neuron, which take place in the cytoplasm of the cell body, include the energy-producing functions, the self-reproducing functions, and the oxidating reactions, whereby energy is made available for the metabolic activities of the cell (Carlson, 2007). Destruction or damage to the cell body can result in the death of the neuron.

Dendrites branch off the cell body and receive impulses from other neurons (Carlson, 2007). Dendrites are afferent in nature and conduct nerve impulses toward the cell body. Dendritic spines are the major point of the synapse, the area of transmission from one cell to another. Individuals with cognitive retardation have fewer spines or points of contact across neurons (Klein-Tasman, Phillips, & Kelderman, 2007). Dendrites can transmit neuronal impulses across neurons through either temporal or graded potentials. In

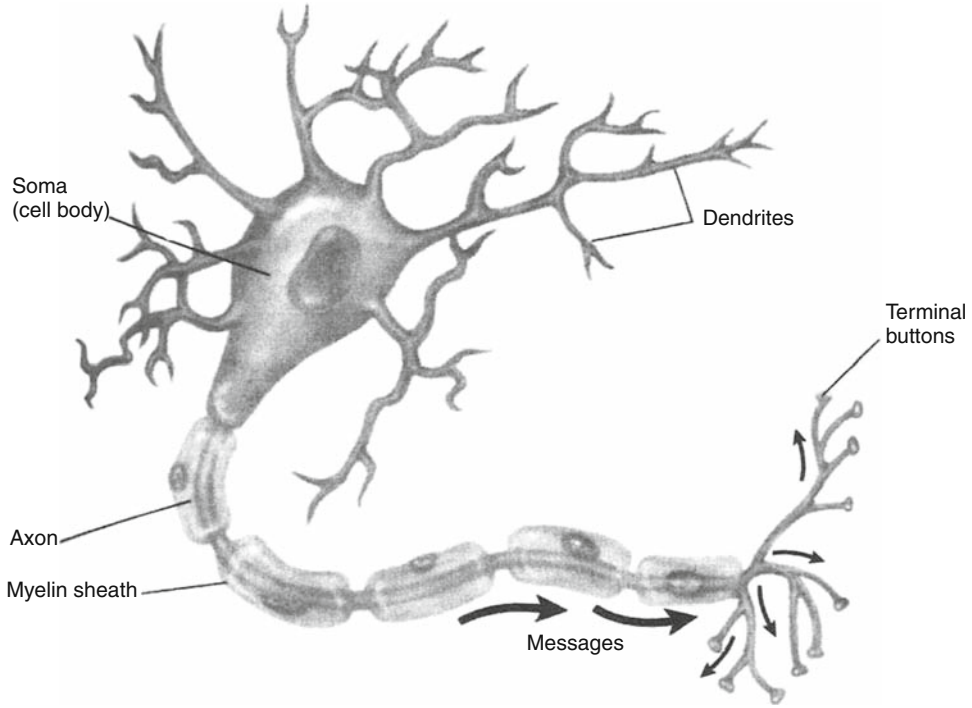

Fig. 2.1 Anatomy of the Neuron
Source: From Neil R. Carlson, *Physiology of Behavior*, 5th edition, p. 21. Copyright © 1994 by Allyn and Bacon. Reprinted by permission

this case, as a neuron receives an impulse it can transmit this impulse if the stimulation is close in time to another impulse or if it is strong enough combined with a previous impulse.

The axon is a long projection or axis from the cell body. Most neurons have only one axon, usually efferent in nature, that conducts nerve impulses away from the cell body. Axons are typically longer than dendrites and can be as much as one yard in length. For example, giant pyramidal cells in the motor cortex send axons to the caudal tip of the spinal cord. The axon hillock is a slender process close to the cell body where action potentials arise. The axon hillock is highly excitable and is activated through electrochemical processes, thereby "turning on" the neuron (Carlson, 2007). The impulse must be of sufficient strength for the neuron to "fire." Axons follow an "all or nothing" rule; if the impulse is not strong enough the neuron will not fire and, thus, will not transmit the message to another neuron. After the neuron fires, there is a period of time when it will not fire again as the neuron "recovers."

Axons are covered by a myelin sheath made up of neurilemma (or Schwann cells), which surround the axon. The myelin sheath gives the axon a white appearance and constitutes most of the white matter in cortical and subcortical areas. Most axons are myelinated at birth particularly in areas necessary for survival (motor-sucking; tactile sensitivity to hot, cold, and pain; auditory, and vision). Some axons continue to myelinate throughout development with myelinization not complete in the frontal lobes until well into the third decade of life. Changes in postnatal brain weight are generally related to increases in dendritic connections and to increases in the number of glial cells that form the myelin sheath along the axon (Shepherd, 2004).

Axons allow the nerve cells to transmit impulses rapidly, particularly along the Nodes of Ranvier. The Nodes of Ranvier are gaps in the myelin and during cell activation, nerve impulses skip from node to node. Myelinated axons permit more rapid transmission of signals, and anesthetics seem to be more effective at the Nodes of Ranvier. The terminal branches of the axon end at the synaptic telodendria.

The presynaptic and postsynaptic sites are both referred to as the synapse. Synapses are specialized for the release of chemicals known as neurotransmitters. Neurotransmitters are released from synaptic knobs at the end foot of the neuron in the presynapse, and they activate neurons at the postsynapse. Neurotransmitters are released from the presynapse (neuron A), travel across the synaptic cleft, and influence the activity of the adjoining neuron (neuron B) (see Fig. 2.2 for a depiction of these activities). There is a collection of vesicles at the synaptic knob at the end of each synapse, where neurotransmitters are stored. Most neurons have thousands of synapses, and each dendritic spine serves as a synapse that is excitatory in nature, which causes neurons to fire. Synapses are quite large for motor neurons and are smaller in the cerebellum and other cortical regions. Synapses usually occur between the axon of one cell and the dendrite of another (axondendritic connections). Although they can connect onto the soma or cell body of another neuron (axosomatic connection), synapses rarely occur from axon to axon (axo-axonal connections).

Types of Neurons

There are two basic types of neurons: efferent and afferent. Efferent neurons originate in the motor cortex of the CNS, descend through vertical pathways into subcortical regions, and culminate in the body's muscles (Gazzaniga, Ivry, & Mangun, 2002). These large descending tracts form columns from the motor cortex connecting higher cortical regions through the brain stem and spinal cord, to the body for the activation of single muscles or muscle groups. Various motor pathways begin to develop prenatally, while postnatal development is marked by changes in primitive reflexes (the Babinski reflex) and automatic reflexes (head and neck righting) (Swaiman et al., 2006).

Afferent neurons, sensory receptors found throughout the body, transmit sensory information into specific cerebral areas. For example, afferent neurons consist of rods and cones (cells that convey information about color or black/white) in the visual system that project into the occipital cortex; hair cells (convey information about tone) in the auditory

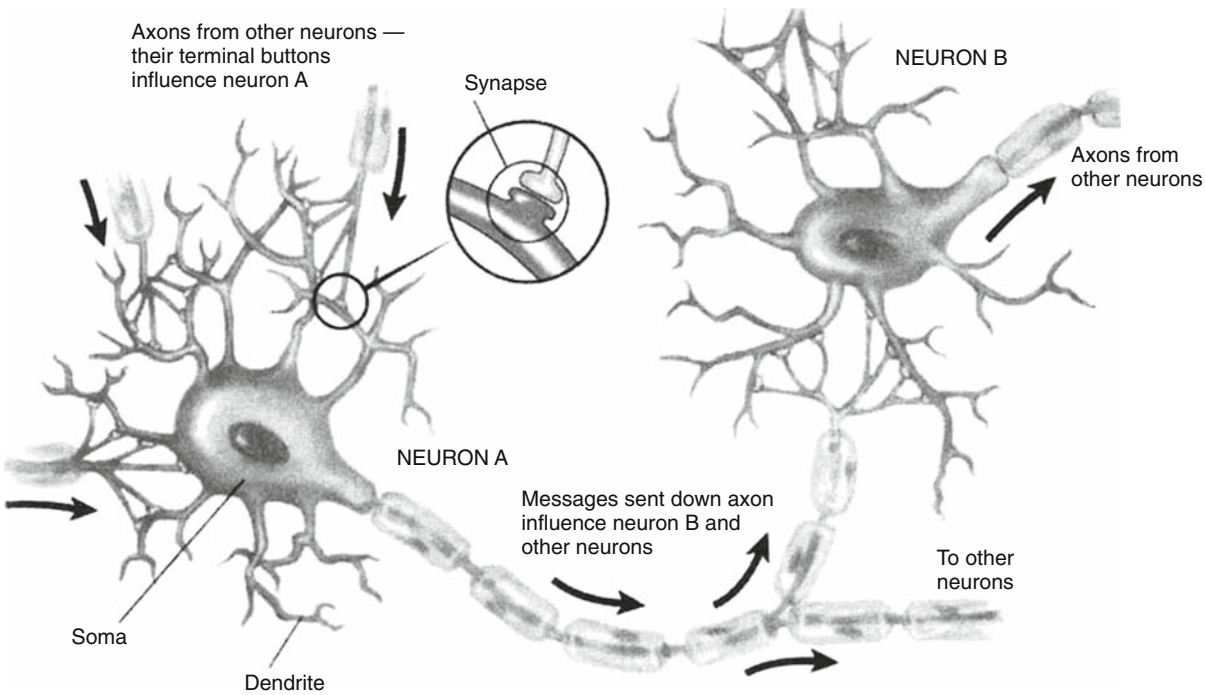

Fig. 2.2 Anatomy Showing Connections between Neuron A and B with Synaptic Cleft
Source: From Neil R. Carlson, *Physiology of Behavio*r, 5th edition, p. 23. Copyright © 1994 by Allyn and Bacon. Reprinted with permission

system that project into the temporal cortex, and pain, touch, temperature, and pressure sensors in the skin that project into the parietal cortex. Somesthetic senses are the first to become functional in the fetus, as early as 7–8 weeks gestation, while auditory and visual neural maturation occurs later in embryonic development (Gazzaniga et al., 2002). Other cells in the corpus callosum (a large bundle of fibers connecting the two hemispheres) and the frontal lobes do not become fully functional until the teenage years through the 20s.

Types of Neuroglia

The neuroglia cells serve a number of important functions in the CNS: (1) providing structural support to neurons; (2) aiding in the regeneration of injured nerve fibers; (3) occupying injured sites by producing scar tissue, and (4) transporting gas, water, and metabolites from blood, and removing wastes from nerve cells (Carlson, 2007). The three major types of neuroglia (astrocytes, oligodendroglia, and microglia) have distinct functions and serve multiple purposes in the CNS. Astrocytes have three primary functions: (1) forming the blood-brain barrier; (2) supporting the cellular structure of the brain, and (3) directing the migration of neurons during early development. Astrocytes are the largest in size and the most abundant type of neuroglia (Carlson, 2007). These star-shaped glial cells attach to capillary blood vessels and cover approximately 80 percent of each capillary. Astrocytes, found primarily in the pia matter (fine membrane on the surface of the brain), cover large blood vessels. When injury occurs to the spinal cord or to the brain, through either disease or trauma, astrocytes go into hypertrophy (Morris, Krawiecki, Kullgren, Ingram, & Kurczynski, 2000). These cells multiply quickly, forming a glial scar that fills in gaps in the cellular structure caused by injury. Astrocytes may also serve a phagocytic function by removing destroyed tissue and cleaning up the site of injury. Astrocytoma, a type of primary neoplasm that frequently reoccurs after surgery, is the second most common brain tumor in adults (Hunter et al., 2005); though rare, astrocytomas do occur in children as well.

Astrocytomas in childhood most frequently occur in the cerebellum and the brain stem. These tumors are found equally in males and females. Although astrocytomas can occur at any age, the most frequent incidence is between five and nine years of age (Hunter et al., 2005). Oligodendroglia cells form and maintain the myelin sheath and, when injured, swell in size. Tumors rarely occur in oligodendroglia cells; when they do they grow slowly and are found primarily in the cortex and white matter. While about 40–60 percent of these tumors can be detected by skull X-rays after they calcify (Cohen & Duggner, 1994), radionuclide brain scans, angiography, and computed tomography scans have been helpful in the diagnostic phase of tumor processes. Finally, microglia cells are predominantly found in the gray matter (Carlson, 2007). Following disease or injury, microglia proliferate, move to the site of injury, and perform a phagocytic function by cleaning up damaged tissue. Tumors rarely occur in microglia cells.

These cells develop at different rates depending on location in the brain, experience of the baby, and genetic programming. In order to understand difficulties children have in development it is first important to understand how a typical brain develops. The following section provides a brief overview of the course of neuronal development.

Spinal Cord

The spinal cord serves two major functions: connecting the brain and the body via large sensory and motor neurons. The spinal cord comprises gray matter and white matter. Gray matter is the central, interior region of the spinal cord and is shaped like a butterfly. It appears gray on inspection and is made up of cell bodies. Neurons leave the spinal cord in segments called dermatomes and enter into muscles and organs. Motor commands from higher cortical centers are conducted at these sites. Sensory receptors connect with motor neurons in the gray matter of the spinal cord, via interneurons. Interneurons remain in the spinal cord and mediate motor activity with sensory stimuli. Interneurons also provide for cooperation among different spinal segments, which control distant muscle groups. For example,

interneurons connect cervical and lumbar regions of the spinal cord to coordinate forelimbs and legs for walking. White matter surrounds the gray matter and consists of the myelin sheath (Brodal, 2004).

The spinal cord conducts signals to and from higher cortical regions, including the brain stem, the cerebellum, and the cortex. The posterior root of the spinal cord is afferent in nature, where sensory fibers enter into the gray matter, synapse with other neurons, and ascend into higher cortical areas in pathways. Conversely, the anterior root is efferent in nature and is made up of motor fibers that receive motor signals from higher cortical areas and communicate to muscle groups for movement. Nerve fibers enter and leave the spinal cord at regular intervals (dermatomes) and provide sensory and motor innervation to specific body segments. There are a total of 30 segments innervating the spinal cord: eight cervical, 12 thoracic, five lumbar, and five sacral (Brodal, 2004). Damage to the spinal cord at specific sites produces localized sensory and motor dysfunction in the body.

Unlike the brain, the spinal cord has little diversification or specialization, but it does carry out sensory, motor, and integrative functions. Four such functions are carried out in the spinal cord: (1) reflex activity, whereby a stimulus is followed by a coordinated motor response; (2) reciprocal activity, whereby one activity starts or stops another (i.e., excitatory or inhibitory); (3) monitoring activity, whereby incoming messages are controlled, coded, and transmitted, and (4) transmission activity, whereby messages are transmitted to and from the brain through the white matter (Kolb & Whishaw, 2003). In summary, the spinal cord is one of two major divisions of the CNS; the second is the brain.

Structure and Function of the Brain

The nervous system is divided into two basic systems: the peripheral (PNS) and the central nervous system (CNS). The PNS consists of the spinal, cranial, and peripheral nerves that connect the CNS to the rest of the body. Table 2.1 lists the cranial nerves and their functions. The CNS is completely encased in bone, is surrounded by protective coverings (meninges), and consists of two major structures: (1) the spinal cord in the vertebral column, and (2) the brain within the skull.

Table 2.1 Cranial nerves

Number	Name	Function
I	Olfactory	Smell
II	Optic	Vision
III	Oculomotor	Eye movement
IV	Trochlear	Eye movement
V	Trigeminal	Masticatory movement
VI	Abducens	Eye movement
VII	Facial	Face movement
VIII	Auditory	Hearing
IX	Glossopharyngeal	Tongue and pharynx movement
X	Vagus	Heart, blood vessels, viscera, larynx, and pharynx movement
XI	Spinal Accessory	Strength of neck and shoulder muscles
XII	Hypoglossal	Tongue muscles

Role and Function of the Meninges

Both the spinal cord and the brain are surrounded by a protective layer of tissue called the meninges. The meninges comprise three layers: the dura mater, the arachnoid, and the pia mater. The dura mater is the tough outer layer of the spinal cord and the brain, and has the consistency of a thin rubber glove. The dura mater attaches to the bones covering the cranium and receives blood vessels that innervate the brain (Brodal, 2004). Head injury may form an epidural hematoma, causing blood to accumulate in the region between the skull and the dura mater. The dura mater is supplied with blood by tiny vessels on its outermost layer near the skull. The subdural space, a fluid-filled layer, separates the dura mater from the arachnoid space. Accumulation of blood in the subdural area following injury can put enormous pressure on the brain (Swaiman et al., 2006). The arachnoid, a spiderlike web, is a delicate network of tissue under the dura mater. Blood accumulation between the dura mater and the arachnoid following injury is referred to as a subdural hematoma. Finally, the pia mater is the fragile, innermost layer of the meninges and contains small blood vessels. The pia mater surrounds the arteries and veins that supply blood to the brain; it serves as a barrier keeping out harmful substances that might invade the brain.

Bilateral infections that attack the meninges, referred to as meningitis, can have serious consequences for the developing brain (Swaiman et al.,

2006). The first year of life is the time of greatest risk for meningitis. The earlier the infection occurs, the higher the mortality rate. Some of the long-term consequences of meningitis are mental retardation, hydrocephalus, seizures, deafness, and hyperactivity (Swaiman et al., 2006). Cerebrospinal fluid (CSF), a clear, colorless fluid, fills the ventricles and the subarachnoid space (Wilkinson, 1986). CSF contains concentrations of sodium, chloride, and magnesium, as well as levels of neurotransmitters and other agents. An assay of the composition of these chemicals can be important for diagnosing disease processes. CSF reproduces at such a rate that total replacement occurs several times a day. The choroid plexus, located in the floor of the ventricles, produces the CSF, while the lateral ventricles contain the highest amounts of CSF. Infectious and metabolic disorders, such as meningitis, encephalitis, and tumors, as well as traumatic injury, can cause discernible changes in the CSF.

Cerebrospinal fluid has three major functions. Specifically, it (1) protects against injury to the brain and spinal cord; (2) diffuses materials into and away from the brain, and (3) maintains a "special environment" for brain tissues. Interference in the circulation and drainage of CSF can result in hydrocephalus, which causes cranial pressure. Hydrocephalus can have a devastating affect on the developing brain and may cause cognitive delays, particularly for nonverbal information; emotional, psychiatric, or behavioral disturbances, and slow motor development (Fletcher, Dennis, & Northrup, 2000). Surgical shunting drains CSF outside the skull. Recent advances in microsurgery in utero have produced successful results by reducing some of the more severe long-term negative effects of brain dysfunction or damage that can occur when hydrocephalus is untreated. Residual effects of hydrocephaly, ranging from mild to severe, depend on individual variables including the age of the child at the time of shunting and the presence of other neurological or medical complications that often accompany this disorder (Fletcher et al., 2000).

Ventricles

The ventricles, large cavities filled with cerebrospinal fluid (CSF), reside in various regions of the brain. The fourth ventricle, also referred to as the aqueduct of Sylvius, resides in the brain stem at the level of the pons and the medulla. The third ventricle is located in the diencephalon, and the lateral ventricles

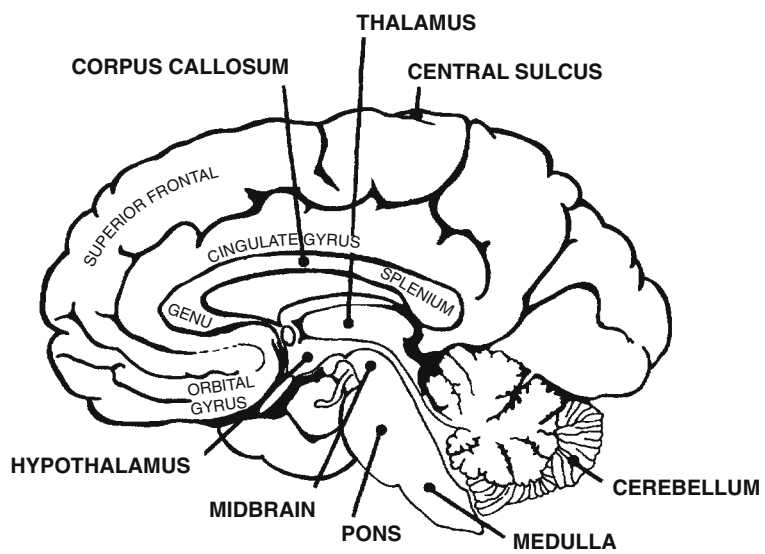

Fig. 2.3 Sagittal Section of the Brain Showing Brain Stem, Midbrain, and Forebrain Structure
Source: Adapted from M. Semrud-Clikeman and P. A. Teeter, "Personality, Intelligence, and Neuropsychology," in D. Saklofske (Ed.), *International Handbook of Personality and Intelligence in Clinical Psychology and Neuropsychology*, copyright © 1995 by Plenum Press, New York

are found in the forebrain region (see Fig. 2.3). Ventricles provide equilibrium as well as the CSF transporting nutrients and wastes throughout the brain. When these ventricles appear enlarged, a diagnosis of a tumor or disease processes, including hydrocephalus, encephalitis, and meningitis, may be made.

Structure and Function of the Brain Stem

The brain stem comprises five areas, including the fourth ventricle, the medulla oblongata, the pons (bridge), the midbrain (mesencephalon), and the diencephalon. Figure 2.4 shows a schematic of these structures and Fig. 2.5 shows a magnetic

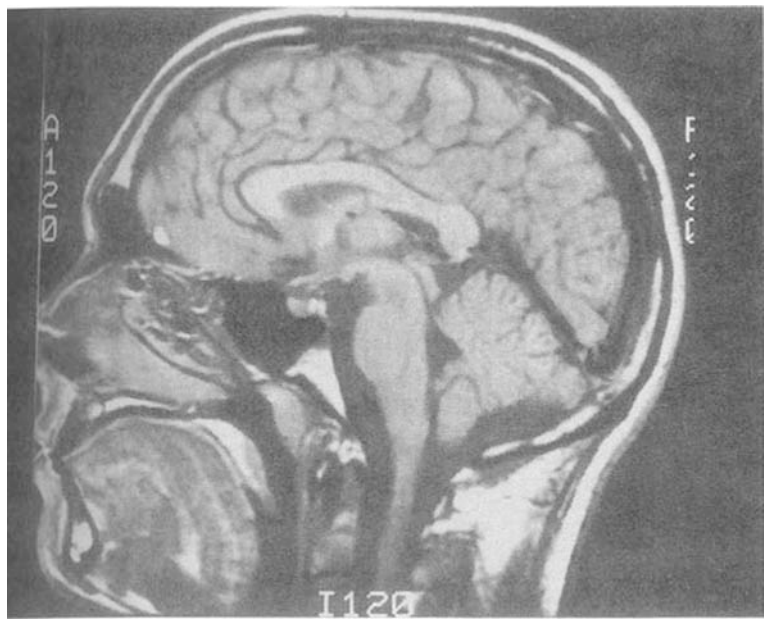

Fig. 2.4 MRI Sagittal Section of CNS Analogous to Brain Areas Depicted in Figure 2.3

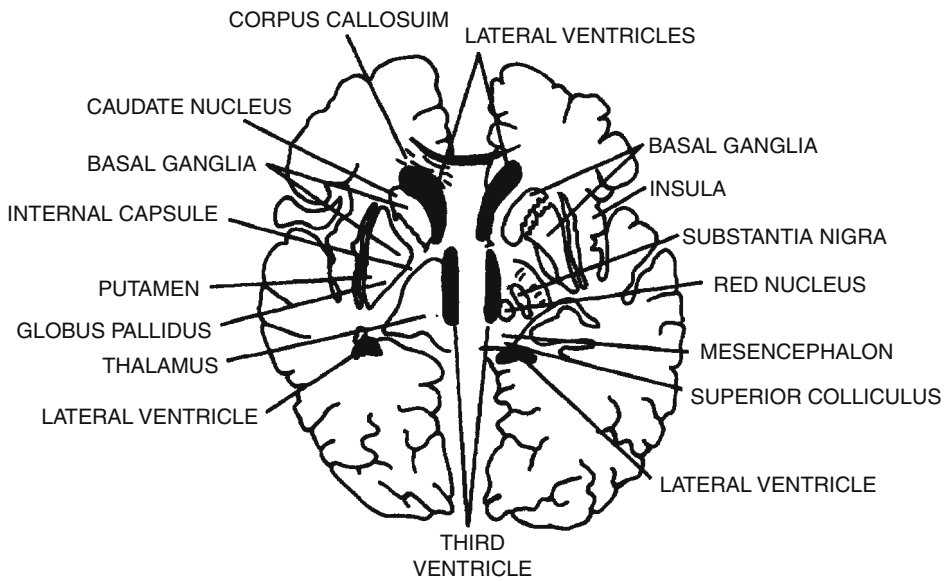

Fig. 2.5 Coronal Section Showing Structures of the Right and Left Hemisphere with Ventricular Systems

resonance image of these same structures. The major regions of the brain stem are discussed in detail in the following sections.

Medulla Oblongata

The medulla is a continuation of the spinal cord and contains nerve tracts similar to those found in the spinal cord. Groups of sensory and motor nuclei are arranged in ascending (i.e., afferent-sensory tracts) or descending (i.e., efferent-motor tracts) cell columns. Projections of the major cranial nerves occur at the level of the medulla, including the hypoglossal (tongue), the glossopharyngeal (pharynx and larynx), and the accessory (neck muscles) nerves. The sensory and motor tracts cross over into the opposite side of the brain at the level of the medulla. The somatosensory (touch, pressure, pain, and temperature) and the motor systems are organized in contralateral fashion, such that sensory information and movement on the right side of the body are primarily controlled by the left hemisphere. Conversely, the left side of the body is controlled by the right hemisphere. The auditory and visual systems also cross in the medulla. These functional systems will be discussed in more detail later in this chapter.

The reticular activating system (RAS) comprises a major portion of the medulla, extends into the midbrain region, and has numerous connections and functions (Brodal, 2004). The RAS, considered the arousal system, plays an important role in maintaining consciousness and attentional states for the entire brain. The RAS has been hypothesized as one of the critical mechanisms involved in ADHD (Sagvolden & Archer, 1989). For example, some RAS functions control blood pressure, blood volume in organs, and heart rate, whereas others regulate sleep and wakefulness.

The RAS receives input from most sensory systems and connects to all levels of the CNS. Because the RAS is directly or indirectly connected to much of the CNS, it can modulate CNS activity. Selective stimuli activate the RAS, which then alerts the cortex to incoming stimuli. Researchers espousing a bottom-up model hypothesize that the RAS may be filtering too much sensory information, thereby not allowing stimulation to reach the higher cortical regions that are necessary for adequate direction and maintenance of attention. When enough information reaches the RAS, it signals the cortex and produces cortical arousal and wakefulness. Thus, in children with ADHD this subcortical filter may not allow sufficient stimuli to reach higher cortical regions. This theory and others will be explored in later chapters.

Secretion of serotonin takes place at the pons, probably in the raphe system. The raphe nuclei are cells located across the medulla, pons, and midbrain regions, with afferent connections to the hypothalamus and limbic system (Brodal, 2004). This region also contains the locus ceruleus (LC), which produces 70 percent of norepinephrine in the brain, and serves as a modulator for other neurotransmitters (Carlson, 2007). The norepinephrine-rich cells in the locus ceruleus connect with the serotonin-rich cells in the raphe nuclei, and each type has a reciprocal affect on the other. Norepinephrine plays a role in vigilance, arousal, filtration of stimuli, and habituation. Finally, the continuation of the RAS at the pontine level appears to mediate sleep.

Serotonin inhibits arousal of the RAS, which then allows the thalamus to bring the cortex to a slow-wave sleep state (Carlson, 2007). Anesthetics appear to depress the RAS, which ultimately depresses the cortex. Fibers in the RAS also project to the limbic system and serve behavioral and emotional mechanisms for the control of pain. Morphine and opiate-like drugs may produce analgesic actions most likely in the raphe system (Shepherd, 2004).

Pons

The pons, between the medulla and midbrain and above the cerebellum, serves as a bridge across the right and the left hemispheres. Major sensory and motor pathways move through the pons, a continuation from the spinal cord and brainstem regions, and enter into higher cortical areas. The pons, in coordination with the cerebellum, receives information concerning movements from the motor cortex and helps modulate movements (Brodal, 2004). Information from the visual cortex is also received at the pontine level, which serves to guide visually

determined movements. Finally, information from the hypothalamus and the limbic system converge in the pons and may influence the impact of emotional and motivational factors on motor activity (Brodal, 2004). A number of cranial nerves converge in the pontine region. Cranial nerves innervating the face and head receive sensory information and transmit signals in the pons for swallowing and chewing (trigeminal nerve), moving facial muscles, and affecting the hearing and equilibrium in the inner ear. Cranial nerves innervating the eye muscles (abducens) also pass through the pons.

Midbrain

The most anterior region of the brainstem is the midbrain or mesencephalon. The midbrain serves a major relay function for sensory-motor fibers. The two major divisions in the midbrain are the tegmentum, which falls below the ventricle and is separated by the substantia nigra, and the tectum, which comprises the superior colliculi (upper region involved in vision) and the inferior colliculi (lower region involved in the integration of auditory and kinesthetic impulses). The RAS also continues into the midbrain region. Several cranial nerves are located in the midbrain region. The oculomotor nerve moves the eye (lateral and downward gaze), and regulates the size of the pupil and the shape of the lens. The trigeminal nerve also resides in the midbrain area and serves as the major sensory nerve of the face.

Diencephalon

The diencephalon, the superior region of the brain stem, contains major relay and integrative centers for all the sensory systems except smell. The diencephalon is not clearly demarcated, but includes the thalamus, the hypothalamus, the pituitary gland, the internal capsule, the third ventricle, and the optic nerve (Brodal, 2004). The thalamus receives input from several sensory sources, including: (1) the visual system (projecting into the lateral geniculate body of the thalamus); (2) the auditory system (projecting into the medial geniculate body), and (3) sensory receptors in the skin for pain, pressure, touch, and temperature.

The hypothalamus, anterior and inferior to the thalamus, plays a role in controlling the autonomic nervous system, including eating, sexual functions and dysfunctions, drinking, sleeping, temperature, rage, and violence. With connections to the limbic system, the hypothalamus influences motivational mechanisms of behavior. The pituitary, following directions from the hypothalamus, secretes hormones that regulate bodily functions. The internal capsule, situated lateral to the thalamus, contains fibers connecting the cortex to lower brain regions including the brainstem and the spinal cord. Major fibers comprise the internal capsule and connect the frontal cortical regions to the thalamus and to the pons. Finally, the optic nerve converges in the diencephalon and forms the optic chiasma (Brodal, 2004). Fibers from the optic nerve cross at the chiasma and project to the lateral geniculate body in the thalamus via the optic tract (Brodal, 2004). Figure 2.6 shows these structures.

Cerebellum

The cerebellum or hindbrain, behind the brain stem, connects to the midbrain, pons, and medulla. The cerebellum receives sensory information about where the limbs are in space and signals where muscles should be positioned. The cerebellum receives information from the semicircular canals (in the inner ear) concerning orientation in space. The cerebellum is involved in the unconscious adjustment of muscles in the body for coordinated, smooth, and complex motor activity. Injury of the cerebellum can result in dystaxia (movement disorders), dysarthria (slurred speech), nystagmus (blurred vision and dizziness), and hypotonia (loss of muscle tone) (Swaiman et al., 2006). Though still relatively uncommon, subtentorial tumors involving the cerebellum and the fourth ventricle are the most frequent type of brain tumor affecting young children (Konczak, Schoch, Dimitrova, Gizewski, & Timmann, 2005).

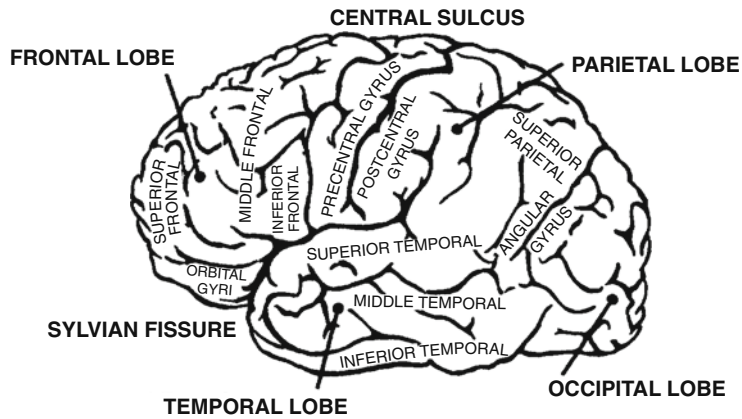

Fig. 2.6 Surface of the Left Hemisphere Showing Sulci, Fissures, and Major Subdivisions of the Cortex
Source: Adapted from M. Semrud-Clikeman and P. A. Teeter, "Personality, Intelligence and Neuropsychology," in D. Saklofske (Ed.), *International handbook of Personality and Intelligence in Clinical Psychology and Neuropsychology*, copyright © 1995 by Plenum Press, New York

Structure and Function of the Forebrain

Neocortex

The neocortex, often referred to simply as the cortex, comprises the highest functional division of the forebrain and makes up about 80 percent of the human brain. The cortex is wrinkled in appearance, with various elevated ridges and convolutions. Ridges are referred to as *gyri*, the deepest indentations are called *fissures*, and the shallower indentations are called *sulci*. The configuration of fissures and large sulci can be identified on visual inspection of the cortex (see Fig. 2.6). The lateral or Sylvian fissure separates the frontal lobe from the temporal lobe, and the central sulcus (fissure of Rolando) separates the frontal from the parietal lobe. The central sulcus is a prominent landmark separating the motor cortex (anterior to the central sulcus) from the sensory cortex (posterior to the central sulcus). The surface areas of posterior temporal and parietal locations are not clearly defined from the occipital regions. Finally, the calcarine sulcus extends from the occipital pole below to the splenium of the corpus callosum. The following sections will describe the structures and functions of the cortex. This brief overview of the structure, function, and development of neurons serves as a foundation for understanding the basic structure of the CNS and will be explored in more detail in a discussion of brain tumors and head trauma (Chapter 10) and in the discussion of psychopharmacology (Chapter 11). In the following sections, the basic divisions of the nervous system will be explored.

Cerebral Hemispheres

The cerebrum comprises the right and left hemispheres, which appear to have anatomical (asymmetry) as well as functional (lateralization) differences (Brodal, 2004). *Asymmetry* typically refers to the structural or morphological differences between the two hemispheres (Rosen, Galaburda, & Sherman, 1990). Although neuroanatomical differences may underlie behavioral variations documented for each hemisphere, it is not known whether chemical as well as structural differences between the hemispheres also account for functional asymmetries (Witelson & Kigar, 1988). Cerebral lateralization refers to the degree to which each hemisphere is specialized for processing specific tasks. The right and left hemispheres appear to differ in terms of their efficiency in processing certain stimuli, such that both hemispheres are "not equally good at all tasks" (Brodal, 2004). Goldberg and Costa (1981) indicate that significant cytoarchitectural differences exist between the two hemispheres that may be related to neurobehavioral differences. The left hemisphere has a greater

ratio of gray matter to white matter, particularly in the frontal, parietal, and temporal regions, compared to the right hemisphere. Conversely, the right hemisphere has greater white-to-gray matter ratios than the left hemisphere.

Major anatomical and functional differences observed in the two hemispheres are described as follows:

1. The left hemisphere has more neuronal representations in modality-specific regions in the three sensory cortices.
2. The right hemisphere has greater association zones, where sensory modalities converge.
3. The left hemisphere is structurally conducive to single modality processing, distinct motor activity, and intraregional integration.
4. The right hemisphere is structurally conducive to multiple modality and intraregional integration.
5. The right hemisphere has a greater capacity for handling informational complexity because of its intraregional connections, whereas the left hemisphere seems best suited for processing unimodal stimuli.

The right hemisphere appears better able to process novel information, whereas the left hemisphere seems able to work more efficiently with information with preexisting codes, such as those found in language activities. These differences will be further explored in a later discussion regarding nonverbal learning disabilities. Although the correlations between structure and function are not perfect, cerebral asymmetry has been of great interest to child neuropsychologists (Baron, 2004). Further, particular anatomical asymmetries between the two hemispheres are present at birth (Kolb & Whishaw, 2003). Measurable differences have been observed in the left planum temporale (near the auditory cortex) by 39 weeks gestation, leading some to suggest that the functional lateralization of language in the left hemisphere is determined prenatally (Witelson & Kigar, 1988). In adults, approximately 70 percent of right-handed individuals show larger planum temporale in the left hemisphere. The planum temporale has been related to phonological coding, a process very important in reading (Semrud-Clikeman, Hynd, Novey, & Eliopulos, 1991). The typical asymmetry of the left hemisphere has not been observed in those with developmental dyslexia and, thus, may be related to the difficulty in encoding letters and words (Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985; Hynd, Semrud-Clikeman, Lorys, Novey, & Eliopulos, 1990; Larsen, Hoeien, & Oedegaard, 1992).

Early accounts of cerebral lateralization often listed specific functions for each hemisphere in a dichotomous, all-or-nothing fashion, implying that all aspects of a given task were carried out by one hemisphere. This all-or-nothing approach is probably overly simplistic because both hemispheres generally play a role in most complex tasks. One hemisphere, however, is usually considered dominant or most important for a specific task, while the other hemisphere is recessive or nondominant. Table 2.2 summarizes the developmental milestones for anatomical and functional asymmetries.

Witelson (1990) suggests that it is unclear whether functional differences between the two hemispheres are "relative" or "absolute," in such a way that each hemisphere is able to process tasks, but does so less efficiently. Others have proposed that the two hemispheres operate in a domain-specific fashion, whereby each hemisphere acts in an autonomous manner with restricted access to information processed by the other hemisphere.

Table 2.2 Major Division of the Nervous System

Brain Divisions	Brain Structures	Functional Divisions
Telencephalon (endbrain)	Neocortex Basal ganglia Limbic system Olfactory bulb Lateral ventricles	Forebrain
Diencephalon (between-brain)	Thalamus Epithalamus Hypothalamns Pineal gland Third ventricle	
Mesencephalon (midbrain)	Tectum Tegmentum Cerebral aqueduct	Brain stem
Metencephalon (across-brain)	Cerebellum Pons Fourth ventricle	
Myelencephalon (spinal brain)	Medulla oblongata Fourth Ventricle	Spinal cord

Source: Adapted with permission from *Fundamentals of Human Neuropsychology*, 3rd edition, by B. Kolb and I. Q. Whishaw (1990). San Francisco: W. H. Freeman.

Zaidal, Clark, and Suyenobu (1990) suggest the following:

(1) the two hemispheres can operate independently of one another, which reinforces the concept of hemispheric specialization, in some domain-specific functions;
(2) hemispheric specialization is "hard-wired" and is apparently innately directed;
(3) developmental patterns of the two hemispheres may differ, and
(4) while the two hemispheres may share processing resources, they can remain autonomous at any stage of processing.

Functional neuroimaging techniques will help answer these questions and will no doubt add to our understanding of the relative contribution of the two hemispheres, as well as specific structures, during certain activities. Some findings have implicated parts of the right hemisphere (particularly the posterior portion) to be important for visual-spatial and mental rotation tasks (Perez-Fabello, Campos, & Gomez-Juncal, 2007). Others have found more activation in the left hemisphere for processing of language and verbal comprehension (Booth et al., 1999). In addition, studies are beginning to show a right hemispheric preference for processing of emotional information. Facial expression processing has been found to be bilateral and to involve the fusiform gyrus of the temporal lobe (Pierce, Muller, Ambrose, Allen, & Courchesne, 2001). While anatomical differences appear early in development, there is insufficient evidence to conclude that morphological variations between the two hemispheres predict functional capabilities in any perfect sense (Kinsbourne, 2003).

Damage to the left hemisphere can result in a shift of language functions to the right hemisphere, particularly if both the posterior and anterior speech zones are damaged (Kolb & Whishaw, 2003). While language functions can be assumed by the right hemisphere, complex visuospatial functions appear to be in jeopardy (Kolb & Whishaw, 2003); further, complex syntactic processing appears vulnerable. So, although the left hemisphere might be better organized anatomically to deal with the language process, as suggested by the Goldberg and Costa (1981) model, the right hemisphere is able to do so under specific conditions. However, there is a price to be paid when one hemisphere assumes the function of the other, usually involving the loss or compromise of higher level functions. These more complex functions also may be more dependent on the anatomical differences generally found between the two hemispheres that exist early in the developing brain. This difference is most likely a result of the differential ratio of gray-to-white matter between the two hemispheres described by Goldberg and Costa (1981). Recovery and loss of functions will be covered in more detail in subsequent chapters.

Interhemispheric Connections

Large bundles of myelinated fibers connect various intra- and interhemispheric regions. The two hemispheres are connected via several transverse commissures or pathways, including the corpus callosum, the anterior commissure, and the posterior commissure. The corpus callosum, comprising the rostrum, the genu, the body, and the splenium, contains approximately 300 million nerve fibers for rapid interhemispheric communication (Carlson, 2007). The genu connects rostral portions of the right and left frontal lobes, while the body has interconnections between the frontal and parietal regions across the two hemispheres. The splenium connects temporal and occipital regions and is reportedly larger in females (Semrud-Clikeman, Fine, & Bledsoe, 2008). The splenium has been implicated in various childhood disorders, including ADHD (Hynd, Semrud-Clikeman, Lorys, Novey, & Eliopulos, 1991; Semrud-Clikeman et al., 1994) and dyslexia (Fine, Semrud-Clikeman, Keith, Stapleton, & Hynd, 2006). The anterior commissure is smaller than the corpus callosum and connects the temporal lobes of the right and left hemispheres (Kolb & Whishaw, 2003).

Intrahemispheric Connections

Association fibers connect cortical regions within each hemisphere (Kandel, Schwartz, & Jessell, 2000b). Association pathways allow for rapid communication within hemispheric regions for the

perception and integration of stimuli and to organize complex output (e.g., emotional responses to stimuli). Short association fibers connect one to another, and longer fibers connect one lobe to another. For example, the arcuate fasciculus connects the frontal and temporal lobes; the longitudinal fasciculus connects the temporal and the occipital lobes with the frontal lobe; the occipitofrontal fasciculus connects the frontal, temporal, and occipital lobes, and the angular gyms connects the parietal and the occipital lobes (Kandel, Schwartz, & Jessell, 2000a). Dysfunction of these pathways can result in a variety of behavioral, cognitive, and personality manifestations including reading, spelling, and computational disorders in children (Zaidel, Iacoboni, Zaidel, & Bogen, 2003).

Structure and Function of the Cortex

The forebrain (telencephalon) comprises the four lobes, the lateral ventricles, the olfactory bulb, the limbic system, the basal ganglia, and the neocortex. Some textbooks also place the thalamus in the forebrain region, while others refer to this as a diencephalic structure (Brodal, 2004). The cortex comprises the right and left hemispheres, each with four major lobes: (1) frontal, motor cortex; (2) parietal, somatosensory cortex; (3) occipital, visual cortex, and (4) temporal, auditory cortex. (See Fig. 2.6 for a view of the cortical regions.) Figure 2.7 illustrates the various functions of the lobes.

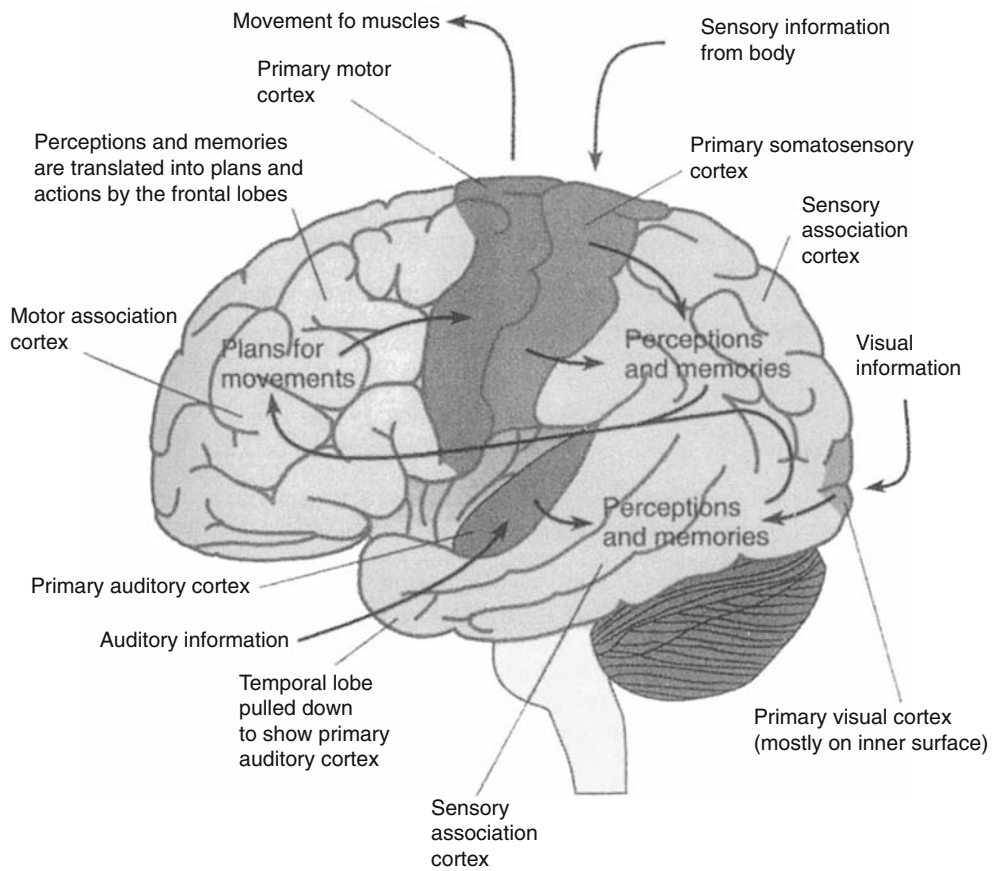

Fig. 2.7 Major Structures and Functions of the Cortex
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Frontal Lobes

The frontal lobes are the most anterior cortical structures and comprise the primary motor cortex, the premotor cortex, an area of expressive language (Broca's area), the medial cortex, and the prefrontal cortex (Damasio & Anderson, 2003). Whereas the primary and premotor areas of the frontal lobes have major motor functions, the prefrontal cortex mediates reasoning and planning and monitors other cortical and subcortical functions. The prefrontal cortex matures the most slowly of all of the areas of the lobes.

Lesions or damage to the primary motor cortex can result in paralysis to the contralateral side of the body, whereas lesions to the premotor cortex can produce more complex coordination problems because this region directs the execution of the primary motor area (Kolb & Whishaw, 2003). Lesions or damage to the prefrontal cortex, with its intricate connections to other brain regions, including thalamic, hypothalamic, and limbic areas, often result in affective dissociations, impaired executive functions and judgment, and intellectual deficits (Lezak, Howieson, & Loring, 2004).

Primary Motor Cortex

The motor system comprises the primary motor, the premotor, and to a lesser degree, the prefrontal, with each region assuming differentiated motor functions. The primary motor cortex is involved with the execution and maintenance of simple motor functions; the premotor cortex directs the primary motor cortex; and the prefrontal cortex influences motor planning and adds flexibility to motor behavior as a result of input from internal and external factors (Lezak et al., 2004).

The primary motor cortex resides immediately anterior to the central sulcus and contains giant pyramidal cells (Betz), which control fine motor and highly skilled voluntary movements (Damasio & Anderson, 2003). The primary motor cortex receives afferent (incoming sensory) signals from the parietal lobe, the cerebellum, and the thalamus for the integration of sensory-motor signals, while efferent (outgoing motor) signals are transmitted to the reticular activating system, the red nucleus (midbrain structure), the pons, and the spinal cord for the production of movement. The primary cortex controls movements to the opposite side of the body and is arranged in a homuncular fashion. A homunculus is a schematic of brain function mapping onto specific body structures. Thus, there is a specific region that is responsible for movement of the thumb, or the ankle, or the nose that maps onto the primary motor cortex.

Specific muscle groups of the body are represented in an inverted pattern stretching across the primary motor area. Stimulation to specific areas of the primary motor cortex produces contractions of highly localized muscle areas. For example, Broca's area resides near the primary motor area in the left hemisphere, controls facial musculature, and mediates speech production (Kolb & Whishaw, 2003).

Premotor Cortex

The premotor cortex, anterior to the primary motor cortex, plays a role in controlling limb and body movements. More complex, coordinated movements appear to be regulated at this level, especially fluid sequential movements. The premotor cortex directs the primary cortex in the execution and maintenance of simple movements. The limbic system also influences the motor cortex, directly and indirectly, primarily in terms of attentional and motivational aspects of motor functions (Damasio & Anderson, 2003).

Prefrontal Cortex

The prefrontal cortex, the most anterior region of the frontal lobe, receives incoming signals from the thalamus, which then project to the hypothalamus. Further, connections to the limbic system allow the prefrontal cortex to mediate, regulate, and control affective, emotional behavior. Prefrontal connections to the temporal, parietal, and occipital association regions allow for a comparison of past and present sensory experiences (Gazzaniga et al., 2002). These intricate connections of the prefrontal cortex with cortical and subcortical regions allow for highly integrative, complex functions. Judgments

and insights arise out of prefrontal activity, whereas motor planning, consequential thinking, and ongoing monitoring of behavior also appear to be regulated by prefrontal regions. The limbic system also seems to play a role in complex, intentional, or volitional motor behaviors, though this is not considered part of the motor area. The development of executive control functions is discussed in more detail in later sections of this chapter. Also see Chapter 6 for a discussion of neuropsychiatric disorders (e.g., ADHD and Tourette syndrome) associated with frontal lobe and executive control damage or dysfunction.

Parietal Lobes

The parietal lobe is separated from the frontal regions by the central sulcus and from the temporal lobe by the lateral fissure. The parietal lobes play a central role in the perception of tactile sensory information, including the recognition of pain, pressure, touch, proprioception, and kinesthetic sense. The parietal lobe is comprised of three areas: the primary sensory projection area, the secondary somatosensory area, and the tertiary or association area (Carlson, 2007).

Primary Sensory Cortex

The primary sensory projection area is immediately posterior to the central sulcus, adjacent to the primary motor cortex. Some have argued that there is a great deal of functional overlap between the sensory and motor cortical areas with approximately one-quarter of the points in the motor area also showing sensory capabilities and one-quarter of the points in the sensory area also showing motor capabilities (Brodal, 2004). Thus, regions posterior to the sulcus have been labeled as the sensory-motor area, while regions anterior to the sulcus are labeled the motor-sensory area. What seems most evident from this research is that the sensory-motor regions are highly interrelated, which probably results in increased functional efficiency.

The primary sensory projection area has four major functions: (1) recognition of the source, quality, and severity of pain; (2) discrimination of light pressure and vibration; (3) recognition of fine touch (proprioception) and (4) awareness of the position and movement of body parts (kinesthetic sense) (Lezak et al., 2004). Numerous fibers converge in the primary sensory projection area, including afferents coming from the thalamus, skin, muscles, joints, and tendons from the opposite side of the body. Lesions to the primary parietal regions can produce sensory deficits to the contralateral (opposite) side of the body, and other more complex deficits can occur when the temporoparietal and/or inferior parietal regions are involved (Tranel, 1992).

Like the primary frontal cortex, the primary sensory projection area is arranged in a homuncular fashion, with the proportion of cortical representation related to the need for sensitivity in a particular body region (Brodal, 2004). For example, the region representing the face, lips, and tongue is quite large because speech production requires multiple sensory input from these various muscles to provide sensory feedback to orchestrate a complex series of movements needed for speaking. The proximity of the primary parietal region to the primary motor regions allows for the rapid cross-communication between sensory-motor systems that is necessary for the execution of motor behavior.

Secondary and Association Cottices

Input from the primary sensory projection regions is synthesized into more complex sensory forms by secondary parietal regions. The tertiary or association region, the most posterior area of the parietal lobe, receives input from the primary sensory projection area and sends efferents into the thalamus. The association region is involved with the integration and utilization of complex sensory information. Gazzaniga et al. (2002) indicate that the association regions synthesize information, whereas the primary areas are involved with finer distinctions and analysis of information. The association region overlaps with other cortical structures, including temporal and occipital areas for the integration of sensory information from different modalities. Although damage to the association region does not produce visual, auditory,

or sensory deficits, damage to the association area can result in disorders of the integration of complex sensory information. Cross-modal matching of visual with auditory and sensory stimuli takes place in the association region, which is considered to be the highest level of sensory analysis. Some argue that this region regulates much of what is measured by intelligence tests, including cognitive and mental functions such as thinking, reasoning, and perception (Kolb & Whishaw, 2003).

Occipital Lobes

The most posterior region of the cortex comprises the occipital lobe (primary visual cortex), which is further divided into dorsal (superior) and ventral (inferior) areas. The inferior and superior regions are divided by the lateral-occipital sulcus, while the calcarine fissure extends from the occipital pole into the splenium of the corpus callosum (see Fig. 2.7). The visual cortex receives projections from the retina in each eye via the lateral geniculate nucleus in the thalamus (see Fig. 2.8). The rods and cones in the retina respond to photic stimulation, and photochemical processes result in nerve impulses in the optic nerve (Carlson, 2007). Once inside the cerebrum, the optic nerve forms the optic chiasm. The optic chiasm is where nerve fibers partially cross, project to the lateral geniculate in the thalamus, and converge in the visual cortex. Damage anywhere along this pathway can produce a variety of visual defects.

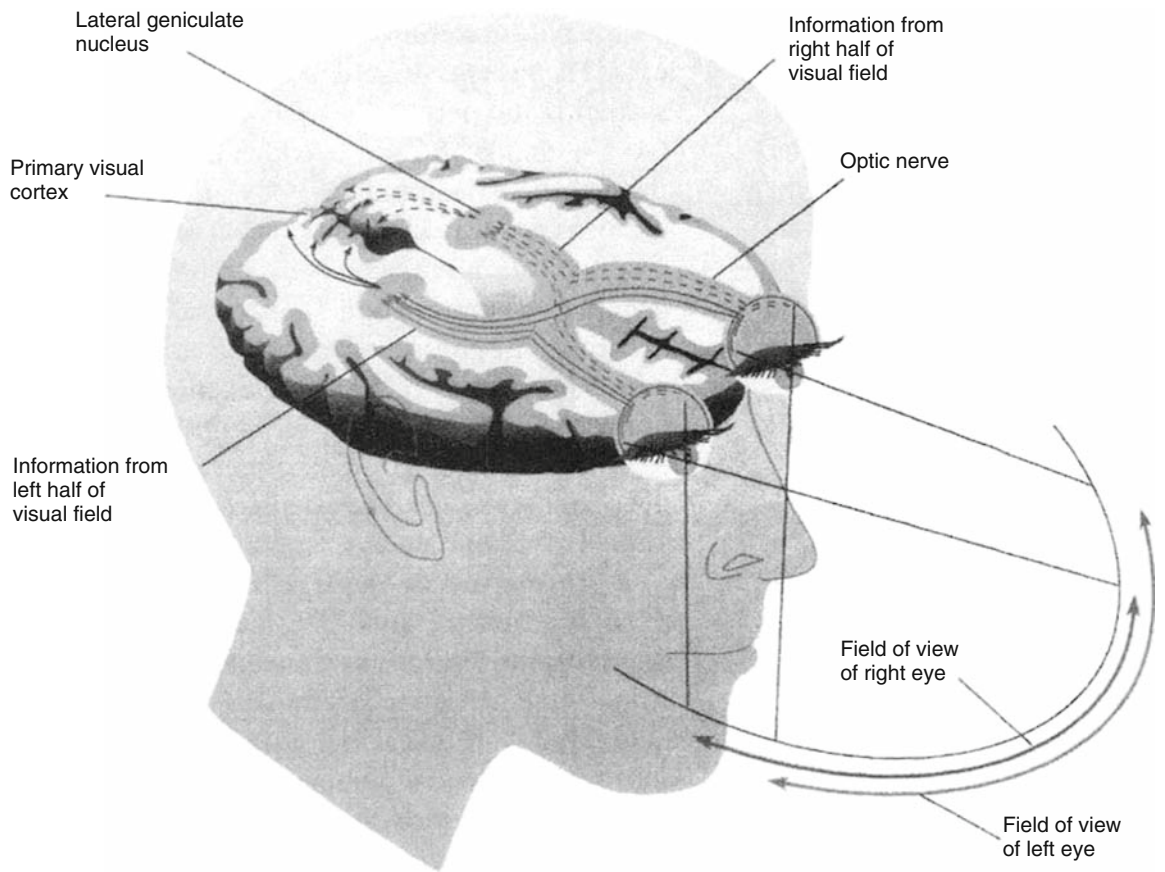

Fig. 2.8 Visual Fields and Cortical Visual Pathways
Source: From Neil R. Carlson, *Physiology of Behavior*, 5th edition, p. 149. Copyright © 1994 by Allyn and Bacon. Reprinted by permission

The occipital lobe comprises primary, secondary, and tertiary or association regions (Kolb & Whishaw, 2003). The primary occipital cortex receives afferent input from the thalamus, which passes through the temporal cortex. Damage to this tract, even if it occurs in the temporal lobe, can produce visual field defects. The association region is involved with complex visual perception, relating past visual stimuli to present stimuli for the recognition and appreciation of what is being seen. Damage to the association region, particularly in the right hemisphere, can produce a variety of visual deficits, including recognition of objects, faces, and drawings.

Temporal Lobes

The temporal lobe has three major divisions: (1) the posterior region of the superior temporal gyrus, which is referred to as Wernicke's area in the left hemisphere; (2) the inferior temporal region, including the occipitotemporal association region, and (3) the mesial temporal aspect, including the hippocampal and amygdala regions (Tranel, 1992). The temporal lobe has complex interconnections, with afferent fibers coming from the parietal lobe, efferent fibers projecting into the parietal and frontal lobes, and the corpus callosum and the anterior commissure connecting the right and left temporal lobes (Kolb & Whishaw, 2003). Three major pathways connect the temporal lobe with other cortical regions for complex integrated functions. The arcuate fasciculus connects the frontal and temporal lobes, the superior longitudinal fasciculus connects the temporal to the occipital and frontal cortices (i.e., the sensory and motor regions of Wernicke's and Broca's areas), and the occipitofrontal fasciculus connects the frontal-temporal-occipital regions.

The anatomical complexity, including large association regions, suggests that the temporal lobes have diverse functions, including the perception of auditory sensations, the analysis of affective tone in auditory stimuli, and long-term memory storage. Although the temporal lobe has primary auditory perception and association functions related to speech and language processing, it also plays a significant role in memory functions and in facial (prosopagnosia) and object recognition (Bauer & Demery, 2003).

The primary temporal cortex is involved with the perception of speech sounds, particularly in the left hemisphere, and nonverbal tonal sequences, particularly in the right hemisphere, while the secondary and association regions are more complex and varied in function. The secondary and association regions add the affective quality to stimuli that is essential for learning to take place. When positive, negative, or neutral affective qualities are attached to stimuli, information takes on motivational or emotional importance to the learner. Without this association, all stimuli would be judged as equal and we would respond to all stimuli with the same affect or emotion (Heilman, Blonder, Bowers, & Valenstein, 2003).

The mesial temporal region, including the adjoining hippocampus and amygdala, appears to be linked to memory processes and plays a role in learning or acquiring new information (Tranel, 1992). Lesions in this area result in impaired retention of new memories, as this region appears to be related to the process by which new memories are stored or are retrieved from storage (Lezak et al., 2004). Asymmetry of functions is evident in the temporal lobes. Memory functions appear to be lateralized. The recall of verbal information, including stories and word lists presented either orally or visually, is stored in the left hemisphere, whereas nonverbal recall for geometric drawings, faces, and tunes is stored in the right hemisphere (Kolb & Whishaw, 2003).

Olfactory Bulb

The olfactory system is the only sensory system that converges in the telencephalon. The olfactory bulb receives sensory information concerning smell directly from the olfactory nerve and converges with the olfactory tract; at this juncture, axons cross to the bulb in the opposite hemisphere via the anterior commissure. The olfactory tract projects to the primary olfactory cortex to a small region called the uncus, close to the end of the temporal lobe (Brodal, 2004). Although olfactory assessment is often ignored, the sense of smell is frequently

associated with various neuropsychiatric disturbances found in adults, particularly schizophrenia, Parkinson's disease, multiple sclerosis, subfrontal tumors, and some brain injuries (Heilman & Valenstein, 2003).

Limbic System

The limbic system is a complex deep collection of structures in the forebrain comprising the hippocampus, amygdale, septum, and cingulate gyms (Kolb & Whishaw, 2003). The limbic system has widespread connections with the neocortex and with the autonomic and endocrinological systems, and is considered a primitive brain structure involved with the olfactory senses. It resides between two brain regions (diencephalon and telencephalon) and serves as an intermediary to cognitive and emotional functions (Wilkinson, 1986). In humans the limbic system has less to do with the olfactory system than with emotional and memory functions that are essential for the survival of the species. It also has preservation functions for the individual.

Wilkinson (1986) describes a number of important functions of the limbic system, including:

(1) analyzing and responding to fearsome, threatening situations;
(2) monitoring sexual responses, including reproducing and nurturing offspring;
(3) remembering recent and past events, and
(4) sensing and responding to feeling states, including pleasure.

Autonomic responses (e.g., heart rate, breathing, blood pressure, and digestive functions) can be influenced by limbic structures, especially the cingulate gyrus. Aggressive reactions and social indifference have been associated with the cingulate gyrus. The cingulate gyrus has also been associated with error checking and self-monitoring of behavior (Semrud-Clikeman, Pliszka, Lancaster, & Liotti, 2006). Feelings of anxiety, deja vu experiences, rage, and fear have been associated with functions of the amygdala (Gazzaniga et al., 2002). With its connections with other limbic and cortical structures, the hippocampus has broad functions involving learning and memory. Seizure activity in limbic structures, particularly the hippocampus, sometimes includes temporal lobe structures as well (Lockman, 1994). Seizures at this site may result in a temporary loss of consciousness and loss of memory.

Basal Ganglia

The term *basal ganglia* refers to all or some of the masses of gray matter within the cerebral hemispheres, including the caudate nucleus, putamen, and globus pallidus. The corpus striatum connects to the neocortex and to the thalamus, and has ascending and descending pathways to midbrain structures (red nucleus and substantia nigra), and to the spinal cord (Brodal, 2004). Serotonin-rich connections from the raphe nuclei also reach the striatum, the prefrontal regions, and the limbic system. These serotonin pathways serve to inhibit motor actions and emotional responses. The basal ganglia are intimately involved with motor functions and, when damaged, can produce postural changes, increases or decreases in muscle tone, and movement changes (e.g., twitches, tremors or jerks). Sydenham's chorea, a childhood disease resulting from poststreptoccal rheumatic fever involving the corpus striatum, is characterized by irregular and purposeless movements. This disease usually appears insidiously, gradually worsening with symptoms of hyperkinetic movement disorder, emotional lability, and hypotonia. Rheumatic heart disease is often found in conjunction with Sydenham's chorea and is the cause of mortality in this disorder. The chorea generally dissipates six months after onset, but the emotional lability remains (Cardona et al., in press).

Summary

This chapter's goal was to provide an introduction to the field of neuropsychology. Defining neuropsychology includes the study of the brain and the transactional effect of neurology and the environment. Neuropsychologists are specialists in assessment and intervention, and specific and

intensive training is necessary for practice in this field. Child (pediatric) neuropsychologists require additional training in child development as well as in child assessment. Adult neuropsychologists have separate training in geriatric, adult disorders, and neuroanatomy that is specific to aging, while child neuropsychologists have emphasis in development and in pediatric disorders. To that end, adult neuropsychologists should not complete pediatric assessments without additional training and child neuropsychologists should not complete adult assessments without specific education.

For child neuropsychologists it is important to have knowledge of appropriate laws that apply to education. Since almost all of the children and adolescents that are evaluated are in school, the most effective clinician will be informed about the contents of IDEA, Section 504, and HIPAA to most appropriately serve the population. Providing assessment without such knowledge may result in less than ideal evaluations, inappropriate interventions, and lead parents to expect services that are unlikely to be delivered. Multicultural issues were also discussed and it is very apparent that research and practice in this area is seriously lacking.

This chapter also sought to provide a review of basic anatomy of the brain and neuron in preparation for subsequent chapters on disorders, assessment, and intervention. A review of basic structures as well as their place in gestation and development was provided. Some structures change dramatically during childhood while others are basically formed prior to birth. These changes appear to be linked to stages of cognitive and neurological development, and the informed clinician will utilize these developmental changes when interpreting findings. Many of the aspects of this chapter are important to understand the next chapter on neuroradiological methods.

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