Structure of the Central Nervous System

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The Brain – Overview

The human central nervous system (CNS) consists of the brain and the spinal cord, which are encased in the cranial bones and the spinal column. The brain is subdivided into the *forebrain*, the *midbrain*, and the *hindbrain*. The forebrain is subdivided into the telencephalon and diencephalon; the midbrain into the tectum and the tegmentum; and the hindbrain into metencephalon and myelencephalon. The brain stem, so named because of its appearance, consists of the midbrain and portions of the hindbrain.

Subdivisions of the Central Nervous System

Forebrain

The forebrain comprises two parts: the telencephalon and the diencephalon. The surface of the forebrain is the cortex, which is mainly made up of cell bodies. These cell bodies give the cortex its characteristic gray color, and therefore its name—"gray matter." The cortex is essential for most higher human faculties, such as perception, cognition, language comprehension, and the control of movement. Functionally, the cortex may be divided into motor areas, sensory areas, and association cortex .
Axons that extend from the cell bodies of the cortex are covered with a *myelin sheath*, which appears white, and therefore they make up the "white matter." A number of subcortical structures (that is, those located beneath the surface of the cortex) are found in the white matter within the telencephalon. These include the basal ganglia (involved in the control of movement) and structures of the limbic system (involved in the regulation of emotion, memory, and certain aspects of movement such as the hippocampus, the amygdala, and the fornix.

The diencephalon comprises two structures: the thalamus, which serves as a relay for sensory information ascending to the cortex; and the hypothalamus, which regulates the activity of the *hormonal system* and the autonomic nervous system.

Midbrain

The midbrain, or the mesencephalon consists of the tectum and the tegmentum. The tectum is located in the dorsal part of the midbrain and includes four small hillocks, a pair of the superior colliculi and a pair of the inferior colliculi. The superior colliculi are important for the coordination of eye movements with head and body movements. The inferior colliculi are part of the auditory system. The tegmentum is the ventral part of the midbrain. It contains a number of nuclei important for control of body movement, such as the *red nucleus* and the substantia nigra, and nuclei important for the regulation of arousal and attention.

Hindbrain

The hindbrain, or rhombencephalon, consists of two divisions: the metencephalon and myelencephalon. The former includes the cerebellum, which is responsible for smooth and coordinated movement; and the pons, which relays information to and from the cerebellum, and includes nuclei involved in the control of sleep and arousal. The main structure within the myelencephalon is the medulla oblongata, which connects the brain and the spinal cord. Sensory information ascends to higher brain areas, and motor information descends to the spinal cord via the medulla oblongata. Nuclei in the medulla are involved in the control of vital functions, such as regulation of the cardiovascular system, respiration, and skeletal muscle tonus.

The Spinal Cord

The spinal cord is a long structure from which the spinal nerves extend. Through these nerves, the brain projects motor information to the skeletal muscles, glands, and visceral organs, and receives sensory information from the limbs, trunk, and many internal organs.

Subcortical Structures

White Matter

Millions of myelinated *axons* extend from neural cell bodies and form the white matter underneath the *cortex*. These axons form tracts that connect between cortical and subcortical areas. The myelin sheath surrounding these axons tints the tracts with an opaque white color—hence the name “white matter.”

Corpus Callosum

The corpus callosum is a cluster of *axons*, mostly myelinated, that connects the two brain hemisphere. As the largest interhemispheric connection, or commissure, in the brain, the corpus callosum allows the two hemispheres to exchange neural information. In a surgical procedure used to treat severe cases of epilepsy, the surgeon cuts the corpus callosum, separating the two hemispheres (the split-brain operation). This procedure leads to a condition in which each of the hemispheres works independently, detached from each other. For example, when an image of an object is projected to the right hemisphere of a split-brain patient, the patient report seeing nothing, because the left hemisphere that controls speech does not "see" the image. However, the patient is able to draw the object with the left hand, which is controlled by the right hemisphere.

The Ventricular System

The brain contains a series of connected ventricles, or cavities, filled with cerebrospinal fluid (CSF). This fluid is produced in a special tissue, the choroid plexus, within the brain ventricles. It is produced from blood and is similar in composition to blood plasma. The CSF flows out of the ventricles and surrounds the entire surface of the brain and spinal cord, so that the brain floats in a bath of CSF. Thus, the CSF serves to reduce physical shocks to the central nervous system. It also serves as a medium for chemical communication and as a means for waste removal.

The brain includes four ventricles: the largest two are the lateral ventricles, one in each *hemisphere*. From the lateral ventricles, the CSF flows (through the foramen of Monroe) to the third ventricle, which is located in the midline of the brain, in the area of the *diencephalon*. From there, the CSF continues to flow through a narrow tube in the midbrain called the cerebral aqueduct to the fourth ventricle in the *pons* and the *medulla oblongata*. The CSF then flows through small apertures in the fourth ventricle to the space that surrounds the entire CNS (the brain and spinal cord). Finally, the CSF is absorbed into the venous blood system.

The Basal Ganglia

Basal ganglia are a group of subcortical nuclei located within the *white matter* motor system. For example, Parkinson's disease is caused by degeneration of certain dopaminergic neuronsthat originate in the midbrain and extend to the basal ganglia. Parkinson's patients are characterized by motor disturbances, including muscular rigidity, slowness of movement, a resting tremor, postural instability, and difficulty in initiating movement.

The basal ganglia receive input from certain area of the *cortex* (particularly from the motor and somatosensory cortex), and the substantia nigra in the midbrain. Their output is projected to the thalamus, and from there to motor areas in the frontal lobe. The input area of the basal ganglia is the *striatum*, which is made of the caudate nucleus and the putamen. Two other important subareas in the basal ganglia are the globus pallidus and the *nucleus accumbens*.

Caudate Nucleus

The caudate nucleus comprises a head, a body, and a tail. The caudate nucleus receives information from extensive cortical areas. It projects information to the globus pallidus, and from there to the thalamus and back to the frontal lobe, so that a neural circuit is established. In this way the basal ganglia control skeletal muscle movement and eye movements. The caudate nucleus also receives information from the frontal and the parietal lobes, and from areas in the *limbic system*, such as the *hippocampus*. Through this neural circuit the basal ganglia regulate learning, long-term memory, and emotions.

Putamen

The putamen is a disk-shaped nucleus that receives information from sensory and motor areas in the parietal and frontal lobes, and sends information back to the area responsible for motor planning in the frontal lobe. This nucleus is associated with regulation and control of movement.

Cell Bridges

Cell bridges, as their name suggests, are bridges that connect the putamen with the caudate nucleus. Between the cell bridges passes an important fibrous tract, the internal capsule, which contains ascending and descending axons.

Nucleus Accumbens

The nucleus accumbens is located ventromedial to the putamen and the caudate nucleus. Anatomically it is part of the basal ganglia, but some researchers ascribe it functionally to the limbic system, as it plays an important role in the reward (reinforcement) system. During eating, for example, the neurotransmitter dopamine is released in the nucleus accumbens, resulting in a rewarding feeling. Consumption of most drugs of abuse, including cocaine, heroin, alcohol, and tobacco, increases neural activity in the nucleus accumbens, which is associated with positive reinforcement.

Globus Pallidus

The globus pallidus is located medially to the putamen nucleus. It receives information from the putamen and the caudate nucleus, and sends information to the *brain stem* and the thalamus. The thalamus itself sends information to various cortical areas. The globus pallidus is involved in a variety of basal ganglia roles, including motor regulation of body and limbs, and control of eye movements.

The Thalamus and Hypothalamus

Surrounding the third ventricle is the *diencephalon*, which consists of the thalamus and the hypothalamus. The thalamus functions as a relay station for sensory (and sometimes motor) information ascending to the cortex. Located under the thalamus is the hypothalamus, involved in regulation of the autonomic nervous system and the *hormonal system*.

Thalamus

The thalamus is a large structure comprising two lobes, one in each hemisphere, connected by a bridge of gray matter (the massa intermedia). The thalamus is divided into numerous nuclei, including nuclei that receive sensory information and transfer it to sensory areas in the cerebral cortex. For example, the *lateral geniculate nucleus* (LGN) receives visual information from the eye and projects it to the primary visual cortex, while the medial geniculate nucleus (MGN) receives auditory information from the inner ear and projects it to the primary auditory cortex.

Other thalamic nuclei provide the cortex with information important to the thalamus receives information from the *cerebellum* and basal ganglia and projects it to the *primary motor cortex*.

Hypothalamus

The hypothalamus is located on both sides of the lower part of the third ventricle, below the thalamus ("hypo" means below). This is a very complex structure, comprised of many nuclei. The hypothalamus supervises the autonomic nervous system Through its connection to the *pituitary gland*, the hypothalamus also regulates the hormonal system. A short "stalk" (the infundibulum) connects the hypothalamus to the pituitary gland, allowing the hypothalamus to control the release of hormones from the pituitary in two ways. First, certain hormones are synthesized in hypothalamic nuclei, carried via axons to the posterior part of the pituitary gland, and released from the pituitary directly into the blood system. Second, other hormones called releasing hormones are secreted from the hypothalamus, reaching the anterior pituitary gland via a specialized blood supply system. These releasing hormones stimulate the production and secretion of anterior pituitary hormones into the blood system.

Mammillary Bodies

Anatomically, the mammillary bodies constitute part of the posterior-inferior area of the hypothalamus, and they are functionally ascribed to the limbic system. They mainly receive information from the *hippocampus* via the fornix. They project to the thalamus and to the *midbrain*. The mammillary bodies play an important role in memory and emotion. Patients suffering from alcoholic Korsakoff's syndrome exhibit damage in the mammillary bodies, which is usually associated with memory impairment.

Pituitary Gland (Hypophysis))

The pituitary gland is connected to the hypothalamus through the pituitary stalk. In response to neural or hormonal messages arriving from the hypothalamus, the pituitary gland releases hormones to the blood system. The release of hormones from the pituitary is controlled by the hypothalamus in two ways: Certain hormones are synthesized in hypothalamic nuclei, carried via axons to the posterior part of the hormones called releasing hormones are secreted from the hypothalamus, reaching the anterior pituitary gland via a specialized blood supply system. These releasing hormones stimulate the production and secretion of anterior pituitary hormones into the blood system.

Functional Neuroanatomy

Sensory Systems

Vision

Vision is one of the most important senses, and a relatively large proportion of the cerebral cortex is devoted to the analysis and processing of visual information. Visual information from the eye is projected through the optic nerves to the *optic chiasm*, where they partially decussate (cross over to the opposite side of the brain). From the optic chiasm, the information proceeds through the optic tracts to the *lateral geniculate nucleus* (LGN) of the thalamus. From there, the visual information is transferred via the optic radiations to the primary visual area in the occipital lobe of the cortex, and it then proceeds to visual associative areas in the cortex, where more complex analysis of visual information occurs.

A secondary neural tract carries visual information from the eyes to the *superior colliculi* in the brain stem, and then to the pulvinar (a large nucleus in the thalamus) and to the cortex. This tract is responsible for the coordination of head and eye movement in the direction of a moving object.

Eye

The eye carries out the initial processing of visual information. Photoreceptors in the retina, transduce light rays into neural information that is conveyed through the optic nerve to the brain.

Optic Nerve

The optic nerve is a cluster of axons extending from the ganglion cells of the retina and conveying visual information through the optic chiasm to the thalamic LGN (lateral geniculate nucleus). The optic nerve is cranial nerve II.

Optic Chiasm

The optic chiasm, at the base of the brain, is where the optic nerves come together, partially decussate, and continue, as the optic tracts, to the LGN (lateral geniculate nucleus). In the optic chiasm, the axons extending from the nasal (proximate to the nose) part of both retinas decussate to the *contralateral* side, while the axons extending from the temporal (proximate to the temple) part of both retinas continue to the ipsilateral side. Each brain hemisphere processes information from the contralateral side of the visual field (the right hemisphere processes information from the left visual field, and vice versa).

Optic Tract

The optic tract is made up of the axons that link the optic chiasm and the LGN. These axons convey information relating to the contralateral side of the visual field. In addition, the optic tract carries visual information from the eyes to the superior colliculi, and from there to the pulvinar (a large nucleus in the *thalamus*) and the cortex.

Lateral Geniculate Nucleus (LGN)

The lateral geniculate nucleus (LGN) is located in the thalamus and comprises six layers of cell bodies. Each of these layers receives input from one eye only.

Superior Colliculi

The superior colliculi (Latin for “mounds”) resemble two hills; they are located in the tectum area of the midbrain. They are involved in the rapid, jerky movement of the eyes when scanning a visual scene (called saccadic movement) and in orientating the eyes and head toward objects in the visual field.

Optic Radiations

Optic radiations are a collection of axons extending from the LGN (lateral geniculate nucleus) to the primary visual cortex.

Primary Visual Cortex

The primary visual cortex is located in the posterior part of the occipital cortex. It consists of six layers. The fourth layer receives information from the LGN and retains the distinction between information arriving from the ipsilateral and the *contralateral* eyes. This monocular information is then converged into binocular information in other layers of the primary visual field (See also “The Primary Visual Cortex” subsection, in the Visual Perception :module) .

Occipital Lobe

The occipital lobe is located in the inferior-posterior area of the cortex, around the calcarine fissure. This lobe includes the primary, secondary, and associative visual cortex. The primary visual cortex surrounds the calcarine fissure and receives input directly from the thalamic LGN. From this area, visual information proceeds to the secondary and the associative visual cortex.

Auditory System

The sense of hearing performs many functions in our everyday lives, including a central role in human verbal communication. From the ear, auditory information is transferred through the cochlear division of the vestibulocochlear nerve to cochlear nuclei in the medulla. Most neurons in the cochlear nuclei send axons to the superior olivary complex. From here, the auditory information continues to the inferior colliculi, located in the *tectum* of the midbrain. The colliculi extend axons to the MGN (medial geniculate nucleus) in the thalamus, which in turn extends axons to the primary auditory cortex. This area is located in the *temporal lobe*, and most of it is hidden within the lateral fissure. In the primary auditory cortex, the brain receives auditory information from both ears, but mainly from the contralateral ear. From this area, the information continues to the auditory associative cortex, located in the superior-posterior part of the temporal lobe.

Vestibulocochlear Nerve

Sound waves are transduced (converted) into neural signals within the cochlea of the inner ear and are then projected through the cochlear division of the vestibulocochlear nerve to the cochlear nuclei in the medulla. The auditory and vestibular nerves comprise the vestibulocochlear cranial nerve (cranial nerve VIII).

Cochlear Nuclei

The cochlear nuclei are located in the medulla. They receive auditory information from the ipsilateral ear and convey that information to the superior olivary complex and to the inferior colliculi in the brain stem. Some of the axons that extend from the cochlear nuclei continue on the ipsilateral side, while others cross to the contralateral side of the brain.

Superior Olivary Complex

The superior olivary complex is located in the caudal area of the *pons* in the brain stem. It consists of a number of nuclei that serve as a relay station for auditory information ascending to the inferior colliculi. This information arrives from the cochlear nuclei on both sides of the brain. The superior olivary complex constitutes the first station of the auditory tract where auditory information from both ears is combined. Receiving information from both ears (binaurally) is an important element in identifying the location of the sound source.

Inferior Colliculi

The inferior colliculi resemble two hillocks in the *tectum* of the midbrain and are located caudally to the superior colliculi. They receive information from the cochlear nuclei, both directly from the contralateral cochlear nucleus and indirectly through the ipsilateral superior olivary complex. From the inferior colliculi, axons extend to the thalamic MGN. Like the superior olivary complex, neurons in the inferior colliculi are also binaural, and this contributes to the ability to locate auditory sources. The main role of the inferior colliculi is to direct the head and body in the direction of auditory stimuli.

Medial Geniculate Nucleus (MGN)

The MGN is a part of the *thalamus*. It receives auditory information from the inferior colliculi and projects it to the primary auditory cortex. The MGN, like lower levels of the auditory system, maintains a tonotopic representation of sounds. This means that the neurons are organized in such a way that cells responding to higher sound frequencies are close to one another and further away from cells responding to lower frequencies.

Auditory radiations are axon tracts that extend from the thalamic MGN and carry auditory information to the auditory cortex.

Primary Auditory Cortex

The primary auditory cortex is located in the temporal lobe; most of it is hidden within the lateral *fissure*. This area receives auditory information from the thalamic MGN and projects the information to associative auditory areas in the posterior-superior parts of the temporal lobe. In the primary auditory cortex, each side of the brain receives information from both ears (binaurally), though not necessarily with the same intensity. Like the MGN, the primary auditory cortex also maintains a tonotopic representation— that is, cells close to each other in the primary auditory cortex are sensitive to similar sound frequencies.

Somatosensory System

The somatosensory system is concerned with sensation from the skin at the body surface. Receptors that transduce sensory stimuli into neural activity are located in the skin, muscles, joints, tendons, and viscera. Body tissues are capable of responding to different types of stimuli: pressure and contact, heating, cooling, and painful stimuli. Sensory information is carried by primary sensory neurons, from the sensory receptor into the spinal cord and the *brain stem*. Cell bodies of the primary sensory neurons are located in the dorsal root ganglia and in the *cranial nerve* ganglia.

There are two main somatosensory systems in the central nervous system: the medial lemniscal system and the anterolateral system (also known as the spinothalamic system). Information from both systems is carried through the spinal nerves to the spinal cord, and from there to the brain stem, thalamus, *limbic system*, and primary somatosensory cortex. The primary somatosensory cortex is located within the post-central gyrus of the *parietal lobe*. Sensory information in the area of the face and cranium is carried via the trigeminal nerve, through the thalamus to the primary somatosensory cortex. Sensory information is further projected to the associative somatosensory cortex, located in the parietal lobe and in the posterior insular cortex.

Medial Lemniscal System

The lemniscal system carries precisely localized information about fine touch, vibrations, and proprioception (information about limb position and muscle tension from muscles, tendons, and joints). Somatosensory axons extending from the skin, muscles, and viscera reach the central nervous system through the spinal nerves. Cell bodies of these neurons are located in the dorsal root ganglion. The somatosensory axons are somatotopically organized, that is, information from adjacent body parts arrives in adjacent segments of the *spinal cord*. Body surface areas innervated by axons extending from a single ganglion are called dermatomes. On entering the spinal cord, a sensory axon splits into two branches: one branch *synapses* within the dorsal horn of the spinal cord, while the other branch ascends through the dorsal column of white matter into the brain stem. Sensory information carried by the dorsal column reaches the dorsal column nuclei in the medulla and from there proceeds to the thalamus through the medial lemniscus.

Dorsal Column

The dorsal column comprises a cluster of sensory axons that carry sensory information from the surface of the body to the dorsal column nuclei in the brain stem.

Dorsal Column Nuclei

The dorsal column nuclei are located at the lower end of the medulla and contribute to precise identification and localization of sensory stimuli.

Medial Lemniscus

The medial lemniscus is a tract connecting the dorsal column nuclei with the ventral posterior (VP) complex in the thalamus. On its way to the *thalamus*, this tract decussates in the medulla to the contralateral side of the brain. From the thalamus, sensory information proceeds to the primary somatosensory cortex in the parietal lobe.

Anterolateral System

The anterolateral system mainly carries information regarding sensation of pain, temperature, and some touch. Axons of this system convey poorly localized enter the dorsal horn of the *spinal cord* with secondary sensory neurons. These, in turn, immediately decussate to the contralateral side of the spinal cord, where they ascend through the anterorlateral column in the white matter of the spinal cord. Some axons of the anterolateral column project directly into the *ventral* posterior complex of the thalamus. These axons comprise the spinothalamic tract, which reports sensations of pain, temperature, and touch. Other axons in the anterolateral column end in the reticular formation (the spinoreticular tract) or in the tectum (spinotectal tract).

Spinothalamic Tract

The spinothalamic tract is part of the anterolateral column. It carries sensations of pain, temperature, and touch to the lateral part of the thalamic ventral posterior (VP) complex.

Trigeminal System

The trigeminal system carries somatosensory information from the head, face, mouth, throat, ears, and nose through the trigeminal nerve (cranial nerve V) to the brain.

Trigeminal Nerve

The trigeminal nerve mainly carries somatosensory information, sensation of touch, pain, and temperature, and proprioceptive sensation from muscles in the face and jaw. Cell somas of the axons that comprise this nerve are located in the trigeminal ganglion in the brain stem.

Trigeminal Tract and Nuclei

Axons of the trigeminal nerve branch off to a number of target sites once they enter the brain stem. These branches are known as the trigeminal tract, while their targets are the trigeminal tract nuclei, located in the area of the medulla and pons.

Trigeminothalamic Tract

The trigeminothalamic tract conveys somatosensory information from the trigeminal nuclei to the thalamus. This tract decussates to the other side of the brain immediately after leaving the nuclei and ascends to the medial part of the ventral posterior (VP) complex of the thalamus. From the thalamus, the sensory information extends to the primary somatosensory area in the parietal lobe of the cortex.

Ventral Posterior Complex in the Thalamus

The ventral posterior complex of the thalamus is the main area receiving somatosensory information from the body, head, and face.

Somatosensory Radiations

Somatosensory radiations are axons that extend from the thalamus and ascend to sensory cortex areas. These axons pass through the internal capsule.

Primary Somatosensory Cortex

The primary somatosensory cortex is located in the postcentral gyrus, behind the central sulcus in the parietal lobe. Most of the input to the primary somatosensory cortex arrives from the *ventral* posterior (VP) complex of the *thalamus*. The primary cortex area is somatotopically organized. From the primary somatosensory cortex, the sensory information continues to the associative somatosensory cortex, located in the parietal lobe and in the posterior insular cortex.

Olfactory System

The sense of smell is a chemical sense that helps us identify food and avoid spoiled food. In many species, the sense of smell helps detect predators or prey and to identify friends, foes, and mates. Olfactory stimuli are volatile materials. They are transduced into nerve messages by the olfactory receptors located in the mucous *membrane* in the roof of the nasal cavity. Axons of these receptors merge to form the olfactory nerve (cranial nerve I). On entering the brain, these axons form synapses with nerve cells in the olfactory bulbs. These nerve cells extend axons through the olfactory tracts, directly to the olfactory cortex in the medial ventral part of the temporal lobe. The olfactory cortex includes the piriform cortex, the uncus, the olfactory tubercle, the entorhinal cortex, and the amygdaloid cortex. All these areas belong to the limbic cortex. From the olfactory cortex, the information proceeds to the *hypothalamus* and the medial dorsal thalamus, thence to the orbitofrontal cortex in the frontal lobe.

Olfactory Bulbs

The olfactory bulb comprises a cluster of cells located at the base of the brain, at the end of the olfactory tract. Axons arriving from the olfactory receptors reach the olfactory bulb where they form synapses within a complex bundle of dendrites and axons known as the olfactory glomeruli. There are about ten thousand such glomeruli and each receives input from about a thousand olfactory receptor axons.

Olfactory Tract

The olfactory tract comprises axons that extend from the olfactory bulbs and reach various areas of the ipsilateral olfactory cortex.

Olfactory Cortex

The olfactory cortex is divided into a number of areas: the anterior olfactory nucleus, the piriform cortex, the uncus, the olfactory tubercle, the entorhinal cortex and the amygdaloid cortex. These cortical areas, often referred to as the “paleocortex,” have an early evolutionary origin and can also be seen in the brains of very primitive vertebrate animals. They are simply structured and have only three cortical layers compared with six layers in the neocortex, a more recent evolutionary development. Most information received by the olfactory cortex comes from the olfactory bulbs, through the olfactory tract. Contrary to other senses, input from the olfactory tract does not pass through the *thalamus* first, but reaches the olfactory cortex directly. Only after it has been processed in the olfactory cortex does the information proceed to the thalamus, and from there to the orbitofrontal cortex. The olfactory cortex also projects information to the hypothalamus, hippocampus, and deeper areas of the amygdala. These areas are part of the limbic system, which explains the intimate relationship between the sense of smell and hormonal regulation, emotions, motivation, and memory.

Olfactory Tubercle

The olfactory tubercle is located in the basal forebrain and is part of the olfactory cortex.

Uncus

The uncus is located in the parahippocampal gyrus of the temporal lobe, close to the

Piriform Cortex

The piriform cortex is located adjacent to the uncus, in the parahippocampal gyrus of the temporal lobe. It belongs to the olfactory cortex and to the associative limbic cortex.

Entorhinal Cortex

The entorhinal cortex is located caudally to the uncus, in the parahippocampal gyrus of the temporal lobe. It belongs to the olfactory cortex and to the associative limbic cortex. It is also connected to the hippocampus.

The Motor System

The motor system comprises a number of subsystems concerned with the control of muscular activities and body movements. These subsystems are organized hierarchically on three control levels: the *spinal cord*, the descending systems of the *brain stem*, and the motor areas of the cortex. Each level sends descending information to the skeletal muscles, and receives sensory information relevant to its function in feedback loops.

The primary motor cortex is located in the frontal cortex, just *rostral* to the central sulcus. Descending tracts from the primary motor cortex are organized in two motor systems: the pyramidal system, which exerts direct and voluntary control of body and limb muscles, particularly fine finger movements; and the extrapyramidal system, which provides indirect control of muscles and regulates relatively gross body movements. Along with the tracts that innervate the skeletal muscles, there are also a number of cranial nerves that innervate muscles of the head and neck area.

Primary Motor Cortex

The primary motor cortex is located in the frontal lobe, within the precentral *gyrus*. It receives motor information from the associative motor cortex (premotor cortex and supplementary motor cortex), which are located rostrally in the frontal lobe. It also receives motor information from the *cerebellum* and the *basal ganglia*, and sensory information from the primary somatosensory cortex. The input is important for the

Neurons in the primary motor cortex are organized somatotopically, so that adjacent body parts are represented in adjacent cells in the cortex. From the primary motor cortex, axons extend through the internal capsule to the brain stem and spinal cord, to innervate skeletal muscles in the head and body.

Motor Radiations

Motor radiations are axons that extend from the motor cortex and reach subcortical structures and the spinal cord. Axons that extend from the primary motor cortex all the way to the spinal cord form the corticospinal tract of the pyramidal system. Other descending motor axons project to a number of motor areas, including the basal ganglia, the subthalamus, the midbrain, the pons, and the medulla, and are part of the extrapyramidal system.

Pyramidal System

The pyramidal system conveys motor information to distal skeletal muscles, mainly controlling fine voluntary movements of the arms, hands, and fingers (such as playing the piano or knitting). The central tract in the system is the pyramidal tract.

Pyramidal Tract

The pyramidal tract, also known as the corticospinal tract, originates at the primary motor cortex. Axons of the tract descend through the internal capsule and proceed through the cerebral peduncles to the pyramids in the ipsilateral side of the medulla. The name "pyramid" refers to the shape of the axon bundles crossing over at the *ventral* surface of the medulla. At the level of the medulla the tract splits into two separate branches with different spinal routes, the lateral and the ventral corticospinal tracts.

Axons of the lateral corticospinal tract cross to the contralateral side of the brain, descending within the lateral column of the white matter in the spinal cord. The lateral corticospinal tract conveys motor information to distal skeletal muscles, mainly controlling voluntary movements of the arms, hands, and fingers. Axons of the ventral pyramidal tract remain ipsilateral and convey information to both axial and proximal skeletal muscles, mainly controlling movement of the neck and the axial skeletal muscles.

Extrapyramidal System

The extrapyramidal system controls gross movements of the head and body, such as standing, posture, and walking, as well as involuntary activities such as breathing and sneezing. The main structures of the system are the cerebellum and the basal ganglia, which receive information from wide areas of the cortex and return information to the motor cortex via the thalamus. The cerebellum also receives information from the brain stem and returns information to it. The cerebellum is involved in motor learning, synchronization of fast and coordinated movements, maintaining posture and balance, and the coordination and refinement of planned movements. The main function of the basal ganglia is to supervise body, limb, and eye movements.

Basal Ganglia

Basal ganglia are a group of subcortical nuclei located within the *white matter* surrounding the lateral *ventricles*. They constitute an important component of the motor system. For example, Parkinson’s disease is caused by degeneration of certain dopaminergic neurons that originate in the midbrain and extend to the basal ganglia. Parkinson’s patients are characterized by motor disturbances, including muscular rigidity, slowness of movement, a resting tremor, postural instability, and difficulty in initiating movement. The basal ganglia receive input from the cortex (particularly from the motor and somatosensory cortex) and the substantia nigra in the midbrain. Their output is projected to the thalamus, and from there to motor areas in the frontal lobe.

Cerebellum

The cerebellum is a large structure located dorsally to the brain stem pons. The cerebellum (“little brain”) resembles the structure of the cerebrum. It comprises two hemispheres, separated by a mid-area called the vermis. The cerebellum is covered by a cortex that has many folds. Underneath the cortex are a number of deep cerebellar nuclei. The cerebellum plays a key role in movement and regulating the functions of the descending motor pathways. It is important for the execution of fast, coordinated equilibrium. Damage to the cerebellum causes jumpy, jerky, and non-coordinated movements.

Pons

The pons is a structure of the hindbrain that works in conjunction with the medulla and *diencephalon* to control respiration and heart rhythms. The pons is a major route by which the forebrain sends information to and receives information from the spinal cord and the peripheral nervous system. It also serves as a major route of connections between the cerebellum and the rest of the brain.

Tectospinal Tract

The tectospinal tract extends from the superior colliculi in the midbrain and ends in the spinal cord. This tract conveys motor information to the *axial* and *proximal* skeletal muscles and coordinates neck and eye movements in response to visual information.

Rubrospinal Tract

The rubrospinal tract extends from the red nucleus in the midbrain. The tract innervates distal muscles, controlling voluntary movements of the limbs.

Reticulospinal Tract

The reticulospinal tract conveys motor information from the reticular formation in the brain stem to the spinal cord. This tract innervates *motor neurons* of axial skeletal muscles, which are important in maintaining muscle tonus and in control of automatic movements, such as posture, breathing, coughing, and sneezing.

Cranial Motor Nerves

Cranial motor nerves are mainly responsible for controlling head and neck movement. Cell bodies of these nerves are found in cranial nerve nuclei located in the pons and medulla. Motor cranial nerves include: the oculomotor nerve (III—eyeball and eyelid movements, pupil contraction, and eye lens flexibility); the trochlear and abducens nerves (IV and VI—eyeball movements); part of the trigeminal nerve (V—chewing); part of the facial nerve (VII—facial expressions, secretion of saliva and tears); part of

(X—controls the viscera); the spinal accessory nerve (XI—swallowing, head and neck movements, and the muscles of the throat and pharynx); and the hypoglossal (XII—tongue muscles during speech and swallowing).

The Limbic System

The limbic system includes a number of interconnected structures in the cortex and subcortical areas, and a few areas in the brain stem. Among the most prominent structures included in this system are the hippocampus, the amygdala, the hypothalamus, and the limbic cortex (a ring-shaped structure which includes the cingulate gyrus and the parahippocampal gyrus). The limbic system plays an important role in the regulation of, motivation, emotion, and memory through modulation of the autonomic nervous system and the endocrinal system.

Amygdala

The amygdala (Latin for "almond") comprises a group of nuclei located anterior to the hippocampus in the temporal lobe. It plays a key role in our emotional experience by modulating the autonomic nervous system and the hormonal system. The amygdala receives sensory information from the brain stem, the olfactory bulb, the thalamus, and primary and associative sensory cortical areas. It sends information to the basal forebrain, to the thalamus and hypothalamus, and to limbic areas in the brain stem. Electrical stimulation of the amygdala in animals can induce a stress response and anxiety. Complete destruction of the amygdala reduces a wide range of emotional and physiological responses.

Hippocampus

The hippocampus is an area of the limbic cortex adjacent to the amygdala in the depth of the temporal lobe. It receives information from other areas of the limbic cortex, the brain stem, and the amygdala. The hippocampus sends information back to the limbic cortex and to the mammillary bodies in the hypothalamus. The hippocampus plays a role in learning, memory, and emotion, and is particularly important in consolidation of long-term memory.

Fornix

The fornix is a crescent-shaped fiber of axons connecting the hippocampus with the hypothalamus (particularly the mammillary bodies) and additional limbic areas in the forebrain.

Hypothalamus

The hypothalamus is located on both sides of the lower part of the third ventricle, below the thalamus (“hypo” means below). This is a very complex structure, comprised of many nuclei. The hypothalamus supervises the *autonomic nervous system* and the *hormonal system*. It regulates emotions (such as anger, sadness, happiness) and drives (such as thirst, hunger, copulation, and sleep). The hypothalamus controls the hormonal system through its connections with the *pituitary gland.*

Mammillary Bodies

Anatomically, the mammillary bodies constitute part of the posterior-inferior area of the hypothalamus, and they are functionally ascribed to the limbic system They mainly receive information from the hippocampus via the fornix. They project to the thalamus and to the midbrain. The mammillary bodies play an important role in memory and emotion. Patients suffering from alcoholic Korsakoff’s syndrome exhibit damage in the mammillary bodies, which is usually associated with memory impairment

Midsagittal section

The limbic system includes a number of interconnected structures in the cortex and subcortical areas, and a few areas in the brain stem. Among the most prominent structures included in this system are the hippocampus, the amygdala, the hypothalamus, and the limbic cortex (a ring-shaped structure which includes the cingulate gyrus and the parahippocampal gyrus). The limbic system plays an important role in the regulation of, motivation, emotion, and memory through modulation of the autonomic nervous system and the endocrinal system.

Temporal Pole

The temporal pole is the inferior-medial end of the temporal lobe. It is a part of the

Uncus

The uncus is located in the parahippocampal gyrus of the temporal lobe, close to the amygdala nuclei. It is also a part of the ring-shaped limbic cortex.

Parahippocampal Gyrus

The parahippocampal gyrus is located in the medial part of the temporal lobe and is part of the ring-shaped limbic cortex. The parahippocampal gyrus is involved in functions of memory and emotion. In addition, this area is also involved in olfactory perception, as it is close to the entorhinal cortex, the piriform cortex, and the uncus—areas that serve a primary role in olfactory perception.

Fornix

The fornix is a crescent-shaped fiber of axons connecting the hippocampus with the hypothalamus (particularly the mammillary bodies) and additional limbic areas in the forebrain.

Corpus Callosum

The corpus callosum is the largest commissure (interhemispheric connection) in the brain. It facilitates communication between parallel cortical areas in the two brain hemispheres.

Cingulate Gyrus

The cingulate gyrus is part of the ring-shaped limbic cortex, located around the corpus callosum. It plays a greater role in memory than in emotion and is important to the integration of pain perception.

Orbital Frontal Gyrus

The orbital frontal gyrus is located at the base of the frontal lobe, over the eye socket (orbit), and is part of the ring-shaped limbic cortex. Because of its proximity to the olfactory areas in the brain, it is thought to be associated with olfactory perception. In addition, this area is associated with emotional response and social behavior. Persons with lesions in the orbital frontal gyrus exhibit uncontrolled, “childish” behavior characterized by irresponsibility, poor self-restraint, and “flattened” emotions (a kind of indifference).

Hypothalamus

The hypothalamus is located on both sides of the lower part of the third ventricle, below the thalamus (“hypo” means below). This is a very complex structure, comprised of many nuclei. The hypothalamus supervises the autonomic nervous system. Through its connection to the pituitary gland, the hypothalamus also regulates the hormonal system. A short “stalk” (the infundibulum) connects the hypothalamus to the pituitary gland, allowing the hypothalamus to control the release of hormones from the pituitary in two ways. First, certain hormones are synthesized in hypothalamic nuclei, carried via axons to the posterior part of the pituitary gland, and released from the pituitary directly into the blood system. Second, other hormones called releasing hormones are secreted from the hypothalamus, reaching the anterior pituitary gland via a specialized blood supply system. These releasing hormones stimulate the production and secretion of anterior pituitary hormones into the blood system.

Limbic Nuclei of the Thalamus

The thalamus comprises many nuclei, including several nuclei functionally associated with the limbic system. The anterior nuclei of the thalamus receive information from the mammillary bodies and project it to the cingulate gyrus. The medial dorsal nuclei receive input from the hypothalamus, the olfactory cortex, and the amygdala and send the output to associative limbic areas in the frontal lobe (particularly to the orbital frontal gyrus). These nuclei are involved in memory and emotions.

Language

The use of language is one of the most important human characteristics, for language constitutes a central means of thought, expression, and communication. Most available information relating to the physiology of language has been obtained by studying verbal behavior in patients with brain lesions. In most people, the primary language areas are located in the left hemisphere. A deficiency in language comprehension or production due to brain lesions is called aphasia. Studying different

For example, Broca's area in the frontal lobe is involved with the production of language, while Wernicke's area in the posterior part of the superior temporal *gyrus* is involved in the perception and comprehension of language.

Auditory Cortex

The auditory cortex is located in the *temporal lobe*, mostly hidden inside the lateral fissure. This area receives auditory input from the thalamic medial geniculate nucleus (MGN) and conveys the information to the associative auditory areas, located in the posterior part of the temporal lobe. The left auditory cortex is involved in identification and processing of verbal sounds, while the right hemisphere specializes in the complex analysis of nonverbal sounds (such as the intonation of speech). *Lesions* to the associative auditory areas, or to the connection between these areas and Wernicke's area, lead to pure word deafness, a syndrome characterized by the inability to understand speech, although the ability to hear, speak, read or write is preserved. As this syndrome is directly related to hearing, persons suffering from pure word deafness are capable of identifying words through other modalities. For example, they may be able to read words or read lips, where the meaning of words is mediated through vision. They are also capable of producing meaningful sentences through both speech and writing.

Wernicke's Area

Wernicke's area is located in the posterior part of the superior temporal gyrus. This area is involved in language comprehension. Lesions to Wernicke's area or adjacent areas lead to Wernicke's aphasia, characterized by the inability to comprehend or produce meaningful speech. People suffering from Wernicke's aphasia have fluent, articulate speech, but it is meaningless. Often, such speech is accompanied by sound exchanges (such as book-cook) or related word exchanges (bread-cake). They also make up meaningless words. (neologism). Persons suffering from Wernicke's aphasia find it difficult to understand what they read or hear, and have a hard time repeating words and sentences. Most such patients are unaware of the meaningless "word salad" they produce.

Angular Gyrus

The angular gyrus is located posterior to Wernicke’s area, proximate to the junction of the frontal, occipital, and parietal lobes. It connects Wernicke’s area with Broca’s area and is involved in the process of reading words.

Supramarginal Gyrus

The supramarginal gyrus is located in the parietal lobe. Damage to the supramarginal gyrus disconnects Wernicke’s area from Broca’s area and causes conduction aphasia, which is characterized by an inability to repeat words that are heard, despite relatively normal speech and comprehension of spoken words.

Arcuate Fasciculus

The arcuate fasciculus is a tract located within the supramarginal gyrus of the parietal lobe and the posterior-superior part of the temporal lobe. This tract connects Wernicke’s and Broca’s areas. Damage to this tract leads to conduction *aphasia*, which is characterized by an inability to repeat words that are heard, despite relatively fluent and proper speech and normal comprehension of spoken words.

Broca’s Area

Broca’s area is located in the inferior frontal gyrus in the left hemisphere. It is close to the primary motor areas controlling the muscles of speech. The production of speech involves fast and precisely coordinated movements of the tongue, lips, and jaw. Broca’s area holds the necessary muscular “patterns” required to produce speech. *Lesions* in this area (or adjacent cortical areas in the frontal lobe) lead to a language deficiency known as Broca’s aphasia. In this type of aphasia, patients have difficulty producing words, and hence in expressing their thoughts (although verbal comprehension is relatively normal). Their speech requires a great deal of effort and is very slow and halted. The grammatical structure of the patients’ sentences is also impaired (a phenomenon known as agrammatism), and patients sometimes miss words or use them inappropriately. For example, instead of saying, “I saw a large gray cat yesterday,” such a patient might say, “see gray cat.” Moreover, patients find it hard to enunciate words in a correct and precise order. Patients suffering from Broca’s aphasia are usually aware of their difficulties in pronouncing words and sentences and attempt to compensate for their deficiency by using physical gestures.

The Brain – The Cortex

The Cortical Lobes

The cortex is divided into four lobes: the frontal lobe, the parietal lobe, the temporal lobe, and the occipital lobe. These lobes are separated by sulci (deep grooves; singular sulcus) and fissures (grooves, larger than sulci). The central sulcus separates the frontal lobe and the parietal lobe, while the lateral fissure separates the temporal lobe from the frontal lobe and the parietal lobe. The part of the cortex hidden within the lateral fissure is known as the insular cortex.

In addition, the brain is divided into two *hemispheres*—the left and the right— by the midsagittal sulcus. The hemispheres are connected by a number of commissures (cross fiber bundles), the largest of which is the corpus callosum. The hemispheres are largely symmetric; certain asymmetric areas are usually related to functions in which one hemisphere is dominant. For example, the left hemisphere is dominant for verbal behavior.

Frontal Lobe

The frontal lobe is located in the superior-anterior part of the cortex, in front of the central sulcus. The frontal lobe includes the primary motor cortex in the precentral gyrus. This lobe specializes in the planning, execution, and control of motor functions. In addition, it includes parts of the limbic system that are associated with emotions, memory, and learning. The frontal lobe seems to participate in higher cognitive abilities such as abstract thinking, organization, and planning action strategies.

Parietal Lobe

The parietal lobe is located in the superior-posterior part of the brain, behind the central sulcus. It includes the primary somatosensory cortex in the postcentral gyrus. The primary somatosensory area projects to the associative somatosensory cortex located in the posterior parietal area. This area also receives visual and auditory information arriving from the occipital and the temporal lobes. Integration of this sensory information allows perception of the body’s location relative to its environment and perception of objects’ location in space.

Occipital Lobe

The occipital lobe is located in the posterior-inferior area of the cortex, around the calcarine fissure. It includes the primary, secondary, and associative visual cortex. It specializes in processing visual information.

Temporal Lobe

The temporal lobe is located in the anterior-inferior part of the cortex, beneath the lateral fissure. It includes the primary auditory cortex in the superior temporal gyrus. This lobe is involved in various functions, including the perception of auditory language, and visual and olfactory information. It is also involved in memory, learning, and emotion.

Right Hemisphere

The right hemisphere is considered dominant in spatial and nonverbal perception. It is more efficient than the left hemisphere in tasks that require spatial orientation and perception of shape, depth, and texture. The right hemisphere is also dominant in the expression and identification of emotions. For example, it is involved in the perception of speech intonation (prosody). Patients with lesions in the right hemisphere often exhibit difficulties in expressing or identifying emotions in speech, facial expression, or physical gestures. The right hemisphere mainly specializes in nonverbal, abstract, holistic thinking. The right hemisphere also plays an important role in directing attention.

Left Hemisphere

The left hemisphere usually specializes in such verbal functions as reading, writing, comprehension, speech, and verbal thinking. In most people, brain areas involved in verbal communication are located in the left hemisphere. Important language areas in the left hemisphere include Broca’s and Wernicke’s areas. In general, the left hemisphere is considered dominant in analytical, sequential processing of verbal information. While the left hemisphere mainly observes details, the right hemisphere emphasizes the whole.

The Cortex—Detailed Anatomy

The cortex surrounds the brain hemispheres like a tree bark (cortex means "tree bark"). In humans, the cortex is extremely convoluted. These convolutions include sulci (singular sulcus), which are relatively minor folds; fissures, which are deeper folds; and gyri (singular gyrus), which are protrusions between adjacent sulci or fissures. These folds increase the surface area of the cortex by a factor of three compared to a smooth surface. The total surface area of the cortex is about 2,000 cm^2. The cortex is mainly composed of glia cells, neuron somas, dendrites, and interneurons. The cortex is rich in nerve cell bodies (somas) that give it its grayish color, which is why the cortex is referred to as the "gray matter." Millions of myelinated axons extend from the cortex, connecting cortical areas with each other and with other parts of the brain. These myelinated bundles provide this area with a whitish appearance and hence its name, the "white matter."

Brain Sections

In order to see the inside of the brain we must dissect it into sections. There is a conventional method of dissecting the brain along three planes: parallel to the forehead plane, which defines coronal sections; parallel to the ground, which defines horizontal sections; and perpendicular to the ground and parallel to the fissure that separates the two brain hemispheres, which defines sagittal sections.

The Brain Stem and Subcortical Structures

Subdivisions of the Brain Stem

The brain stem includes the midbrain, the pons, and the *medulla oblongata*. All sensory information to the brain and motor information out of the brain passes through the brain stem. This information is carried to and from the brain by the carnial nerves and the spinal nerves. The brain stem includes many nuclei responsible for a variety of functions, such as arousal, motor control, and regulation of visceral organs (heart, lungs, glands).

Subcortical forebrain

A number of subcortical structures (that is, those located beneath the surface of the cortex) are found in the white matter within the telencephalon. The model includes several subcortical structures of the forebrain: the basal ganglia, thalamus, and hypothalamus, which are located between the brain stem and the cortex, within the white matter.

Basal ganglia

Basal ganglia are a group of subcortical nuclei located within the *white matter* surrounding the lateral *ventricles*. They constitute an important component of the motor system. For example, Parkinson's disease is caused by degeneration of certain dopaminergic neurons that originate in the midbrain and extend to the basal ganglia. Parkinson's patients are characterized by motor disturbances, including muscular rigidity, slowness of movement, a resting tremor, postural instability, and difficulty in initiating movement. The basal ganglia receive input from the cortex (particularly from the motor and somatosensory cortex) and the substantia nigra in the midbrain. Their output is projected to the thalamus, and from there to motor areas in the frontal lobe.

Thalamus

The thalamus is a large structure comprising two lobes, one in each hemisphere, connected by a bridge of *gray matter* (the massa intermedia). The thalamus is divided into numerous nuclei, including nuclei that receive sensory information and transfer it to sensory areas in the cerebral cortex. For example, the *lateral geniculate nucleus* (LGN) receives visual information from the eye and projects it to the primary visual cortex, while the medial geniculate nucleus (MGN) receives auditory information from the inner ear and projects it to the primary auditory cortex.

Other thalamic nuclei provide the cortex with information important to the coordination of movement. For example, the ventrolateral nucleus (VL) of the thalamus receives information from the cerebellum and basal ganglia and projects it to the *primary motor cortex*.

Hypothalamus

The hypothalamus is located on both sides of the lower part of the third ventricle, below the thalamus ("hypo" means below). This is a very complex structure, system. Through its connection to the *pituitary gland*, the hypothalamus also regulates the endocrinal system. A short “stalk” (the infundibulum) connects the hypothalamus to the pituitary gland, allowing the hypothalamus to control the release of hormones from the pituitary in two ways. First, certain hormones are synthesized in hypothalamic nuclei, carried via axons to the posterior part of the pituitary gland, and released from the pituitary directly into the blood system. Second, other hormones called releasing hormones are secreted from the hypothalamus, reaching the anterior pituitary gland via a specialized blood supply system. These releasing hormones stimulate the production and secretion of anterior pituitary hormones into the blood system.

Midbrain

The midbrain, or the mesencephalon consists of the tectum and the tegmentum. The tectum is located in the dorsal part of the midbrain and includes four small hillocks, a pair of the superior colliculi and a pair of the inferior colliculi. The superior colliculi are important for the coordination of eye movements with head and body movements. The inferior colliculi are part of the auditory system. The tegmentum is the *ventral* part of the midbrain. It contains a number of nuclei important for control of body movement, such as the *red nucleus* and the substantia nigra, and nuclei important for the regulation of arousal and attention.

Pons

The pons is a structure of the hindbrain that works in conjunction with the medulla and *diencephalon* to control respiration and heart rhythms. The pons is a major route by which the forebrain sends information to and receives information from the spinal cord and the peripheral nervous system. It also serves as a major route of connections between the cerebellum and the rest of the brain.

Medulla Oblongata

The medulla and the pons constitute the hindbrain. The medulla is a major route by which the forebrain sends information to and receives information from the spinal cord and the peripheral nervous system. It includes sensory and motor nuclei that constitute relay and data processing stations, as well as the nuclei of five cranial nerves. In addition, the medulla participates in regulating vital bodily functions including respiration, blood pressure, and heart rhythm.

Spinal Cord

The spinal cord is an elongated, cone-like structure. Its main role is to convey motor commands from the brain to the muscles and glands, and to bring sensory information from the body to the brain.

Detailed Anatomy of the Brain Stem

Caudate Nucleus

The caudate nucleus comprises a head, a body, and a tail. The caudate nucleus receives information from extensive cortical areas. It projects information to the globus pallidus, and from there to the thalamus and back to the frontal lobe, so that a neural circuit is established. In this way the basal ganglia control skeletal muscle movement and eye movements. The caudate nucleus also receives information from the frontal and the parietal lobes, and from areas in the *limbic system*, such as the hippocampus. Through this neural circuit the *basal ganglia* regulate learning, long-term memory, and emotions.

Putamen

The putamen is a disk-shaped nucleus that receives information from sensory and motor areas in the parietal and frontal lobes, and sends information back to the area responsible for motor planning in the frontal lobe. This nucleus is associated with regulation and control of movement.

Nucleus Accumbens

The nucleus accumbens is located ventromedial to the putamen and the caudate nucleus. Anatomically it is part of the basal ganglia, but some researchers ascribe it functionally to the limbic system, as it plays an important role in the reward (reinforcement) system. During eating, for example, the *neurotransmitter* dopamine is released in the nucleus accumbens, resulting in a rewarding feeling. Consumption of most drugs of abuse, including cocaine, heroin, alcohol, and tobacco, increases neural activity in the nucleus accumbens, which is associated with positive reinforcement.

Thalamus

The thalamus is a large structure comprising two lobes, one in each hemisphere, connected by a bridge of gray matter (the massa intermedia). The thalamus is divided into numerous nuclei, including nuclei that receive sensory information and transfer it to sensory areas in the cerebral cortex. For example, the lateral geniculate nucleus (LGN) receives visual information from the eye and projects it to the primary visual cortex, while the medial geniculate nucleus (MGN) receives auditory information from the inner ear and projects it to the primary auditory cortex.

Other thalamic nuclei provide the cortex with information important to the coordination of movement. For example, the ventrolateral nucleus (VL) of the thalamus receives information from the *cerebellum* and basal ganglia and projects it to the primary motor cortex.

Hypothalamus

The hypothalamus is located on both sides of the lower part of the third ventricle, below the thalamus ("hypo" means below). This is a very complex structure, comprised of many nuclei. The hypothalamus supervises the *autonomic nervous system*. Through its connection to the pituitary gland, the hypothalamus also regulates the hormonal system. A short "stalk" (the infundibulum) connects the hypothalamus to the pituitary gland, allowing the hypothalamus to control the release of hormones from the pituitary in two ways. First, certain hormones are synthesized in hypothalamic nuclei, carried via *axons* to the posterior part of the pituitary gland, and released from the pituitary directly into the blood system. Second, other hormones called releasing hormones are secreted from the hypothalamus, reaching the anterior pituitary gland via a specialized blood supply system. These releasing hormones stimulate the production and secretion of anterior pituitary hormones into the blood system.

Pineal Gland

The pineal gland is located along the brain midline, above the superior colliculi. This is a nonneural tissue, so despite its location, many researchers do not consider it part control of the peripheral nervous system, the pineal gland secretes the hormone melatonin into the blood. This hormone is primarily released during the night and is involved in regulation of the 24-hour cycles of human activity.

Mammillary Bodies

Anatomically, the mammillary bodies constitute part of the posterior-inferior area of the hypothalamus, and they are functionally ascribed to the *limbic system*. They mainly receive information from the *hippocampus* via the fornix. They project to the thalamus and to the midbrain. The mammillary bodies play an important role in memory and emotion. Patients suffering from alcoholic Korsakoff's syndrome exhibit damage in the mammillary bodies, which is usually associated with memory impairment.

Superior Colliculi

The superior colliculi (Latin for "mounds") resemble two hills; they are located in the *tectum* area of the midbrain. They are involved in the rapid, jerky movement of the eyes when scanning a visual scene (called saccadic movement) and in orientating the eyes and head toward objects in the visual field.

Inferior Colliculi

The inferior colliculi resemble two hillocks in the tectum of the midbrain and are located *caudal*ly to the superior colliculi. They receive information from the cochlear nuclei, both directly from the *contralateral* cochlear nucleus and indirectly through the ipsilateral superior olivary complex. From the inferior colliculi, axons extend to the thalamic MGN. Like the superior olivary complex, neurons in the inferior colliculi are also binaural, and this contributes to the ability to locate auditory sources. The main role of the inferior colliculi is to direct the head and body in the direction of auditory stimuli.

Cerebellar Peduncles

Cerebellar peduncles are bundles of axons that connect the cerebellum and the brain stem. There are three such peduncles—superior, middle, and inferior. The first consists mainly of efferent axons, which project motor commands from the cerebellum to the muscles and glands, while the other two consist mainly of afferent axons, which bring sensory information into the cerebellum.

Facial Colliculus

The facial colliculus looks like a protrusion on the floor of the fourth ventricle, in the dorsal part of the pons. This protrusion is formed by the bending of the facial nerve (cranial nerve. VII) around the abducens nerve (cranial nerve VI) nucleus at this point. The facial colliculus also contains the abducens nerve nucleus.

Pons

The pons is a structure of the *hindbrain* that works in conjunction with the medulla and *diencephalon* to control respiration and heart rhythms. The pons is a major route by which the forebrain sends information to and receives information from the spinal cord and the peripheral nervous system. It also serves as a major route of connections between the cerebellum and the rest of the brain.

Pyramid

The pyramid is an area of the medulla in which axons of the lateral corticospinal tract decussate (cross over) to the contralateral side of the brain. The name "pyramid" refers to the shape of the axon bundles decussating at the ventral surface of the medulla. The lateral corticospinal tract conveys motor information to distal skeletal muscles, mainly controlling voluntary movements of the arms, hands, and fingers

Cuneate Fascicle

The cuneate fascicle is a cluster of axons located in the lateral part of the dorsal column of the spinal cord and brain stem. The dorsal column conveys somatosensory information of fine touch, vibrations, and proprioceptive information (from muscles, tendons, and joints) from the body to the brain. The cuneate fascicles (one on each side of the brain) convey somatosensory information from the upper trunk, arms, neck, and back of the head

Gracil Fascicle

The gracil fascicle is a cluster of axons located in the medial part of the dorsal column information of fine touch, vibrations, and proprioceptive information (from muscles, tendons, and joints) from the body to the brain. The gracil fascicles (one on each side of the brain) convey somatosensory information from the lower trunk and limb.

Cranial Nerves

The cranial nerves are twelve pairs of nerves that control motor and sensory functions of the head and neck area. Their role is similar to that of the *spinal nerves* that innervate the trunk and limbs. Ten of the cranial nerves extend from the brain stem. The first two nerves, the olfactory and the optic nerves, enter the forebrain directly from the sensory organs without passing through the brain stem. Some of the cranial nerves (I, II, and VIII) only convey sensory information, some (III, IV, VI, XI, and XII) only convey motor information, while some are "mixed" nerves with both sensory and motor branches (V, VII, IX, and X). The olfactory nerve (I) is the only cranial nerve that directly enters the *cortex* - i.e., not passing through the brain stem or thalamus (and is therefore not shown in the model).

II. Optic Nerve

The optic nerve is the second cranial nerve; it is made up of axons of ganglion cells originating in the retina. From there, the optic nerve extends to the *lateral geniculate nucleus* (LGN) of the thalamus and to the superior colliculi in the midbrain. Some of the axons that make up the two optic nerves (one from each eye) cross to the other side of the brain (decussation). The point of decussation is called the optic chiasm. From the optic chiasm, the information proceeds through the optic tracts to the lateral geniculate nucleus (LGN) of the thalamus. It is the only cranial nerve that is considered part of the central rather than the peripheral nervous system, since it extends from the retina, which is part of the diencephalon.

III. Oculomotor Nerve

The oculomotor nerve is the third cranial nerve; it extends from the midbrain. This nerve, along with cranial nerves IV and VI, is responsible for eye movements, as well as control of lens shape and pupil size. It also engages in activities of the parasympathetic system.

The trochlear nerve is the fourth cranial nerve, extending from the midbrain. This nerve, along with cranial nerves III and VI, is responsible for eye movements.

V. Trigeminal Nerve

The trigeminal nerve is the fifth cranial nerve; it conveys various types of somatosensory information from the face, such as sensations of touch, pain, and temperature. In addition, the trigeminal nerve includes motor branches that innervate the chewing muscles.

VI. Abducens Nerve

The abducens nerve is the sixth cranial nerve; it extends from the area where the pons and the medulla intersect. This nerve, together with cranial nerves III and IV, is responsible for eye movements.

VII. Facial Nerve

The facial nerve is the seventh cranial nerve; it contains motor and sensory axons. The motor axons extend from the area where the *pons* and the medulla intersect. These axons innervate the saliva and lacrimal (tear) glands, and muscles that control facial expressions. A special extension of sensory fibers innervates the frontal part of the tongue and conveys information of taste to the nucleus of the solitary tract, a synaptic relay station located in the medulla.

VIII. Vestibulocochlear Nerve

The vestibulocochlear nerve is the eighth cranial nerve; it includes two sensory branches: the cochlear, nerve and the vestibular nerve. The cochlear nerve extends from the cochlea, the inner ear organ, and conveys auditory information. The vestibular nerve extends from the vestibular organ in the inner ear and conveys information relating to balance and equilibrium of the head and body.

IX. Glossopharyngeal Nerve

The glossopharyngeal nerve is the ninth cranial nerve; it contains motor and sensory axons. Motor axons extend from the medulla and innervate the muscles of the pharynx, and the saliva and lacrimal (tear) glands. A branch of sensory fibers of the solitary tract, a relay station located in the medulla. The glossopharyngeal nerve participates in activities of the parasympathetic system.

X. Vagus Nerve

The vagus nerve is the tenth cranial nerve; the name “vagus” (wandering) refers to its wide branching throughout the cavities of the chest and abdomen. This nerve regulates the functioning of viscera in these cavities and includes both motor and sensory axons. The motor axons extend from the medulla and innervate the viscera. They participate in regulation of cardiac rate, respiration, and gut function. Some of the sensory fibers of this nerve innervate the palate and convey information of taste to the nucleus of the solitary tract in the medulla. The vagus nerve plays a central role in the parasympathetic system.

XI. Spinal Accessory Nerve

The spinal accessory nerve is the eleventh cranial nerve; it extends from the medulla and provides motor innervation to some of the shoulder and neck muscles.

XII. Hypoglossal Nerve

The hypoglossal nerve is the twelfth cranial nerve; it extends from the medulla and provides motor innervation to muscles of the tongue, throat, and neck. It participates in speech and swallowing functions.

Brain Stem Sections

The transverse section of the brain is carried out perpendicular to the neuraxis. As the human neuraxis (unlike that of quadrupeds) bends in the area of the head, the transverse section (also called a cross section) of the brain stem is actually parallel to the ground. This differs from the transverse brain section, which is parallel to the forehead.

Illustrated are three frontal sections of the brain stem at the levels of the midbrain, *pons*, and medulla.

The Cerebellum

The cerebellum is a large structure located dorsally to the pons and the fourth ventricle and is part of the *hindbrain*. The cerebellum ("little brain") resembles the structure of the cerebrum. It comprises two hemispheres, separated by a mid-area called the vermis. The cerebellum is covered by a *cortex* that has many folds. Underneath the cortex are a number of deep cerebellar nuclei. The cerebellum plays a key role in movement, the regulation of descending motor pathway functions, and the execution of fast, coordinated movements. It also participates in motor learning and in maintaining posture and equilibrium. Damage to the cerebellum causes jumpy, jerky, and non-coordinated movements.

Cerebellar Hemispheres

The cerebellum comprises two hemispheres covered by a cortex. Motor and sensory input enters the cerebellar cortex from the brain stem and from extensive cortical areas in the parietal and frontal lobes. From the cerebellar cortex, neural information is conveyed to deep cerebellar nuclei, which project information to motor circuits in the frontal lobe and brain stem. This neural circuit allows the cerebellum to participate in the planning and monitoring of movements, and to control the ongoing execution of limb movement.

Vermis

The vermis is located along the midline separating the two cerebellar hemispheres. This area receives auditory and visual information from the *tectum* in the midbrai*n*. In addition, it receives somatosensory information from the body and from the head. The vermis sends output to deep cerebral nuclei, which in turn convey the neural signal to vestibular nuclei in the medulla, to the reticular formation, and to the *red nucleus*. Moreover, some of the output is transferred back to the cortex, through the thalamus. The vermis is involved in control of posture and equilibrium.

Cranial Nerves

The cranial nerves are twelve pairs of nerves that control motor and sensory functions of the head and neck area. Their role is similar to that of the spinal nerves that innervate the trunk and limbs. Ten of the cranial nerves extend from the brain stem.

The first two nerves, the olfactory and the optic nerves, enter the forebrain directly from the sensory organs without passing through the brain stem. Some of the cranial nerves (I, II, and VIII) only convey sensory information, some (III, IV, VI, XI, and XII) only convey motor information, while some are “mixed” nerves with both sensory and motor branches (V, VII, IX, and X). The olfactory nerve (I) is the only cranial nerve that directly enters the cortex - i.e., not passing through the brain stem or thalamus (and is therefore not shown in the model).

II. Optic Nerve

The optic nerve is the second cranial nerve; it is made up of *axons* of ganglion cells originating in the retina. From there, the optic nerve extends to the *lateral geniculate nucleus* (LGN) of the thalamus and to the superior colliculi in the midbrain. Some of the axons that make up the two optic nerves (one from each eye) cross to the other side of the brain (decussation). The point of decussation is called the optic chiasm. From the optic chiasm, the information proceeds through the optic tracts to the lateral geniculate nucleus (LGN) of the thalamus. It is the only cranial nerve that is considered part of the central rather than the peripheral nervous system, since it extends from the retina, which is part of the diencephalon.

III. Oculomotor Nerve

The oculomotor nerve is the third cranial nerve; it extends from the midbrain. This nerve, along with cranial nerves IV and VI, is responsible for eye movements, as well as control of lens shape and *pupil* size. It also engages in activities of the parasympathetic system.

IV. Trochlear Nerve

The trochlear nerve is the fourth cranial nerve, extending from the midbrain. This nerve, along with cranial nerves III and VI, is responsible for eye movements.

V. Trigeminal Nerve

The trigeminal nerve is the fifth cranial nerve; it conveys various types of somatosensory information from the face, such as sensations of touch, pain, and temperature. In addition, the trigeminal nerve includes motor branches that innervate

VI. Abducens Nerve

The abducens nerve is the sixth cranial nerve; it extends from the area where the pons and the medulla intersect. This nerve, together with cranial nerves III and IV, is responsible for eye movements.

VII. Facial Nerve

The facial nerve is the seventh cranial nerve; it contains motor and sensory *axons*. The motor axons extend from the area where the pons and the medulla intersect. These axons innervate the saliva and lacrimal (tear) glands, and muscles that control facial expressions. A special extension of sensory fibers innervates the frontal part of the tongue and conveys information of taste to the nucleus of the solitary tract, a synaptic relay station located in the medulla.

VIII. Vestibulocochlear Nerve

The vestibulocochlear nerve is the eighth cranial nerve; it includes two sensory branches: the cochlear, nerve and the vestibular nerve. The cochlear nerve extends from the cochlea, the inner ear organ, and conveys auditory information. The vestibular nerve extends from the vestibular organ in the inner ear and conveys information relating to balance and equilibrium of the head and body.

IX. Glossopharyngeal Nerve

The glossopharyngeal nerve is the ninth cranial nerve; it contains motor and sensory axons. Motor axons extend from the medulla and innervate the muscles of the pharynx, and the saliva and lacrimal (tear) glands. A branch of sensory fibers innervates the back part of the tongue and conveys information of taste to the nuclear of the solitary tract, a relay station located in the medulla. The glossopharyngeal nerve participates in activities of the parasympathetic system.

X. Vagus Nerve

The vagus nerve is the tenth cranial nerve; the name “vagus” (wandering) refers to its wide branching throughout the cavities of the chest and abdomen. This nerve regulates the functioning of viscera in these cavities and includes both motor and

They participate in regulation of cardiac rate, respiration, and gut function. Some of the sensory fibers of this nerve innervate the palate and convey information of taste to the nucleus of the solitary tract in the medulla. The vagus nerve plays a central role in the *parasympathetic system*.

XI. Spinal Accessory Nerve

The spinal accessory nerve is the eleventh cranial nerve; it extends from the medulla and provides motor innervation to some of the shoulder and neck muscles.

XII. Hypoglossal Nerve

The hypoglossal nerve is the twelfth cranial nerve; it extends from the medulla and provides motor innervation to muscles of the tongue, throat, and neck. It participates in speech and swallowing functions.

The Spinal Cord

Subdivisions of the Spinal Cord

The spinal cord is an elongated, cone-like structure located within the spinal column vertebrae, which protect it. Its main role is to convey motor commands from the brain to the muscles and glands, and to bring sensory information from the body to the brain. In addition, the spinal cord contains neuronal circuits that mediate numerous automatic and stereotyped motor patterns (such as walking) and reflexes (such as the stretch reflex). The spinal cord is organized in segments associated with the vertebrae that make up the spinal column.

Spinal Column

The spinal column is built of vertebrae that encircle and protect the spinal cord. Two spinal nerves extend between every two vertebrae. The spinal column is divided into four segments, the cervical vertebrae (C1-7), the thoracic vertebrae (T1-12), the lumbar vertebrae (L1-5), and the sacrum vertebrae (S1-5).

Spinal Cord

The spinal cord is an elongated, cone-like structure. Its main role is to convey motor commands from the brain to the muscles and glands, and to bring sensory information from the body to the brain.

Cervical Segments

The cervical segments comprise eight pairs of spinal nerves that innervate the palms of the hand, the arms, the neck, and the back part of the head

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Thoracic Segments

The thoracic segments comprise twelve pairs of spinal nerves that innervate the center of the body.

Lumbar Segments

The lumbar segments comprise five pairs of spinal nerves that innervate the pelvis and part of the legs

Sacral Segments

The sacral segments comprise five pairs of spinal nerves that innervate the back part of the legs and the buttocks.

Coccyx Root

The coccyx root comprises a pair of nerves of the sacral segments. These nerves pass close to the coccyx and innervate a small part of the buttocks. In animals, the coccyx root innervates the tail.

Termination of the Spinal Cord

In adults, the spinal cord extends along no more than two-thirds of the length of the spinal column. The spinal cord ends in the region of the L1 vertebra; the rest of the internal spinal cavity is filled by the cauda equina.

Cauda Equina

The cauda equina is located in the lowest part of the spinal cord. It consists of a mass of spinal roots, including the sacral, lumbar, and coccyx roots. These roots innervate

Detailed Anatomy

The spinal column is built of vertebrae that encircle and protect the spinal cord. A pair of spinal nerves extend from the spinal cord between every two vertebrae. Each spinal nerve is made of *dorsal* and *ventral roots*. The dorsal roots contain only sensory axons, while the ventral roots contain only motor axons. Similarly to the brain, the spinal cord comprises white matter (mainly myelinated axons) and gray matter (mainly the *somas* of neurons).

Dorsal Root Ganglion

The dorsal root ganglion is a protuberance of the dorsal root where the spinal nerve enters the spinal cord through the spinal column vertebrae. The ganglion includes the cell bodies of sensory nerve fibers entering the spinal cord.

Ventral Root

The ventral root is a bundle of motor *axons* extending from the spinal cord. Cell somas of these axons are located within the ventral horn of the gray matter of the spinal cord. Axons of the ventral roots project motor information to muscles and glands of the body. The ventral root and the dorsal root join together to form the spinal nerve.

Dorsal Root

The dorsal root is a bundle of sensory axons that enter the spinal cord. The somas of these axons are located in the dorsal root ganglion. These axons bring sensory information from the skin, muscles, and viscera. The dorsal root and the ventral root join together to form the spinal nerve.

White Matter

The white matter of the spinal cord is made of myelinated bundles of axons that give it a whitish color. These axons connect the body with the brain. The white matter surrounds the spinal gray matter (for further information, see “The Spinal Cord” subsection in the “Control of Movement” module).

Gray Matter

The gray matter is made of cell bodies that give it its grayish color. It is found in the center of the spinal cord and has a butterfly shape. Each of the butterfly wings includes two horns: a dorsal horn and a ventral horn. The dorsal horn receives sensory input from the dorsal root, while the ventral horn comprises somas of *motor neurons* that extend their axons through the ventral roots. The intermediate area between the two roots includes interneurons, neurons with short axons or no axons, whose processes are contained within the central nervous system.

Spinal Nerve

The spinal nerve comprises both ventral and dorsal roots. The *ventral root* includes motor nerve fibers, while the dorsal root includes sensory fibers. These two roots intermingle to form the spinal nerve.

Spinal Vertebrae

The spinal column comprises thirty-three vertebrae through which the spinal cord passes. The vertebrae encircle the spinal cord and protect it. A pair of spinal nerves pass between each two vertebrae (one on each side of the spinal column).

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