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ESSENTIALS IN THE NEURONAL ORGANIZATION OF THE CENTRAL NERVOUS SYSTEM

Handout

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INTRODUCTION

The neuronal organization of the central nervous system provides the backbone to the functional studies of the nervous system. Without the fundamental knowledge of the form, location and connectivity of the neurons in the brain and in the spinal cord, neurological diagnosis would be impossible.

Excellent textbooks are available for students studying in the English language courses. Depending on the orientation of the authors, these descriptions are of various lengths and complexities.

This provisional handout contains, as the title indicates, the essentials to understand the neuronal organization of the central nervous system. It was written based on several years of teaching experience both as a lecturer and as a laboratory instructor. It will, presumably, help the students to select the chapters of the textbooks and within the chapters ultimately the necessary subjects that the faculty of the Anatomy Department finds essential to appreciate the structure and function of the central nervous system. It is important to see clearly, however, that this handout does not substitute for the textbooks, but it can be used best in combination with the texts and the illustrations found in them.

It will be important to read the Glossary on the first few pages to become familiar with the wording and notions. Several tables will be found in the Appendix. The main idea behind the frequent use of tables is to call attention to the similarities and differences between related subjects.

The handout was written within a very short time period. The author would receive any suggestions for improvements or for the correction of mistakes with the greatest expectation and thanks.

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Dr. Miklós Réthelyi

GLOSSARY

Neurons - Specialized elongated cells, one of the cell types of the nervous tissue deriving from the ectoderm. Neurons are interconnected through synapses and form chains or networks.

Perikaryon - Enlarged portion of a neuron containing the nucleus surrounded by the cytoplasm. The perikarya are of various sizes; the neurons can be subdivided based on the diameter of their perikarya into small, medium sized, and large neurons. The surface of the perikaryon may serve as a postsynaptic site (i.e. receiving synapses). The location of the perikaryon determines the position of the neuron in the nervous system.

Ganglion - Groups of perikarya outside the central nervous system. The ganglia are of two types: sensory or autonomous ganglia.

Nucleus – A group of nerve cells in the central nervous system.

Dendrites - Cytoplasmic processes of neurons radiating from their perikarya. Dendrites could be straight or wavy; they may branch and may or may not carry dendritic protrusions or spines. The majority of neurons possess several dendrites (*multipolar neurons*). A specific group of neurons *(primary sensory neurons*) has no dendrites at all (*pseudounipolar neurons*). Some types of neurons have characteristic dendritic trees (e.g. Purkinje neurons in the cerebellum, pyramidal neurons in the cerebral cortex). Dendrites are the postsynaptic sites of the neuron, i.e. they receive synapses from axon terminals. Occasionally dendrites may contain clusters of synaptic vesicles and may act as presynaptic components.

Dendritic spines - Small, drumstick-like, regular expansions along the dendritic tree, spines are usually the postsynaptic sites of the neurons, i.e. they receive synapses from axon terminals.

Dendritic protrusions - Small, irregular expansions along the dendritic tree, protrusions are usually postsynaptic sites, i.e. they receive synapses from axon terminals. Protrusions participate in complex synapses, called *synaptic glomeruli*.

Axon - A special protrusion of the neuron. The axon originates either from the perikaryon or from one of the main dendrites with a conic portion (*axon hillock*) followed by the *initial segment* of the axon. Axons either course away from the parent perikaryon and terminate in another location of the nervous system (*Golgi type I* *neurons, tract neurons*) or arborize in the vicinity of the perikaryon with several branches (*Golgi type II neurons, interneurons*). Axons terminate in en passant and terminal boutons. Axons may branch giving rise to *collateral branches*. (The terms "axon" and "nerve fiber" can be used interchangeably.)

Terminal boutons - End-portions of the axon establishing synapses with one or several neurons. The boutons contain vesicles of different sizes, shapes and characters.

En passant boutons - Synapse forming a thickening along the axon preceding the terminal bouton.

Grey matter - one of the two parts of the central nervous system consisting of neuronal perikarya, dendrites, initial and terminal portions of axons or the entire axon arborizations of Golgi type II interneurons, glial cells and blood vessels. Grey matter occurs as interconnected areas (e.g. spinal cord), nuclei (e.g. brain stem nuclei) or cortical structures (e.g. cerebral and cerebellar cortices).

White matter - one of the two parts of the central nervous system consisting exclusively of nerve fibers, glial cells and blood vessels. White matter appears as funiculi (e.g. spinal cord), tracts (e.g. brain stem) or commissural structures (e.g. corpus callosum).

Nerve fiber - Axon surrounded by various sheaths (e.g. myelin sheath, sheath of Schwann cells). The terms "axon" and "nerve fiber" can be used interchangeably. Classification of nerve fibers in the peripheral nervous system: **Aα fibers**: thick myelinated fibers (e.g. motoneurons), conduction velocity: 60-120 m/sec; **Aβ fibers**: thick myelinated fibers, conduction velocity: 30-90 m/sec (e.g. Type IA muscle afferent neurons); **Aγ fibers**: myelinated fibers, conduction velocity: 6-60 m/sec (motoneurons innervating intrafusal fibers of the muscle spindle); **Aδ fibers**: thin myelinated fibers, conduction velocity: 6-30 m/sec (sensory neurons); **B fibers**: thin myelinated fibers (preganglionic autonomous neurons), conduction velocity: 3-15 m/sec; **C fibers**: unmyelinated fibers, conduction velocity: 0.5-2.0 m/sec (sensory and postganglionic autonomous neurons).

Nerve - Bundle of nerve fibers outside the central nervous system.

Tract - Bundle of nerve fibers inside the central nervous system.

Axon collateral - Branches along axons that terminate with the terminal type and en passant type boutons, similar to the main branches. Collaterals branching off near the axon hillock are called *initial axon collaterals*.

Synapses - Functional contacts between neurons. They may be simple or complex synapses. A simple synapse consists of one axon terminal (presynaptic component) and part of the perikaryon, a dendrite or a dendritic spine or a protrusion (postsynaptic component). In complex synapses the number of both the pre- and post-synaptic components are multiplied.

Reflex arc - Chain of several neurons. Each reflex arc consists of a sensory and a motor neuron and interneurons. The simplest reflex arc has one sensory and one motor neuron (monosynaptic reflex arc).

SPINAL CORD

The spinal cord consists of **grey** and **white matter.** Parts of the grey matter are termed the **dorsal** and **ventral horns** and the **intermediate zone.** In the thoracic and middle sacral spinal segments the grey matter expands laterally forming the small **lateral horn**.

The grey matter is surrounded by white matter which is subdivided into posterior, lateral and anterior funiculi. The **Lissauer tract** at the dorsal root entrance and the **anterior white commissure** ventral to the central canal are special parts of the white matter. The white matter consists of nerve fibers of different origins, destinations, and diameters.

Perikarya in the grey matter are arranged in laminae (described first by Rexed). Lamina I is the most dorsal lamina of the grey matter and contains a few large perikarya and several small and medium size neurons. Lamina II (earlier called **substantia gelatinosa**) is a collection of small neurons oriented along the axis of the spinal cord. Laminae III and IV contain few large perikarya and a great number of small and medium sized neurons (**nucl. proprius**). Laminae I-IV correspond to the dorsal horn.

Laminae V, VI and VII consist of medium sized neurons with a characteristic transverse orientation of the dendritic trees; they fill the **intermediate zone** of the grey matter.

Lamina VIII contains large neurons along the medial aspect of the ventral horn. Lamina IX contains the large sized motoneurons surrounded by numerous medium sized neurons. Lamina X is the grey matter around the central canal.

The grey matter is the termination area of nerve fibers from two sources: the dorsal roots (i.e. nerve fibers from the periphery), and the funiculi of the spinal cord (i.e. nerve fibers of supraspinal origin and intraspinal tracts).

The dorsal root fibers are the central branches of the sensory neurons, the perikarya of which are located in the spinal (sensory) ganglia. The peripheral branch could be followed to the site of sensory innervation (e.g. skin, joints, muscles, viscera). The much shorter central branches of the sensory neurons course in one of the dorsal roots and enter the spinal cord. At the dorsal root entrance the sensory fibers gather into medial and lateral bundles. In the medial bundle the thick sensory fibers enter the spinal cord. The majority of these fibers course uninterrupted cranially in the dorsal funiculus. These ascending branches give off collateral branches to the grey matter mainly at the segment of entry. These collaterals terminate in laminae III and IV. Another group of thick sensory fibers courses towards the intermediate zone reaching as far as lamina IX. Many of these fibers give rise to collateral branches which take an ascending course in the dorsal funiculus. Thus the dorsal funiculus is a collection of ascending fibers. Some of them course along the spinal cord and terminate in the gracile and cuneate nuclei of the medulla. Some others return into the spinal grey matter and terminate in Clarke's column. Surrounded by the ascending fibers, a small bundle of axons forms the descending collateral branches of the sensory neurons.

The lateral bundle of the dorsal root collects the small caliber nerve fibers which upon entering the spinal cord bifurcate and course upwards and downwards in the **Lissauer tract**. The ascending and descending branches of the sensory neurons give off several collateral branches that ultimately terminate in Laminae I and II (**superficial dorsal horn**) and less densely in Lamina V.

SPINAL REFLEX ARCS

The reflex activity of the spinal cord will be shown in three types of reflex arcs:

1) stretch reflex arc,
2) withdrawal reflex arc
3) autonomous reflex arc.

Each will be characterized by their components (sensory receptor, sensory neuron, interneurons, effector neuron(s), effector organs), and by the brief description of the significance of the reflex arc.

1. Stretch reflex arc
(synonyms: monosynaptic reflex arc, proprioceptive reflex arc, myotactic reflex arc)

Sensory receptor	muscle spindle in striated muscle
Sensory neuron	Type IA muscle sensory neuron (pseudounipolar neuron)
Interneurons	-
Effector neuron	Aα motoneuron
Effector organ	motor end plate in **same** striated muscle

Muscle spindles are complex sensory organs consisting of bundles of fine, striated muscle fibers (**intrafusal fibers**) surrounded by a connective tissue capsule. Peripheral branches of Type IA sensory neurons spiral around the intrafusal muscle fibers (**anulospiral nerve endings**) and are activated by the elongation of the muscle fiber (i.e. the stretch of the muscle). The same muscle fiber receives a second type of sensory nerve ending (**flower spray nerve endings**). The axon of a motor neuron located in the ventral horn of the spinal cord innervates the intrafusal fiber (**Aγ motoneurons**).

Type Ia sensory neurons are among the largest sensory neurons. The large sized perikarya sit in the spinal ganglia. The thick myelinated peripheral branch runs in one of the nerves innervating muscles, and innervates the intrafusal fibers with multiple sensory endings. The equally thick central branch of the neuron follows one of the dorsal roots, enters the spinal cord along the medial aspect of the dorsal root and terminates with its main branch in the ventral horn among the perikarya and dendrites of the large size motoneurons.

In addition to the main termination area the central branch of the sensory neuron sends collateral branches to **Clarke's column** via the dorsal funiculus.[1] Another set of collateral branches terminates in the intermediate zone of the spinal grey matter.

The **spinal cord termination** of the sensory neuron is restricted to the segment of entry; the only exceptions are the collateral branches in Clarke's column.

No direct **interneurons** are included into the reflex arc, hence its name: monosynaptic reflex arc. However, inhibitory interneurons located in the intermediate zone of the spinal cord receive synaptic connections from the collateral branches of the sensory neurons. The axons of these interneurons descend 1-2 segments and

[1]This description is characteristic to the sensory neurons of the lumbar region.

terminate on the motoneurons innervating muscles **antagonistic** to the motoneurons of the stretch reflex arc.

Effector neurons are the **Aα motoneurons** with large size perikarya in the ventral horn (lamina IX). The thick, myelinated axons of these neurons leave the spinal cord along the ventral root and ultimately join a nerve innervating the very same muscle in which the muscle spindle is located. Hence another name is used: proprioceptive reflex arc, i.e. the muscle's own reflex arc. The sensory receptor and the effector organ are, therefore, in the same muscle.

Effector organ is the motor end plate (**myoneural junction**) located in the same muscle. For its structure see the histology text books.

The functioning of the stretch reflex arc: The stretch (elongation) of the muscle activates the anulospiral sensory nerve endings in the muscle spindle. This activity is transported along the peripheral and central branches of the sensory neurons and a restricted group of Aα motoneurons will be activated directly. The activity of the motoneurons is transmitted back to the same muscle. The nerve impulses activate the muscle fibers via the motor end plate, and the muscle contracts (shortens).

The aim of the stretch reflex is to keep the length of a given muscle standard. Any attempt to elongate the muscle activates the reflex arc and the muscle inherently regains its original length. This control device is of paramount importance in muscles acting against gravity, particularly in the extensor muscles of the lower extremities. The stretch reflex arc shows an ongoing activity, as a continuous counteraction against the spontaneous flexion of the hip, knee and ankle joints due to the weight of the body.

One of the support connections is found through the collateral branches of the sensory neuron in the intermediate zone and the inhibitory interneurons preventing the activation of the motoneurons innervating the antagonistic (flexor) muscles. This type of inhibition is called **collateral inhibition**, and it facilitates the contraction of the extensor muscle by weakening the tone of the flexor muscles.

Another by-pass connectivity is through **Clarke's column**. The ascending collateral branches in the posterior funiculus excite the tract neurons in Clarke's column. Via this route, the activity of the muscle spindle will reach the cerebellum (see page 25).

The role of the Aγ motoneurons is to set the length of the muscle spindle through innervation of the intrafusal fibers. In this way the muscle spindle may adequately function (i.e. react to the stretch of the muscle) irrespective of the graded state of contraction of the muscle. The significance of the Aγ motoneurons in the transmission of descending impulses and the γ-loop will be mentioned in connection with the descending (motor) pathways (see page32).

2. Withdrawal reflex arc
(synonyms: ipsilateral flexor and contralateral extensor reflex arc, nociceptive reflex arc)

Sensory receptor	free nerve endings in the skin - nocireceptors
Sensory neuron	neurons with fine myelinated (Aδ) or unmyelinated (C) branches (pseudounipolar neurons)
Interneurons	at least one or several in the dorsal horn and intermediate zone
Effector neuron	Aα motoneuron
Effector organ	motor end plate in striated muscle

Free nerve endings (i.e. terminal ramification of the fine caliber peripheral branches of small and medium sized sensory neurons) occur widespread throughout the skin as well as in joint capsules, muscles, periosteum and viscera. Free nerve endings are sensitive to various stimuli; in this connection mechanical, thermal and chemical stimuli with the potential to damage tissue will be considered. The general name of these receptors: **nocireceptors** (sensitive to damage = noxa).

The peripheral branches of the **sensory neurons** are collected in skin nerves, whereas the central branches follow the dorsal root. Upon entering the spinal cord, the fine fibers form a bundle in the **lateral aspect** of the root. The fibers bifurcate and course rostrally and caudally in **Lissauer's tract** near the dorsal root entry. The ascending and descending branches issue collateral branches that terminate in the superficial part of the dorsal horn (laminae I and II) and at the junction of the dorsal horn and intermediate zone (i.e. lamina V).

There are one or more **interneurons** intercalated between the sensory and the motor neurons. They are located at the site of termination of the terminal branches of the sensory neuron. The last interneuron in the row ultimately **excites** a motoneuron in the ventral horn innervating a flexor muscle. The interneurons activate tract neurons, the axons of which cross the midline in the anterior white commissure and turn into an ascending course in the contralateral ventrolateral funiculus. These axons form the **spinothalamic tract**. Contralateral collateral branches of these axons form synaptic connections with contralateral motoneurons innervating extensor muscles.

Effector neurons are the Aα motoneurons with large size perikarya in the ventral horn (lamina IX). The thick, myelinated axons of these neurons leave the spinal cord via the ventral root and ultimately join a nerve and innervate flexor muscles. Flexor muscles shorten the extremity, hence the name: withdrawal reflex arc.

Effector organ is the motor end plate (myoneural junction). For its structure see the histology text books.

The functioning of the withdrawal reflex arc: Tissue damaging stimuli or stimuli threatening the integrity of the skin evoke a quick protective reaction, i.e. the withdrawal of the body or part of it away from the zone of the dangerous stimulus. The intensity of the stimulus will set the activity of the receptors, the number of the interneurons, the number of the motoneurons and eventually the strength and extent of the flexor muscle activity. A light, but tissue damaging stimulus (e.g. a pin prick) evokes the activity of one or two muscles, while a strong stimulus may elicit the withdrawal of the entire extremity.

One of the by-pass connections is the activation of the contralateral extensor muscles. In quadruped animals and also in connections with the lower extremities of the erect human being the withdrawal of the extremity on one side must be balanced by an increased extensor activity on the other side of the body. The synonym reflects these connections: ipsilateral flexor and contralateral extensor reflex arc.

Another by-pass connection leads to the thalamus and from there to the sensory cerebral cortex. Via this way the stimulus is felt as pain in man and initiates nociceptive reactions in animals, hence the less fortunate synonym: nociceptive reflex arc.

3. Autonomous reflex arc

Sensory receptor	free nerve endings in the viscera
Sensory neuron	neurons with fine myelinated (Aδ) or unmyelinated (C) branches (pseudounipolar neurons)
Interneurons	at least one or several in the dorsal horn and intermediate zone
Effector neurons	chain of two neurons: preganglionic and postganglionic autonomous neurons
Effector organ	Groundplexus

Free nerve endings (i.e. terminal ramification of the fine caliber peripheral branches of small and medium sized sensory neurons) occur widespread in the wall of the viscera as well as in the parenchyma. The specific stimuli are: stretching of the organ, the tension induced by obliteration of a tube-like organ (e.g. ureter), or the strongest stimulus - insufficient blood supply (ischemia).

The peripheral branches of the **sensory neurons** are collected in visceral nerves[2]. The perikarya of the sensory neurons are located in the spinal ganglia, and the central branches follow the dorsal roots. Upon entering the spinal cord, the **fine fibers** form a bundle in the **lateral aspect** of the root. Similarly to the fine sensory fibers from somatic structures, the fibers of visceral origin bifurcate and course rostrally and caudally in Lissauer's tract near their dorsal root entry. The ascending and descending branches issue collateral branches that terminate in the superficial part of the dorsal horn (exclusively to Lamina I) and at the junction of the dorsal horn and intermediate zone (Lamina V).

The same group of **interneurons** mentioned in connection with the withdrawal reflex arc establishes the linkage between the sensory and the motor neurons for this autonomic reflex arc. This joint set of interneurons will have a special significance in mismatched signaling between the neurons of the two reflex arcs (see later in this chapter).

The uniqueness of the autonomous reflex arc is on the **effector** side. Contrary to the two previous reflex arcs which involve somatic effector organs (striated muscles), the autonomous reflex arc activates visceral effector organs (smooth muscles or

[2]Visceral sensory nerve fibers may join both the sympathetic and the parasympathetic subdivisions of the visceral (autonomic) nervous system. In connections with the spinal reflex arcs only those following the sympathetic nerves will be considered here.

glandular cells) the motor innervation of which is executed by two neurons**. The perikaryon of the first neuron** is located in the **lateral horn** of the spinal grey matter in the thoracic and upper lumbar segments.[3] The axons of these neurons join the axons of the Aα and Aγ motoneurons leaving the spinal cord through the thoracic ventral roots. The axons then detach from the ventral branch of the spinal nerve, thus forming the **white communicating rami** and join the **sympathetic trunk** where they have two options. They can either terminate in one of the ganglia of the sympathetic trunk (**autonomic ganglia**), or descend in the sympathetic trunk, joining one of the splanchnic nerves (**lesser** or **greater splanchnic nerves**) terminating ultimately in one of the autonomous ganglia in the abdominal cavity, usually in the **celiac ganglion**. Since none of these neurons reach the peripheral organ, but rather terminate in one of the autonomous ganglia, they are called **preganglionic autonomous neurons**. Preganglionic neurons synapse with neurons in the ganglia (**postganglionic autonomous neurons**), the axons of which innervate the appropriate effector organs, i.e. smooth muscles or glandular cells. Axons of the postganglionic neurons located in the thoracic ganglia of the sympathetic trunk (**paravertebral ganglia**) rejoin the ventral branches of the thoracic spinal nerves (**intercostal nerves**) via the **grey communicating rami** (grey because most are unmyelinated) and course parallel with the somatic fibers. Axons of the postganglionic neurons located in the cervical, lumbar or sacral ganglia may join one of the plexuses of spinal nerves which innervate the somatic structures of the trunk and extremities, or may follow the main arteries of the extremities (axillary or femoral arteries). The postganglionic fibers ultimately innervate smooth muscles in the blood vessels (**vasomotor activity**), smooth muscles attached to hair follicles (**pilomotor activity**) or sweat glands (**sudomotor activity**). Axons of the postganglionic fibers located in the abdominal autonomous ganglia (**prevertebral ganglia**) reach the viscera through autonomous plexuses which follow the arteries of the abdominal cavity or the pelvis. These fibers innervate smooth muscles in the wall of the viscera or in blood vessels, as well as glands.

Effector organ is the terminal ramification of the axons of the postganglionic neurons (**Grundplexus**). The terminal portion of these fibers loses its Schwann cell

[3]Identical neurons could also be found in the middle sacral segments, but the reflex connections of these neurons are more complicated than those in the thoracic segments.

covering and contains several expansions filled with synaptic and dense-core vesicles. No specific synaptic connection is known to exist between the nerve fibers and the cells to be innervated.

Mechanical and chemical stimuli affecting the viscera could elicit spinal autonomous reflexes, although the large majority of the autonomous reflexes pass through the brain stem autonomic centers.

Due to the joint interneuron pool for the withdrawal and autonomic reflex arcs, painful cutaneous stimuli may elicit autonomic reactions (i.e. vasoconstriction or vasodilatation, sweating) and noxious visceral stimuli might result in the contraction of level-related somatic muscles (defense musculaire, i.e. contraction of the abdominal muscles as a symptom of the irritation of the peritoneum.)

SPINAL PATHWAYS (TRACTS)

Axons coursing in the white matter of the spinal cord form bundles of fibers with similar origins, courses and destinations. These bundles are called **tracts** that can be subdivided into long ascending, long descending, and intraspinal (intersegmental) tracts.

Tracts should be characterized by the location of their perikarya, the course and termination of the axon of the tract neurons.

Table I.
Long ascending spinal tracts

Table II.
Long descending spinal tracts

Ascending as well as descending tracts show an “onion skin”-like arrangement of axons originating from or terminating at a given segmental level (**eccentricity of the long axons**). Ascending tract fibers joining the tract at any segmental level start to ascend at the central aspect of the tract thus pushing the axons of more caudal origin into a more peripheral (lateral) position. Descending fibers with the destination to a cranial segment travel more centrally than those terminating in more caudal segments. This topography is modified in the dorsal funiculus. Ascending fibers of adjacent segmental origin are distributed in sheets oriented in a somewhat tilted position with respect to the glial septum marking the posterior midline. Thus the caudalmost fibers ascend at both sides of the glial septum, whereas fibers from the following segments in the cranial direction are attached layer by layer to the lateral aspect of the caudalmost fibers.

Intraspinal (intersegmental) tracts

A large number of spinal cord neurons interconnect adjacent or far away spinal segments. The axons of these neurons form a loosely defined tract around the lateral and ventral aspect of the grey matter (**tractus fundamentalis**).

BRAIN STEM

The brain stem (medulla, pons and midbrain) consists of well delineated groups of neurons having similar afferent and efferent connections (**nuclei**), and of neurons scattered without any clustering and bundles of nerve fibers (axons) having similar origins and destinations (**tracts**). The grey and white matter distribution of the spinal cord can be recognized in a modified arrangement in the medulla. Nuclei, tracts and scattered neurons show characteristic patterns in the pons and in the midbrain.

Table III.
Types of nuclei in the brain stem

Types of tracts in the brain stem

1. Descending tracts coursing without interruption through the brain stem.
2. Descending tracts terminating in the brain stem
3. Descending tracts originating in the brain stem and coursing to the spinal cord.
4. Descending tracts confined to the brain stem.
5. Ascending tracts coursing without interruption through the brain stem.
6. Ascending tracts from the spinal cord terminating in the brain stem.
7. Ascending tracts originating from the brain stem and coursing to the thalamus.
8. Ascending tracts confined to the brain stem
9. Afferent and efferent cerebellar tracts.
10. Medial longitudinal fasciculus.

INNER STRUCTURE OF THE MEDULLA, CAUDAL PORTION

The characteristic shape of the spinal grey matter can be discerned with minor modifications in the cross section of the caudal portion of the medulla. The dorsal horn, called the spinal nucleus of the trigeminal nerve is dislocated into a lateral direction due to the appearance of the **gracile** and **cuneate nuclei** in the continuation of the dorsal funiculus (**dorsal column nuclei**). The intermediate zone of the spinal grey matter continues into the most caudal extension of the **reticular formation**. The group of motoneurons is subdivided into ventrolateral and dorsomedial motor nuclei. The axons of the motoneurons in the ventrolateral group (**nucleus ambiguous**) join the accessory and vagus nerves; the axons of the dorsomedial group of motoneurons (**hypoglossal nucleus**) form the hypoglossal nerve.

Axons of the neurons in the spinal nucleus of the trigeminal nerve cross the midline, ventral to the central canal, and take an ascending course towards the thalamus (**trigeminal lemniscus**). Also, the axons of the neurons in the gracile and cuneate nuclei cross the midline ventral to the central canal (**decussatio lemniscorum, internal arcuate fibers**) and take an ascending course on both sides of the midline with a final destination in the thalamus (**medial lemniscus**). At the ventrolateral aspect of the grey matter develops a large nucleus of folded contour (**inferior olivary nucleus**) accompanied by **accessory olivary nuclei**. The axons of the olivary nuclei take an oblique course, cross the midline in front of the central canal and course towards the cerebellum via the inferior cerebellar peduncle.

Ascending branches of the large pseudounipolar spinal ganglion cells coursing in the dorsal funiculi terminate in the gracile and cuneate nuclei and synapse with the neurons of these nuclei. The Lissauer tract continues in the **spinal tract of the trigeminal nerve,** in which the fine caliber sensory fibers of the trigeminal nerve descend before they terminate in the **spinal nucleus of the trigeminal nerve**. Some of the trigeminal sensory fibers course caudally in the Lissauer tract. Fine sensory fibers from the facial, glossopharyngeal and vagus nerves course in the spinal tract of the trigeminal nerve, too. The continuation of the lateral funiculus contains the spinothalamic tract, and the ventral and dorsal spinocerebellar tracts. The latter two leave the medulla and enter the cerebellum via the inferior cerebellar peduncles. The continuation of the spinal anterior funiculi contain the corticospinal tract. The majority of the corticospinal tract fibers cross the midline at this level (**pyramidal decussation**) and descend contralaterally in the lateral funiculi (**lateral corticospinal tract**). The remaining corticospinal fibers continue in the anterior funiculi (**anterior corticospinal tract**). The other descending tracts to the spinal cord cluster around the ventral portion of the grey matter.

A small group of neurons next to the cuneate nucleus (**external** [**or accessory**] **cuneate nucleus**) receive the central branches of the sensory neurons from the muscles of the upper extremity and relay the impulses towards the cerebellum through the inferior cerebellar peduncles (**cuneocerebellar tract**).

INNER STRUCTURE OF THE MEDULLA, ROSTRAL PORTION

Here the grey and white matter distribution is hardly discernible. The spinal tract and the spinal nucleus of the trigeminal nerve and the ensuing trigeminal lemniscus, the dorsal column nuclei and the ensuing medial lemniscus, the inferior olivary nucleus and the ensuing olivocerebellar tract, the nucleus ambiguous and the hypoglossal nucleus, the reticular formation, the corticospinal tract, and the ascending spinal tracts can be found in their similar locations as found in the caudal portion of the medulla. Axons of the nucleus ambiguous neurons join the vagus and glossopharyngeus nerves. The central canal here expands into the fourth ventricle, the floor of which is the **rhomboid fossa**.

Dorsal to the nucleus ambiguus and lateral from the hypoglossal nucleus two groups of neurons appear. The axons of the medial nucleus (**dorsal nucleus of the vagus nerve**) join the vagus nerve and continue along its branches up to the viscera innervated by the vagus nerve. These fibers terminate in small autonomous (parasympathetic) ganglia in the wall of the tube-like viscera and at the entrance of the dense parenchymal viscera. The lateral group of neurons (**solitary nucleus**) receives the visceral afferent fibers of the facial, glossopharyngeal and vagus nerves (**solitary tract**) which is surrounded by the nucleus. An ascending tract originates from the solitary nucleus carrying the **gustatory impulses** into the thalamus.

At the caudal tip of the rhomboid fossa a small group of neurons richly surrounded by large sinusoids form the **area postrema**. The blood-brain barrier is apparently lacking in this nucleus. The neurons possess chemosensory activity and seem to be the center of vomiting.

INNER STRUCTURE OF THE PONTO-MEDULLARY JUNCTION

The spinal tract and spinal nucleus of the trigeminal nerve and the ensuing trigeminal lemniscus, the medial lemniscus, the corticospinal tract, and the ascending spinal tracts can be found in similar locations as they are found in the rostral portion of the medulla.

At the location just rostral of the nucleus ambiguous another group of motoneurons appear (**facial nucleus**), the axons of which form a loop before they leave the ponto-medullary junction to form the facial nerve. Surrounded by the loop of facial motor axons, in a similar location but rostral to the hypoglossal nucleus is a group of motoneurons called the **abducens nucleus**. The axons of the motoneurons in the abducens nucleus take a ventral course and leave the ponto-medullary junction close to the ventral midline.

Dorsal to the facial nucleus a small group of neurons (**inferior salivatory nucleus**) can be found, the axons of which descend and join the glossopharyngeal nerve. The axons course in the tympanic nerve and terminate in the **otic ganglion**. The postganglionic neurons of the otic ganglion innervate the **parotid gland** with secretory fibers.

In the dorsolateral region of the rostral medulla two sets of nuclei can be found: the cochlear and vestibular nuclei. The **ventral** and **dorsal cochlear nuclei** are the termination site of the central branches of the bipolar sensory spiral (cochlear) ganglion cells; they approach the brain stem in the cochlear portion of the vestibulocochlear nerve. The central branches of the bipolar vestibular ganglion cells arrive in the vestibular part of the vestibulocochlear nerve and terminate in the **vestibular nuclei** (**superior**, **medial, inferior and lateral** [**or Deiter's**] **vestibular nuclei**) which are located medially to the cochlear nuclei.

The axons of the neurons in the ventral and dorsal cochlear nuclei course towards the medullary relay nuclei of the acoustic system (**superior olive, trapezoid**

body). Axons of the neurons of the superior olive form the ascending **lateral lemniscus** terminating in the midbrain inferior colliculus.

The connections of the vestibular nuclei will be treated separately under the heading Vestibular system, page 46.

INNER STRUCTURE OF THE PONS

The spinal tract and the spinal nucleus of the trigeminal nerve and the ensuing trigeminal lemniscus can be found in the caudal portion of the pons, just caudal to the entrance of the trigeminal nerve. The medial lemniscus, the ascending spinal tracts and the lateral lemniscus course in the dorsal portion of the pons, called the **tegmentum pontis**. Also, the pontine reticular formation is to be seen in the middle portion of the tegmentum.

The fibers of the corticospinal tract dissociate and course in multiple bundles in the ventral portion of the pons (**basis pontis**).

Two components of the trigeminal nuclear complex can be found in the pontine tegmentum: the **motor** and the **main sensory** [**or pontine**] **trigeminal nucleus**. The motor nucleus of the trigeminal nerve represents the continuation (rostrally) of the facial motor nucleus. The axons of the motoneurons form a small loop and after a short course leave the pons and form the smaller (motor) division of the trigeminal nerve. The main sensory nucleus is the termination site of the thick sensory fibers of the trigeminal nerve. (The main nucleus corresponds to the dorsal column nuclei in the caudal medulla.) The axons of the neurons in the main sensory nucleus cross the midline at the level of their perikarya and ascend contralaterally towards the thalamus (**dorsal trigeminal lemniscus**).

Sandwiched between the sensory and motor nuclei is a group of preganglionic (parasympathetic) neurons (**superior salivatory nucleus**), the axons of which descend in the pons and join the intermediate nerve which carries sensory and preganglionic autonomous fibers and merges with the facial nerve. The axons from the superior salivatory nucleus course in the greater petrosal nerve and in the chorda tympani, both which are branches of the facial nerve and which terminate in the **pterygopalatine** and **submandibular ganglia**, respectively. The postganglionic neurons along their course innervate the small glands in the mucous membrane of the nasal and oral cavities, the lacrimal glands, as well as the submandibular and sublingual glands.

Close to the dorsal aspect of the pons-midbrain junction a group of pigmented nerve cells form the **locus ceruleus** which is one of the sources of noradrenergic fibers. Axons of the neurons in the locus ceruleus project to practically all parts of the brain.

Scattered groups of neurons can be found in the basis of the pons (**nuclei pontis**). They receive the fibers of the descending **corticopontine tracts** and relay their impulses into the contralateral cerebellar hemispheres via the middle cerebellar peduncles (**pontocerebellar tract**).

INNER STRUCTURE OF THE MIDBRAIN

The cross section of the midbrain reveals three levels in dorso-ventral succession: **tectum**, **tegmentum** and **basis**.

The ascending tracts from the spinal cord, medulla and pons, namely the spinothalamic tract, medial lemniscus, trigeminal lemniscus, dorsal trigeminal lemniscus, and the lateral lemniscus form a transverse elongated area at the junction of the tegmentum and basis. The descending tracts, namely the corticospinal and corticopontine tracts, fill entirely the basis of the midbrain.

The midbrain tectum carries two large paired structures: the superior and inferior colliculi (the four together: **lamina quadrigemina**). The **superior colliculus** has a layered, cortex-like structure, it will be described in detail in connection with the visual pathway (see page 44). The **inferior colliculus**, as a relay nucleus in the auditory system, receives the fibers from the lateral lemniscus. The neurons of the inferior colliculus project to the medial geniculate body located under the caudal pole of the thalamus.

The midbrain tegmentum contains a round nucleus (**red nucleus**), one of the relay nuclei of the extrapyramidal system (see Motor system, extrapyramidal subsystem; page 43). The tegmentum is well separated from the basis by an elongated group of neurons (**substantia nigra**). This nucleus is visible on the brain cross sections due to the melanin pigment granules in the cytoplasm of the neurons.

Similarly to the red nucleus, the substantia nigra is also part of the extrapyramidal system.

The large majority of the efferent cerebellar fibers, especially from the dentate nucleus, course towards the midbrain via the superior cerebellar peduncle. The tract decussates caudal to the red nucleus and the fibers pass cranially around the red nucleus en route to the thalamus (**dentatothalamic tract**). Collateral branches are issued to the neurons of the red nucleus. The **rubrospinal tract** originates at the red nucleus; the fibers decussate caudal to the nucleus and course through the pons and medulla towards the spinal cord.

Neurons surrounding the cerebral aqueduct form the **midbrain central grey**. Attached to its lateral aspect are located the large pseudounipolar neurons of the trigeminal nerve (**mesencephalic nucleus of the trigeminal nerve**). In a unique way, sensory neurons from the trigeminal (Gasserian) ganglion migrate into the central nervous system and settle in the midbrain. The peripheral branches of the sensory neurons join the trigeminal nerve and terminate in the muscle spindles of the masticatory muscles. The central branches descend into the pons (**mesencephalic tract of the trigeminal nerve**) and the fibers synapse with the trigeminal motoneurons innervating the masticatory muscles. The reflex arc formed by the sensory neurons of the mesencephalic nucleus of the trigeminal nerve represents **the only monosynaptic (proprioceptive) reflex arc in the brain stem**.

Two groups of motoneurons are located in the midbrain, both of which are attached to the ventral aspect of the central grey. Caudally the motoneurons of the trochlear nerve form a motor nucleus (**nucleus of the trochlear nerve**), the axons of which decussate and course towards the dorsal surface of the midbrain. They reach the dorsal surface near the midline (on each side of the **frenulum veli medullaris**), at the origin of the superior cerebellar peduncles. Cranially, in an identical position, the **motor nucleus of the oculomotor nerve** can be found. The axons of these motoneurons course towards the ventral surface of the midbrain, pass along the medial aspect of the red nucleus, and ultimately leave the midbrain on the side walls of the interpeduncular fossa (namely through the medial mesencephalic sulcus). Attached dorsally to the motor nucleus, one finds a group of preganglionic (parasympathetic) neurons, forming the **Edinger-Westphal nucleus.** The axons of the neurons in this nucleus course with the motor axons of the oculomotor nerve, and ultimately terminate in the ciliary ganglion. The postganglionic neurons of the ciliary ganglion innervate the ciliary and the sphincter iridis muscles (see Visual pathway, pupillary reflex arc; page 44).

Table IV.
Summary table of the brain stem nuclei

Table V.
Summary table of the cranial nerve nuclei

RETICULAR FORMATION AND THE RAPHE NUCLEI

The central portion of the medulla and the pontine and midbrain tegmentum are populated with loosely delineated and ambiguously interconnected groups of neurons which form the **reticular formation**. The three large components of the nervous system: the **somatic**, the **visceral**, and the **connectivity of the organs of special senses** merge in the reticular formation, i.e. all systems provide afferentation to the reticular nuclei or areas of the reticular formation. Therefore, it is involved practically in all kinds of neuronal events.

Included into the reticular formation are several groups of neurons located in the midline, forming the **raphe nuclei**.

The major efferent projections from the reticular formation and the raphe nuclei lead to the cerebral cortex (**ascending reticular activating system**), to the cerebellar cortex, and to the spinal cord. Several groups of neurons in the reticular formation contain noradrenalin as their transmitter, among them the most significant being the **locus ceruleus**. Ascending and descending noradrenergic nerve fibers from the reticular formation project to all parts of the central nervous system. In a similar manner, serotonin containing neurons in the raphe nuclei have a widespread axonal projection parallel with the noradrenergic fibers to the entire central nervous system.[4]

Among their various roles, noradrenergic and serotoninergic neurons participate in the sleep and wake cycles, and also in the internal (“inherent”) anesthesia. In the latter case they interact with groups of neurons containing the internal (“natural” or “inherent”) morphine-like peptides: endorphin, dynorphin and enkephalin.

THALAMUS

The largest portion of the diencephalon, the thalamus, consists of three large nuclear groups divided by the Y-shaped, sagittally oriented white lamina: **anterior, dorsomedial, and ventrolateral nuclear groups**. Small sized nuclei are enclosed into the lamina, and a shell-like grey structure covers the lateral aspect of the thalamus, called the **reticular nucleus**. Attached to its caudal pole two discrete elevations serve as relay nuclei in the visual (**lateral geniculate body**, LGB) and acoustic pathways (**medial geniculate body**, MGB). The geniculate bodies form the **metathalamus,** together with the pulvinar. Attached to the dorsomedial surface of the thalamus, the stria medullaris, the habenular trigones and the habenular commissure can be found as components of the **epithalamus**. They will be treated in connection with the limbic system (see page 38).

Two basic types of neurons can be found widespread throughout the thalamus; the **thalamocortical relay neurons** and the **Golgi type II local interneurons**.

The thalamocortical relay neurons are medium sized nerve cells with 4 to 6 main dendrites that split into 6 to 8 straight secondary branches abruptly about 200-300 μm away from their perikarya. The dendrites are studded with spines and protrusions. The axons of the relay neurons leave the thalamus and course towards the cerebral cortex forming the **thalamic peduncles**. The relay cells represent the last order neurons in the corticopetal tracts (**thalamocortical neurons**), their terminal arborization ending predominantly in the IVth layer of the cerebral cortex (**inner granular layer**).

The Golgi type II neurons are smaller than the relay neurons, possessing 3 to 4 long dendrites having a wavy course. Irregular protrusions are seen along the entire length of the dendrites. The axons of the neurons split repeatedly within the dendritic field and terminate with many en passant and terminal boutons.

Each thalamic nucleus receives a dense arborization of nerve fibers from the cerebral cortex (**corticothalamic tract**).

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[4] A third type of nomoamine, dopamine, is found in two discrete populations of neurons: substantia nigra and the hypothalamic infundibular nucleus.

Axon terminals, dendrites, dendritic spines and protrusions form complex synaptic structures characteristic to the thalamic nuclei. The functional significance of the complex synapses (**synaptic glomeruli**) is conjectural.

The various thalamic nuclei can be described by the source of the main afferent connection and by the destination of the axon of the thalamocortical relay neurons.

Table VI.
Connections and functional significance of the thalamic nuclei

SENSORY SYSTEMS

In a simplistic way, the sensory systems consist of chains of synaptically interconnected neurons (**sensory pathways**). The sensory paths start with a sensory receptor located in the skin, subcutaneous tissue, joints, muscles, periosteum and viscera, and terminate in the postcentral gyrus of the cerebral cortex. The activity of the receptors to specific stimuli (mechanical, thermal, chemical stimuli) is relayed through several neurons into the cerebral cortex where the stimulus evokes a conscious experience.

Somatosensory systems are subdivided into 4 paths, based firstly on the characteristic features of the sensory receptors, and secondly on body regions supplied. The activity of low threshold mechanoreceptors is carried from the body (trunk, neck and extremities) by the **dorsal column medial lemniscus** path, and from the head by the **trigeminal lemniscus**. The activity of mechanoreceptors, thermoreceptors, chemoreceptors, including those reacting only to stimuli of tissue damaging intensity (**nocireceptors**) is transmitted from the body by the **spinothalamic tract** and from the head by the **spinal trigeminal lemniscus**. All four paths end in the contralateral cerebral cortex.

Table VII.
Summary table of the sensory pathways

CEREBELLUM

The cerebellum consists of the vermis and the cerebellar hemispheres. Three pairs of cerebellar peduncles connect the cerebellum to the brain stem: the **inferior cerebellar peduncle** (**restiform body**) between the medulla and the cerebellum, the **middle cerebellar peduncle** (**brachium pontis**) between the pons and the cerebellum, and the **superior cerebellar peduncle** (**brachium conjunctivum**) between the midbrain and the cerebellum. The afferent and efferent connections of the cerebellum are maintained through the fiber tracts of the peduncles.

The grey matter is distributed into the **cerebellar nuclei** (**dentate, fastigial, globose and emboliform nuclei**) and into the **cerebellar cortex**.

Neurons in the cerebellar nuclei receive collateral branches from the cerebellar afferent fibers en route to the cerebellar cortex. **The only type of efferent neurons** of the cerebellar cortex, the Purkinje neurons, project also to the cerebellar nuclei.

The neurons in the cortex are arranged in three layers: the **molecular layer** (most superficial), the layer of the **Purkinje neurons,** and the **granular layer**. The molecular layer contains a small number of perikarya; it is filled with dendritic trees from Purkinje cells and with thin **parallel fibers**. The layer of the Purkinje neurons is marked by the particularly large perikarya of the neurons. The granular layer is densely filled with small granule cells.

The afferent fibers terminate in the cerebellar cortex either in the granular layer with repeated large axon bulbs (**mossy fibers**) or with elongated terminal portions twisting around the dendrites of a Purkinje neuron (**climbing fibers**). Mossy fibers synapse with the dendrites of several granule neurons, while the climbing fibers synapse with several preterminal branches on the entire dendritic tree of a given Purkinje neuron.

AFFERENT CEREBELLAR PATHWAYS

The cerebellum has three phylogenetically different parts. The oldest part of the cerebellum is the nodulus in the vermis and the flocculi in the hemispheres (**archicerebellum**, **vestibulocerebellum**). The rest of the vermis and the adjacent paravermal parts of the hemisphere can be lumped together (**paleocerebellum**, **spinocerebellum**). The two hemispheres represent the most recent parts of the cerebellum (**neocerebellum**, **pontocerebellum**). The afferent connections terminating with mossy fibers follow the above delineation of the cerebellum. (The olivocerebellar tract, the fibers of which terminate as climbing fibers, show a diffuse distribution in all parts of the cortex.)

Table VIII.
Types of the neurons in the cerebellar cortex

Table IX.
Afferent cerebellar connections

The efferent connections originate from the cerebellar nuclei. Exceptions are some Purkinje neurons in the nodulus-flocculus whose axons leave the cerebellum via the inferior cerebellar peduncle and terminate directly in the vestibular nuclei.

Table X.
Efferent cerebellar connections originating from the cerebellar nuclei

NEURONAL INTERACTIONS IN THE CEREBELLAR CORTEX

Theoretically there are two neuronal circuitries in the cerebellar cortex.

1. The mossy fibers excite the granule cells, the axons of the granule cells (parallel fibers) excite the Purkinje neurons. Both synapses are inhibited: the mossy fiber - granule neurons synapse is directly inhibited by Golgi neurons and the parallel fiber - Purkinje neuron synapse is indirectly inhibited via the inhibition of the Purkinje neurons by the basket cells. The inhibitory synaptic actions seem to shape the distribution of the simultaneously active Purkinje neurons. Apparently, Purkinje neurons are excited by the same bundle of parallel fibers. (i.e. Purkinje neurons in a transverse row are active and Purkinje neurons on both sides of the active row are inhibited by the basket neurons.)

2. Climbing fibers excite Purkinje neurons directly, overriding the inhibitory action of the basket neurons.

The interplay of the two circuitries can be summarized by assuming that both a set of Purkinje neurons as well as individual Purkinje neurons as single elements can be activated, depending on the activity of the afferent fibers and cortical neurons.

NEURONAL INTERACTIONS IN THE CEREBELLAR NUCLEI

The neurons of the cerebellar nuclei receive in an orderly fashion excitatory synapses from the afferent cerebellar pathways and inhibitory synapses from the Purkinje neurons. Thus, the activity of the cerebellum is realized by selective inhibition of certain connections (active Purkinje neurons), while other synapses in the cerebellar nuclei are uninhibited.[5]

BASAL GANGLIA

Basal ganglia are grey masses located deep in the cerebral hemispheres. They can be subdivided into the **lentiform nucleus**, **caudate nucleus** and **claustrum**. The medial two thirds of the lentiform nucleus is called the **globus pallidus** (medial and lateral segments), while the lateral one third is the **putamen**. The caudate nucleus and the putamen form the **corpus striatum**.

Table XI.
Connections and cell types of the basal ganglia

SUBTHALAMUS

The subthalamus is at the ventral portion of the midbrain-diencephalon junction. It contains the ascending sensory pathways en route to the thalamus. The efferent cerebellar fibers also course in this region toward the thalamus.

[5] János Szentágothai explained the unusual activity of the cerebellum by using the analogy of playing the organ. There are two ways to play an organ. The conventional way is to activate a certain combination of the inactive pipes. In contrast, music could be generated by disactivating a certain combination of the active pipes. The cerebellum with a large number of efferent (Purkinje) neurons apparently "chose" this latter, unconventional way.

Areas in the subthalamus:

1. **Field H1 of Forel**. White matter, made by the **thalamic fasciculus** from the globus pallidus to the thalamus.

2. **Field H2 of Forel**. White matter, made by fibers of the **lenticular fasciculus** from the globus pallidus to the thalamus.

3. **Zona incerta**. Grey matter, reticular formation between the lenticular and thalamic fasciculi.

4. **Subthalamic nucleus**. Reciprocal connection with the globus pallidus (**subthalamic fasciculus**).

MOTOR SYSTEM

The task of the motor system is to innervate the striated muscle fibers in the skeletal muscles, the result of which is muscle tone (**tonic action**) and the sudden shortening of the muscles (contraction, **phasic action**). This complicated task is elaborated by three sets of neurons.

1. The **motoneurons** in the spinal ventral horn and in the cranial nerve motor nuclei innervate the muscle fibers (Aα and Aγ motoneurons). The collection of the Aα-motoneurons form the **final common pathway**. “Final” because there is no other motor route to the striated muscle fibers. “Common” because the activity of the Aα-motoneurons is the joint result of several excitatory and inhibitory neurons converging on the dendrites and on the perikaryon of the motoneurons. Upon the action of the motoneurons, the muscle fibers contract, provided there is an intact myoneural junction. The Aγ motoneurons innervate the intrafusal muscle fibers in the muscle spindle.

2. Spinal and brain stem motoneurons are directly contacted by the nerve fibers whose perikarya are located in the cerebral cortex (motor cortical areas; corticospinal and corticonuclear tract neurons). Since the corticospinal tract concentrates in the medullary pyramid, these long descending tracts form the **pyramidal subsystem** of the motor system.

3. A complicated set of neurons organized into several nuclei and tracts can be found in the brain stem and telencephalon with two efferent connections. One of the connections is directed to the motor cortical areas; the other is towards the brain stem

and spinal motoneurons. These nuclei and tracts are lumped together as the **extrapyramidal subsystem** of the motor system.

THE MOTONEURONS

By definition, motoneurons are nerve cells, the axons of which leave the spinal cord through one of the ventral roots, join the appropriate spinal nerve, and continue in either the ventral or the dorsal branch of that nerve. The axons ultimately reach their destination - the skeletal muscles, via a peripheral nerve, and terminate with various numbers of branches. Each terminal portion of the large size Aα motoneurons innervates one muscle fiber with a specialized synapse, called the **myoneural junction**. The above description applies also to the brain stem motoneurons with the necessary modifications (ventral root = cranial nerve). The muscle fibers innervated by the terminal branches of one motoneuron form a **motor unit**, i.e. muscle fibers contracting simultaneously. The activity of the muscle depends on the integrity of the Aα motoneurons and the myoneural junction. Impairment of the Aα motoneurons results in paresis or in a more severe case, paralysis of the muscle.

The innervation of each muscle can be described in two ways: either by the nerve carrying the motor axons to the muscle (**peripheral innervation**), or the spinal segment(s) housing the motoneurons (**segmental innervation**). E.g. The diaphragm is innervated by the phrenic nerve from the cervical plexus, whereas the motoneurons of the axons sit in the C_4 spinal segment.

The axons of the medium sized **Aγ motoneurons** branch less profusely, course to the muscle spindles, and innervate the intrafusal muscle fibers, e.g. fine muscle fibers in the muscle spindle. The correct function of the muscle spindle is directly related to the integrity of the Aγ motoneurons.

The axon of the Aα motoneurons issues initial collaterals that remain within the spinal cord and terminate on medium sized neurons in the ventral horn. The axon of these neurons (called **Renshaw neurons**) form inhibitory synaptic connections with the nearby motoneurons. Renshaw neurons are involved in fine tuning the ongoing activity of one motoneuron in respect to the other motoneurons innervating the same muscle.

PYRAMIDAL SUBSYSTEM

The pyramidal subsystem of the motor system consists of two related descending tracts: cortiocospinal and corticonuclear tracts. The spinal portion of the former, and the brain stem portions of both, were mentioned already in the appropriate sections.

Table XII.
Corticospinal and corticonuclear tracts

Neurons of the pyramidal subsystem act in concert with the motoneurons in the execution of intentional movements. In the clinical practice, the corticospinal and corticonuclear neurons are called **upper motoneurons**, while the $A\alpha$ motoneurons are called **lower motoneurons**. A lesion of the corticospinal and corticonuclear neurons will also result in paresis, or in more serious cases in paralysis. The prime task for the clinician in observing a patient with paresis or paralysis is to determine the involvement of the upper or the lower motoneurons, e.g. central versus peripheral paresis or paralysis.

EXTRAPYRAMIDAL SUBSYSTEM

The extrapyramidal subsystem consists of nuclei interconnected with several fiber tracts resulting in a complicated network with two efferent connections: one is directed towards the beginning of the pyramidal system (motor cortex), the other to the end of the pyramidal system (motoneurons in the spinal cord and cranial nerve nuclei). The grey areas (nuclei) of the extrapyramidal system are the **basal ganglia**, **cerebellar nuclei**, **VA and VL nuclei of the thalamus**, **subthalamu**s, **certain grey masses in the midbrain**, the **vestibular nuclei** and the **reticular formation**. These areas are interconnected with multiple fiber tracts as listed below.

The striatum (caudate nucleus and putamen, see basal ganglia; page 28) receives axons from the entire cerebral cortex (**corticostriate path**). The efferent striate connection could be followed into the globus pallidus (**striopallidal path**). The striatum is reciprocally interconnected with the substantia nigra (**strionigral** and **nigrostriatal paths**; the latter being one of the major dopaminergic tracts of the brain

– it is this path that is interrupted in Parkinson's disease). Two bundles of pallidothalamic fibers course from the globus pallidus through the subthalamus into the VA and VL nuclei of the thalamus. The globus pallidus is reciprocally interconnected with the subthalamic nucleus.

The main targets of the **efferent cerebellar pathways** from the cerebellar nuclei are the VA and VL nuclei of the thalamus (**dentatothalamic tract**), the red nucleus, the reticular formation and the vestibular nuclei.

Combining all these connections, one can conclude that the neurons of the extrapyramidal subsystem form two loops converging in the thalamus. Each loop starts with widespread fields from the cerebral cortex. One of the loops involves the striatum and globus pallidus before the fibers terminate in the thalamus. The other loop relays through the pontine nuclei, deep cerebellar nuclei and cerebellar cortex, before merging with the first loop in the thalamus. The combined activity of both loops will be transmitted by the thalamocortical neurons to the motor cortex. The action of the extrapyramidal system on the motoneurons is mediated by several descending tracts into the spinal cord, and apparently by short distance connections to the cranial nerve motoneurons. The descending tracts originate from the red nucleus (**rubrospinal tract**), reticular formation (**reticulospinal tract**) and vestibular nuclei (**vestibulospinal tract**). The axons of these tracts terminate on interneurons which synapse with both types of motoneurons. The activity of the descending spinal pathways is influenced mostly by the cerebellar efferent fibers.

The impairment of the neurons in the extrapyramidal subsystem results in abnormal muscle tone and impaired movements. The tone of the muscles usually increases (spasticity, rigor), while forced movements may appear (tremor), or the execution of rapidly alternating movements becomes difficult or impossible.

The loss of dopamine in the substantia nigra and in the nigrostriatal tract causes Parkinson's disease. Disturbances in the equilibrium, and the loss of skill executing rapidly alternating movements (**adiadochokinesis**) could be related to the disease of the cerebellum.

COMBINED EFFECT OF SPINAL REFLEX PATHWAYS AND MOTOR SYSTEMS ON SKELETAL MUSCLES

Activity of the central neurons could reach the striated muscle fibers directly through the Aα motoneurons. However, descending fibers may and do activate the Aγ motoneurons parallel with the activation of the Aα motoneurons. In this case, the proprioceptive spinal reflex arc will be involved in the contraction of the striated muscle via the route: **descending fibers - Aγ motoneuron - intrafusal muscle fibers - anulospiral ending of the Type I muscle afferent - Type I muscle afferent - Aα motoneuron - striated muscle fibers**. This connection is called **γ-loop**. With acceptable approximation, the tone of the muscles is set through the activation of this pathway.

MOTOR CONTROL OF THE EYE MOVEMENT

The six pairs of straight and oblique extrinsic eye muscles are innervated by three cranial nerves: oculomotor, trochlear and abducens nerves. The conjugated movements of the two eyes are controlled by cortical and vestibular efferent paths.

The **frontal eye field**, coordinating the coordinated eye movements (gaze), is located in the inferior frontal gyrus in the vicinity of motor cortical area (precentral gyrus). Neurons from this cortical region project through the superior colliculus and pretectal region (a restricted area around the posterior commissure) to the pontine reticular formation. This area near the abducens nucleus contains the neurons that synapse with the motoneurons of the appropriate muscles (e.g. right lateral rectus innervated by the abducens nerve together with the left medial rectus innervated by the oculomotor nerve) to produce a right sided deviation of the eyes (horizontal gaze). The axons of the neurons interconnecting the motor nuclei of the oculomotor, trochlear and abducens motor nuclei travel in the **medial longitudinal fasciculus** (see Vestibular system; page 46). The coordinating nuclei of vertical gaze is located in the rostral portion of the midbrain, at the rostral end of the medial longitudinal fasciculus (**interstitial nucleus of Cajal**).

Convergence occurs when both eyes are focused on a near object. Apparently the **occipital eye field** in the occipital lobe coordinates the actions of muscles producing the convergence.

CEREBRAL CORTEX

One of the characteristic aspects of the development of the cerebral cortex (surface layer of the cerebral hemispheres) has to be considered for the better understanding of the cortical neuronal organization. Namely, the cortical neurons differentiate in a cellular layer (**cortical plate**), and reach their final position with a migration towards the surface of the hemisphere. The radial glial cells form a scaffolding along which the neurons migrate. The migration occurs over a certain period of time in several groups. Neurons that start the migration settle in the basal layer of the cerebral cortex. Those following the first group migrate through the settled basal neuronal layer and settle above them, and so on. Finally, the last group of migrating neurons must course through all the former groups before they arrive at the most superficial cortical layer. In this way, neurons in one columnar space are closely related by ancestry, and neurons in a given cortical layer share a common time of differentiation.

The cerebral cortex consists of two types of neurons: **pyramidal** and **non-pyramidal**. Pyramidal neurons vary in size, while several subtypes of non-pyramidal cells have been distinguished, like **basket neurons**, **stellate neurons**, **chandelier neurons**, **fusiform neurons,** etc. Pyramidal and non-pyramidal neurons form six layers in large portions of the cerebral cortex (**neocortex**). Phylogenetically older cortical areas in a large circle around the interventricular foramen show a different structure (**archicortex** and **paleocortex**). In the rest of this chapter only the structure of the neocortex will be dealt with. The structure of the archi- and paleocortex will be shown in connection with the olfactory and limbic systems (see page 36).

Pyramidal neurons have a conical perikaryon, the tip of the cone pointing to the surface of the hemisphere. An apical dendrite originates from the tip of the perikaryon and courses superficially, while a multitude of basal dendrites radiate at the base of the perikaryon forming a dendritic plate. All dendrites, but mostly the apical dendrites, are richly studded with short dendritic spines. The axon of the pyramidal neuron emerges from the base of the perikaryon and runs towards the depth of the cerebral cortex. Axons frequently give off oblique local collaterals that arborize and terminate within the cortex. The axon of the pyramidal neuron leaves the cortex with two major sites of destination: it either terminates in the ipsi- or contralateral cerebral cortex (**association and commissural neurons**) or courses to subcortical neuronal groups (e.g. corticostriate, corticothalamic, corticopontine, corticonuclear, corticospinal tracts; **projection neurons**). Although pyramidal neurons are widespread in the cerebral cortex, they form two concentrations called the **external pyramidal layer** (layer III) and the **internal pyramidal layer** (layer V). Pyramidal neurons are excitatory neurons.

Non-pyramidal neurons are scattered in the cerebral cortex, but they concentrate in three layers: **external granular layer** (layer II), **internal granular layer** (layer IV) and **multiform layer** (layer VI). **Stellate neurons** are named after their star-shaped dendritic arborization. Their axons arborize within the cortex and synapse mainly with the dendrites of the pyramidal neurons. Stellate neurons are excitatory neurons. **Basket neurons** are named after the characteristic arborization of the axonal tree terminating around the perikarya of the pyramidal neurons in the form of baskets. Basket neurons are inhibitory neurons. **Chandelier neurons** have specific axon arborizations. The axon branches repeatedly in the vicinity of the perikaryon and the branches course dorsally forming multiple arcs.[6] Each axon branch terminates with several synapses on the initial portion (axon hillock - initial segment) of the axon of pyramidal neurons. Axons of several neurons may converge and mix around the axon hillock of a given pyramidal neuron. Chandelier neurons are also inhibitory neurons. Stellate, basket and chandelier neurons are located in layers II and IV. **Fusiform neurons** are to be found in layer VI. Some of them are projection neurons, their axons join the axons of the pyramidal neurons. Some other fusiform neurons possess fine axons that course vertically and terminate in the superficial layer of the cerebral cortex (**molecular layer**, layer I).

Afferent nerve fibers arrive to the cerebral cortex from two sources: fibers of the **thalamocortical tracts** and fibers from the cerebral cortex itself (**cortico-cortical**

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[6] The axon tree resembles a chandelier with multiple arms pointing towards the ceiling and holding the bulbs.

connections). The vast majority of the afferent fibers are of the cortico-cortical character. Afferent fibers of the thalamocortical tracts richly arborize and terminate mainly in layer IV on the dendrites of the stellate neurons. Cortico-cortical fibers course relatively straight vertically and terminate in the superficial layers (layers I and II).

The internal granular layer divides the cerebral cortex into two areas with distinctly different connections. Layers I, II and III form the **supragranular area** of the cortex that is the origin (layer III pyramidal neurons) and termination site of the cortico-cortical fibers. Layers V and VI form the **infragranular area**. Together with layer IV this area receives the thalamocortical fibers and gives rise to subcortical efferent connections (layer V pyramidal neurons and layer VI multiform neurons).

The neuronal structure of the cerebral cortex shows function dependent local variations. Sensory cortical areas (somatosensory cortex, visual cortex, auditory cortex) excel in having numerous non-pyramidal neurons (**granular cortex**), while the motor cortical areas (motor cortex) are recognizable in that they show a well developed layer V with many pyramidal neurons (**Betz-type giant pyramidal neurons**; **agranular cortex**). Association cortical areas show the general six layered cortical structure.

The **columnar architecture** of the cerebral cortex is arranged around the cortico-cortical fibers. Neurons distributed in a **columnar area of 300 μm in diameter** appear to function synchronously. Columns may partially overlap.

Thalamocortical afferent fibers drive the pyramidal neurons via the stellate neurons. Therefore the sequence of specific impulse transmission is: **corticothalamic afferent fibers - stellate neuron - pyramidal neuron - efferent fibers** (axons of the pyramidal neurons). The inhibitory interneurons can interfere with the stellate neuron - pyramidal neuron synapse at the dendritic tree; they may block the activity of the pyramidal neurons through inhibitory synapses on the perikaryon (basket neurons) and even more effectively with inhibitory neurons along the initial axon portion (chandelier neurons).

LIMBIC SYSTEM

The limbic system is the most complex system in the CNS, consisting essentially of two kinds of components:

i) cortical areas

ii) subcortical nuclei and fiber tracts

The notion limbic derives from the word limbus. i.e. The edge or rim of something. The cortical areas of the limbic system are located at the rim of the telencephalon vesicle arranged in two concentric circles and surrounding roughly and grossly the interventricular foramen. The elements of the larger outer circle is the **parahippocampal gyrus** and the **uncus** in the temporal lobe, the **cingulate gyrus** in the parietal and frontal lobes as well as the **subcallosal gyrus** ventral from the rostrum corporis callosi and the **orbitofrontal gyri** in the frontal lobe. The elements of the smaller inner circle are attached to those of the outer one. The inner circle starts with the**dentate gyrus** in the temporal lobe and continues in a narrow layer of grey matter on the dorsal surface of the corpus callosum (**indusium griseum** or **stria longitudinalis**) and the **paraterminal gyrus**.

The **septum pellucidum** developmentally is part of the edge of the telencephalon, and hence the limbic system. Due to the later expansion of the corpus callosum, the septum pellucidum separated from the rest of the cortical areas and it never attained cortical structure. Neurons in the septum pellucidum will be treated among the subcortical nuclei and tracts.

Intercalated between the two circles, more precisely between the parahippocampal and dentate gyri, one finds a special portion of the cerebral cortex, the **hippocampus**.

The cortical structure of the parahippocampal gyrus adjacent to the hippocampus (**subiculum**) shows a transition in its histological structure from the six layered neocortex to the three layered **archicortex** (hippocampus and dentate gyrus). The inner pyramidal layer (layer V) continues in the pyramidal layer of the hippocampus and the granule cell layer of the dentate gyrus. The molecular layer (layer I) can be followed in the archicortex with the same name. The multiform layer of the neocortex (layer VI) continues in the hippocampus and dentate gyrus underneath the pyramidal and granular layers.

FINE STRUCTURE OF THE HIPPOCAMPUS AND THE DENTATE GYRUS

The principal type of neuron in the hippocampus is the pyramidal cell, having several apical and basal dendrites spreading across the entire depth of the hippocampus. The axons of the pyramidal neurons originate at the base of the perikaryon and course dorsally and medially forming the **fimbria hippocampi**. The axons on their way to the fimbria form the **alveus hippocampi** which is the medial wall of the inferior horn of the lateral ventricle. The fimbria runs parallel with the dentate gyrus and gradually continues into the crus fornicis.

Other types of neurons are the **basket neurons** and the **chandelier neurons**. The axons of the basket neurons form inhibitory synapses around the perikarya of the pyramidal neurons. Repeatedly branching axons of the chandelier neurons, like in the neocortex, form inhibitory synapses with the axon hillock region of the pyramidal neurons (see cerebral cortex, page 34).

Afferent fibers to the hippocampus arrive from four major sources:

parahippocampal gyrus
contralateral hippocampus (commissural fibers)
dentate gyrus (granule cells, mossy fibers)
Schaffer’s collaterals (axon collaterals from pyramidal neurons of ipsilateral hippocampus)

Fiber bundles course in the parahippocampal gyrus (**entorhinal cortex**) and terminate on the dendrites of the pyramidal neurons (**alvear path**). Commissural hippocampal fibers course in the hippocampal commissure (between the crura fornicis) and terminate in the contralateral hippocampus. Granule cells of the dentate gyrus terminate in the hippocampus as **mossy fibers**. Finally, axon collaterals of the pyramidal neurons (**Schaffer's collaterals**) terminate on the dendrites of the pyramidal neurons.

The principal type of neuron in the dentate gyrus is the **granule cell,** the axon of which terminates as mossy fibers in the hippocampus. The dentate gyrus receives a major afferent connection from the parahippocampal gyrus (**perforant path**).

THE SUBCORTICAL NUCLEI AND TRACTS OF THE LIMBIC SYSTEM

The **fornix,** carrying the axons of the hippocampal pyramidal neurons, courses immediately ventral to the corpus callosum. It runs along the caudal edge of the septum pellucidum, bordering the interventricular foramen along its anterior aspect, and reaches the anterior commissure. At this level the majority of the fibers continues caudally from the anterior commissure (**postcommissural fibers**), and courses in the columna fornicis until it ends in the **mammillary body**. A small bundle of fibers courses anterior to the anterior commissure (**precommissural fibers**) and terminates in the **preoptic area**, a narrow region between the hypothalamus and the telencephalon.

Axons of the mammillary neurons project into the anterior nuclei of the thalamus (**mammillothalamic fasciculus** or **Vicq d'Azyr's tract**), while the anterior nucleus of the thalamus projects to the **cingulate gyrus**. Within the cingulate cortex, association cortical fibers form the **cingulum,** which projects to the parahippocampal gyrus completing a circle (**Papez circuit**).

A major nucleus of the limbic system is the **amygdaloid complex** in the tip of the temporal lobe between the inferior horn (lateral ventricle) and temporal pole. The amygdaloid complex consists of several nuclei from which neurons project to the **septal nuclei** and **preoptic area** (via the **stria terminalis** at the junction between the caudate nucleus and thalamus) and to the **hypothalamus**. The amygdaloid complex receives a major bundle of afferent fibers from the olfactory system.

The **diagonal band of Broca** located in front of the optic tract connects the amygdaloid complex to the septal area.

Neurons in the **septum pellucidum** project to the habenular nuclei (via the **stria medullaris** at the junction between the superior (extraventricular) and medial (intraventricular) surfaces of the thalamus - corresponding to the tenia thalami). The habenular nuclei project into the **interpeduncular nucleus** of the midbrain via the **fasciculus retroflexus**. From here the fiber projection reaches the pontine tegmentum.

The **dorsomedial nucleus** of the thalamus is to be considered as a nucleus of the limbic system, relaying the pain evoked activities of the spinothalamic and trigeminal lemniscal pathways towards the orbitofrontal cortical areas (frontal lobe), which has multiple connections with the limbic cortical areas (some studies include the entire frontal lobe with the limbic system).

In a simplistic way, the limbic system could be viewed as a complicated network of neurons with two major sources of afferentation. One is the olfactory system via the amygdaloid complex; the other is the spinothalamic tract, especially the pain evoking components via the dorsomedial thalamic nucleus.

The functional significance of the limbic system can be summarized into three points: In harmony with the hypothalamus, it plays a major role in the neural control of **visceral activities** through the tracts terminating in the brain stem and spinal cord visceral nuclei. The limbic system and especially the amygdaloid nucleus is the key component in controlling the **emotional status and activities** of individuals. Finally, the limbic system, and especially the hippocampus, is indispensable in the generation and containment of **short term memory**.

HYPOTHALAMUS

The hypothalamus is part of the diencephalon; it is attached to the ventral surface of the thalamus; the sulcus hypothalmicus separates the two regions. The hypothalamus forms the floor and part of the lateral walls of the third ventricle. The infundibulum is the funnel shaped protrusion on the ventral surface of the hypothalamus that continues in the pituitary stalk and ends as the posterior pituitary. The lamina terminalis borders the hypothalamus rostrally, while caudally the hypothalamus tapers and disappears at the level of the junction between the third ventricle and the cerebral aqueduct. Laterally, the hypothalamus is adjacent to the fibers of the internal capsule.

The hypothalamus could be subdivided into lateral and medial areas. The **lateral hypothalamus** consists of scattered groups of neurons and an extensive fiber system (medial forebrain bundle) coursing in a rostro-caudal direction. The **medial forebrain bundle** carries fibers from the preoptic area, septum pellucidum and anterior hypothalamic areas towards the brain stem and vice versa.

The medial hypothalamus consists mainly of discrete nuclei which could be grouped in the rostro-caudal direction. A bundle of nerve fibers follows the wall of the third ventricle and courses from the medial hypothalamus to the central grey substance of the midbrain (**dorsal longitudinal fasciculus** - Schütz bundle).

1. **Nuclei of the preoptic and anterior hypothalamic region**. This region of the hypothalamus is intimately connected to the limbic system. The efferent connections of the preoptic and anterior hypothalamic regions can be followed into the more caudal regions of the hypothalamus and into the various nuclei and regions of the brain stem. Groups of neurons in the preoptic region are involved in the onset of puberty and in the timing of ovulation. A sexually dimorphic area is present in the preoptic region.

2. **Nuclei of the supraoptic region**. A group of neurons can be seen immediately above the optic chiasma (**suprachiasmatic nucleus**). Some of the retinal efferent fibers or collaterals terminate in the suprachiasmatic nucleus. It seems to be involved in the neuronal machinery of the rhythmic changes in physiological activities (e.g. diurnal rhythm of hormone secretion). The **supraoptic nucleus** located dorsal to the optic tract and the **paraventricular nucleus** located further dorsally, adjacent to the ventricular wall, both contain large size neurons which produce peptide hormones (oxytocin and vasopressin). On this basis these are called **neurosecretory neurons**. The peptides, combined with carrier molecules (neurophysins), are transported along the axons of the neurons to the posterior pituitary. The bundle of neurosecretory axons forms the **hypothalamo-hypophyseal tract**. Arriving at the posterior pituitary, the terminal portions of the axons surround blood capillaries of fenestrated endothelial lining. The peptide hormones are transmitted from the axon terminals across the capillary endothelium to the lumen of the vessels. Oxytocin acts on the smooth muscles of the uterus and on the breast, while vasopressin (antidiuretic hormone - ADH) is the major agent facilitating water resorption in the kidney. An insufficient amount of vasopressin results in polyuria (excess amount of diluted urine) and polydipsia (excessive thirst); the name of the disease is diabetes insipidus.

3. **Nuclei of the infundibular region** (tuber cinereum). The dorsomedial, ventromedial, and infundibular (hypothalamic arcuate) nuclei fill this middle region of the hypothalamus, arranged around the infundibulum. The **dorsomedial** and **ventromedial nuclei** seem to serve as relay sites between extrahypothalamic areas and the **infundibular** (**tuberal**) **nucleus**. This latter one contains small size nerve cells, the axons of which course towards the surface of the pituitary stalk and

terminate on blood capillaries lined with fenestrated endothelial cells. The axons of the neurons originating from the infundibular nucleus form the **tuberoinfundibular tract**. The tuberoinfundibular neurons are neurosecretory cells, because they synthesize peptides in the perikarya, transport them along their axons, and release them at the axon terminals. These peptides stimulate or inhibit the hormone production of the anterior pituitary cells. They are called releasing and inhibiting hormones. Examples: luteinizing hormone releasing hormone (LHRH) stimulates the production of pituitary FSH and LH, corticotrophin releasing hormone (CRH) stimulates the production of ACTH, somatostatin release inhibiting hormone (SRIH) inhibits the release of somatostatin.

To fully appreciate the involvement of the tuberoinfundibular neurons on the hormone production of the anterior pituitary, the **pituitary portal circulation** has to be understood.

Fine arteries from the superior pituitary artery run to the pituitary stalk and form a capillary bed on its ventral surface (first capillary bed; **median eminence**). Some of the capillaries penetrate into the depths of the pituitary stalk. The capillaries join into venules that course ventrally towards the anterior pituitary, where they branch and establish another capillary bed among the cell groups of the anterior pituitary (second capillary bed; sinuses of the anterior pituitary). These latter sinuses are channeled by pituitary veins that collect the blood and carry it into the systemic circulation.

The first capillary bed is the site of the **neurovascular contact** between the axons of the tuberoinfundibular neurons and the portal capillaries. Releasing and inhibiting hormones and many other molecules are released from the axon terminals; they are taken up by the capillaries and transported to the anterior pituitary. The second capillary bed is the site of action between circulating releasing and inhibiting hormones and the cells of the anterior pituitary. Pituitary hormones secreted by the pituitary cells find their way to the circulation at the same site.

4. **Nuclei of the posterior hypothalamus and the mammillary region**. The main representatives are the **mammillary nuclei**. The medial mammillary nucleus is one of the major relay sites of the Papez circuit, receiving the hippocampal efferents through the fornix and issuing the mammillothalamic tract of Vicq d'Azyr towards the anterior thalamic nuclei. The medial mammillary nucleus also projects to the pontine tegmentum (**mammillotegmental tract**).

OLFACTORY SYSTEM

The olfactory sensory system is unique in having **primary sensory neuroepithelial receptor cells** located in the olfactory mucosa of the nasal cavity. The central processes of the receptor cells terminate in the **olfactory bulb** forming complex synapses (**olfactory glomeruli**). The principal type of neuron in the olfactory bulb is the mitral cell. **Mitral cells** are directly contacted by the processes of the olfactory receptor cells in the glomeruli, while their axons form the efferent connection of the olfactory bulb. Interneurons in the olfactory bulb are the **periglomerular** and **granule cells**. **Tufted cells** form a second type of efferent neuron; the axons of these neurons join the axons of the mitral cells and course in the **olfactory tract**. Nerve fibers terminating in the olfactory bulb originate from the nucleus of the diagonal band and from the contralateral olfactory tract.

The olfactory tract ends in the **olfactory trigone** in the vicinity of the anterior perforated substance. From here the majority of the axons from the olfactory bulb runs in the **lateral olfactory stria** to the **lateral olfactory area** consisting of the uncus, the anterior portion of the parahippocampal gyrus (**entorhinal cortex**) and the limen insulae. The lateral olfactory area forms the **pyriform cortex** or **lobe**. Fibers from the olfactory bulb terminate also in the amygdaloid complex. (See: Limbic system, page 37.) The pyriform cortex represents the primary olfactory cortical area.

Smells detected by the olfactory receptors may induce visceral reactions through the limbic system and the lateral hypothalamus. Examples of such reactions are: salivation upon sensing pleasing smells or nausea and vomitus upon sensing unpleasant smells.

VISUAL PATHWAY

The axons of the ganglion cells[7] in the VIIIth layer of the retina converge to the optic disc, pierce the sclera and form the optic nerve.[8] The optic nerves of both sides partially decussate in the optic chiasm: fibers originating from the temporal half of the retina (projection area of the nasal half of the visual field) course ipsilaterally in the optic tract, while fibers originating from the nasal half of the retina (projection area of the temporal half of the visual field) decussate and course in the contralateral optic tract. Due to the hemidecussation, fibers activated by identical halves of the visual fields can be found in the identical optic tract (e.g. the identical part of the visual field projects to the temporal retinal half of the right eye and the nasal retinal half of the left eye). Fibers in the optic tract terminate in alternating layers in the **lateral geniculate body** (LGB) at the caudal end of the thalamus. The **geniculostriate neurons** (**optic radiation**) project from the LGB to the ipsilateral **striate cortex** (occipital lobe, upper and lower lips of the calcarine fissure).

The form and extent of defects of the visual field can reveal the site of injury along the visual pathway. Partial or complete blindness of one of the eyes indicate an **injury of the optic nerve**. Partial or complete blindness in identical halves of the visual fields of both eyes (homonymus hemianopsia) indicate a **lesion of the optic tract**. A similar type of blindness can be caused by a **lesion of the optic radiation**. The significant difference is that the macular vision is spared in this latter case, because the optic fibers from the macula have a bilateral projection into the LGB (macular sparing). Symmetrical type of blindness in both temporal visual fields (bitemporal hemianopsia) may indicate a **lesion of the decussating fibers** in the optic chiasma (due to a tumor of the pituitary gland).

Collateral branches leave the optic tract, and terminate bilaterally in the pretectal region in the vicinity of the posterior commissure. These fibers decussate in the posterior commissure. Neurons in the pretectal region project to the Edinger-Westphal nucleus in the midbrain. The optic tract - pretectal area - Edinger-Westphal

[7] Retinal receptors (rods and cones) activated by light interact with the bipolar, horizontal, and amacrine cells. The sum of activity of these cells is transmitted to the ganglion cells in the inner plexiform layer (see neuronal connectivity in the retina).

[8] The optic nerve is part of the central nervous system. The myelin around the axon is formed by oligodendriglia, and the optic nerve is surrounded by all three layers of meninges.

nucleus connectivity forms the afferent branch of the **pupillary light reflex**. The efferent branch is made by axons of the preganglionic neurons following the oculomotor nerve, the ciliary ganglion and postganglionic parasympathetic neurons reaching the sphincter pupillae muscle in the iris through the branches of the nasociliary nerve. Due to the bilateral representation of the optic tract fibers, the constriction of the pupil can be evoked by shading the light to either of the eyes (**consensual pupillary reflex**).[9]

Although not directly involved in the visual pathway, the **superior colliculus** is an important subcortical reflex center in the visual system. It receives afferent fibers from the LGB through the brachium of the superior colliculus, from the visual cortex and from the spinal cord. The **tectospinal tract** originates from the superior colliculus and courses in the anterior funiculus of the cervical spinal cord. The function of this connection is to move the head parallel with moving objects crossing the visual field. The superior colliculus projects to the facial motor nucleus forming the multisynaptic reflex arc of the protecting blinking reflex (reflex closure of the eyelids).

AUDITORY PATHWAY

The auditory pathway starts with sensory neurons, the bipolar perikarya of which sit in the **spiral ganglion** of the cochlea. The peripheral branches of the sensory neurons make synapses with the inner and outer secondary neuroepithelial receptor cells (**hair cells**) of the organ of Corti. The central branches follow the cochlear portion of the vestibulocochlear nerve (VIIIth nerve). The sensory axons enter the brain stem at the junction of the pons and medulla, bifurcate, and terminate in the **ventral** and **dorsal cochlear nuclei**. The axons of the neurons in the dorsal cochlear nucleus project to the contralateral **superior olivary nucleus**, while the projection from the ventral cochlear nucleus can be followed into the ipsilateral superior olivary nucleus. Superior olivary nuclei are interconnected via the **trapezoid body** which also contains small groups of neurons. The ascending auditory pathway originates from the superior olivary nuclei, forming the **lateral lemniscus** which terminates in the

[9] Pupillary reflex could be used to differentiate between lesions of the optic tract vs. optic radiation. Lesions of the optic tract disrupt the afferent branch of the pupillary reflex arc, while in the case of the

inferior colliculus. Small groups of neurons along the lateral lemniscus form the **nuclei of the lateral lemniscus**. Neurons in the inferior colliculus project to the **medial geniculate body** (MGB), located under the caudal end of the thalamus. The geniculocortical projection (**acoustic radiation**) runs in the caudal limb of the internal capsule and the fibers terminate in the **auditory cortex** (temporal lobe, superior temporal gyrus, **Heschl's gyrus**). The auditory projection is bilateral.

Parallel with the neurons of the ascending auditory pathway, the relay nuclei are interconnected by descending fibers. The auditory cortex projects to the MGB - the MGB to the inferior colliculus. Efferent fibers originate from the superior olivary nucleus and terminate in the organ of Corti upon the sensory nerve terminals and on the outer hair cells. The descending connections modify the transmission of sensory messages through collateral inhibition.

The organ of Corti, the relay nuclei and the auditory cortex are tonotopically organized. The activity of the sensory neurons innervating the hair cells at the **base of the cochlea** is projected to the **caudal pole of the auditory cortex**, while the projection of the apical end of the organ of Corti is in its rostral pole.

VESTIBULAR SYSTEM

The vestibular system consists of the secondary sensory neuroepithelial receptor cells in the membranous labyrinth (**maculae** and **cristae**), the sensory neurons, vestibular nuclei and the connectivity between these latter and several other nuclei and regions. Contrary to all other sensory systems, the vestibular system has **no cortical representation.**

The sensory hair cells of the **macula utriculi and sacculi** are sensitive to **linear acceleration**, while the sensory hair cells in the cristae ampullares are activated by angular (circular) acceleration. The activity of the hair cells is transmitted to the vestibular nuclei by the bipolar vestibular sensory neurons. The perikarya are sitting in the vestibular ganglion (**ganglion of Scarpa**) located at the fundus of the internal acoustic meatus. The central branches of these neurons are arranged into three nerves (n. utriculoampullaris, n. saccularis, n. vestibularis posterior) which form the

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optic radiation these same fibers are spared. Thus, if pupillary constriction can be evoked from the blind portion of the retina, the lesion is in the optic radiation rather than in the optic tract.

vestibular portion of the vestibulocochlear nerve (VIIIth nerve). The vestibular nerve fibers enter the brain stem at the pontomedullary junction and terminate in the vestibular nuclei (**nucl. vestibularis superior, lateralis and inferior** as well as **nucl. vestibularis medialis**) in a topographically arranged fashion. In addition to the vestibular sensory fibers, the vestibular nuclei receive an afferent connection from the cerebellum. Purkinje neurons from the nodulus and flocculus bypass the cerebellar nuclei and terminate directly in the vestibular nuclei.

Neurons in the medial and inferior vestibular nuclei project to the vestibulocerebellum (**vestibulocerebellar tract**). Neurons in the lateral vestibular nucleus project down the spinal cord (**vestibulospinal tract**). This tract is uncrossed and the fibers terminate in the intermediate zone and ventral horn along the length of the spinal cord. Axons of the neurons in the superior, medial and inferior vestibular nuclei form a major fiber bundle that can be detected from the upper cervical segments to the midbrain (**medial longitudinal fasciculus**, MLF). The projection from the vestibular nuclei to the MLF is both crossed and uncrossed. Nerve fibers coursing in the MLF terminate in the motor nuclei of the cranial nerves involved in the movement of the eyeballs (oculomotor, trochlear and abducens nerves). Fibers from the **interstitial nucleus** join the MLF; this latter group of neurons is located dorsally at the junction of the midbrain and diencephalon.

The vestibular sensory apparatus and neuronal system is involved in the maintenance of equilibrium. Disturbances of the vestibular apparatus may result in vertigo, postural deviations and pathological conjugated eye movements called **nystagmus**.

Nystagmus is the biphasic movement of the eyes. The initial slow deviation of the eyeballs is due to the vestibular activity; the late rapid movement of the eyeballs reconstituting the original position is a cortically initiated action. Nystagmus can be provoked by rotating the patient (**rotational nystagmus**) or by injecting warm, then cold water, into the external auditory meatus (**thermal nystagmus**). In both cases the cristae in the lateral semicircular canals are stimulated by the movement of the endolymph. In the first case, the nystagmus is evoked by the displacement of the endolymph due to the rotation through the integrated action of the right and left lateral semicircular canals. In the second case, the displacement of the endolymph is provoked by warming (dilatation of the fluid) or cooling (retraction of the fluid) of the endolymph.

Important contributions to the peripheral and central vestibular mechanisms were made by three eminent Hungarian scientists, **Békésy, Bárány** and **Hőgyes**.

GUSTATORY PATHWAY

The activity of the secondary neuropeithelial taste receptor cells in the **taste buds** of the tongue is carried to the brain stem by sensory neurons of the facial and glossophyaryngeal nerves. These sensory fibers course in the **solitary tract** and terminate in the cranial portion of the **solitary nucleus** in the medulla. An ascending path originating from the solitary nucleus runs to and terminates in the VPM nucleus of the thalamus. The thalamocortical connection ends in the gustatory cortical area which is adjacent to the sensory representation of the tongue.

APPENDIX

Table I. Long ascending spinal tracts

	Gracile tract (Goll)	Cuneate tract (Burdach)	Spinothalamic tract (Edinger)	Spinoreticular tract	Posterior spinocerebellar tract (Flechsiq)	Anterior spinocerebellar tract (Gowers)
Location of the perikaryon	Large size pseudounipolar neurons in the sacral, lumbar and lower thoracic spinal ganglia	Large size pseudounipolar neurons in the upper thoracic and cervical spinal ganglia	Large to medium size neurons in the superficial laminae of the dorsal horn and intermediate zone	Identical or similar to the neurons of the spinothalamic tract	Large size neurons in the Clarke's column	Medium to large size neurons in the inter-mediate zone and ventral horn
Course of the axon	Medial portion of the ipsilateral dorsal funiculus	Lateral portion of the ipsilateral dorsal funiculus	Axons cross the midline in the anterior white commissure at the segmental level of the perikaryon and course in the contra-lateral ventrolateral funiculus	Identical or similar to the neurons of the spinothalamic tract	Dorsal half of the lateral funiculus, underneath the surface of the spinal cord	Axons cross the midline in the anterior white commissure at the seg-mental level of the peri-karyon and course in the ventral half of the contralateral lateral funiculus in a superficial position
Termination of the axon	Gracile nucleus in the caudal portion of the medulla	Cuneate nucleus in the caudal portion of the medulla	Thalamus	Reticular formation	Cerebellum (vermis, cerebellar nuclei)	Cerebellum (vermis, cerebellar nuclei)
Functional significance	See Sensory pathways, Dorsal column – medial lemniscus system (Table VII)		See Sensory pathways Spinothalamic system (Table VII)	See Sensory pathways	See Afferent cerebellar connections (Table IX)	

Table II. Long descending spinal tracts

	Lateral cortico-spinal tract	**Ventral corticospinal tract**	**Rubrospinal tract**	**Reticulospinal tract**	**Tectospinal tract**	**Vestibulo-spinal tract**	**Descending autonomous pathways**
Location of the peri-karyon	Cerebral cortex, precentral gyrus		Red nucleus	Reticular formation	Superior colliculus	Lateral vestibular nucleus	Various hypo-thalamic and brain stem nuclei
Course of the axon	Dorsal half of the contralateral lateral funiculus	Ipsilateral anterior funiculus	Dorsal half of the contralateral lateral funiculus	Ventrolateral funiculus	Anterior funiculus	Anterior funiculus	Lateral funiculus
Termi-nation of the axon	Ventral horn, contra-lateral to the site of the perikarya	Ventral horn, contralateral to the site of the perikarya after crossing in the anterior white commissure at the level of termination	Intermediate zone and ventral horn				Intermediate zone
Functio-nal signi-ficance	See Motor system, Corticospinal tract (Table XII)		See Motor system, Extrapyramidal system, page 31.				

Table III. Types of nuclei in the brain stem

Name	Definition	Equivalent structure in the spinal cord	Afferent connectivity	Equivalent connectivity in the spinal cord	Efferent connectivity	Equivalent connectivity in the spinal cord
Sensory nuclei of the cranial nerves (branchiogen subdivision)	Group of neurons receiving the central branches of the sensory neurons in the cranial nerves	Dorsal horn, intermediate zone	By definition the central branches of the sensory neurons in the cranial nerves	The central branches of the sensory neurons of the spinal nerves	The axons of the neurons in the sensory nuclei form ascending sensory tracts	Spinothalamic and spinoreticular tracts
Motor nuclei of the cranial nerves	Group of neurons (motoneurons) the axons of which leave the brain stem and innervate striated muscles.	Motoneurons in the ventral horn (lamina IX)	Motoneurons receive synaptic connection from descending tract fibers (cortico-nuclear tract) directly or through interneurons.	Corticospinal tract and interneurons	By definition the axons of the brain stem motoneurons join the cranial nerves	Axons of the spinal motoneurons in the spinal nerves
Autonomous nuclei of the cranial nerves	Group of neurons the axons of which leave the brain stem and terminate in autonomous ganglia (pregangli-onic neurons)	Preganglionic neurons in the thoracic and sacral lateral horn	Brain stem pre-ganglionic neurons receive synaptic connections from autonomous pathways	Descending autonomous pathways	By definition the axons of the brain stem preganglionic neurons join the cranial nerves and synapse with neu-rons in auto-nomous ganglia	Axons of the spinal preganglionic neurons terminating in the para- or pre-vertebral ganglia

Table III. Types of nuclei in the brain stem (cont.'d)

Name	Definition	Equivalent structure in the spinal cord	Afferent connectivity	Equivalent connectivity in the spinal cord	Efferent connectivity	Equivalent connectivity in the spinal cord
Mesencephalic nucleus of the trigeminal nerve	Pseudounipolar sensory neurons displaced into the midbrain	No equivalent structure (Equivalent neurons are located in the spinal ganglia.)	The peripheral branches of the sensory neurons join the trigeminal nerve and terminate mostly in muscle spindles of the masticatory muscles	Type Ia sensory neurons innervating the intrafusal muscle fibers (anulospiral endings)	The central branches of the sensory neurons synapse with the motoneurons of the trigeminal nerve innervating the masticatory muscles	Central branches of the Type Ia sensory neurons synapsing with the motoneurons
Relay nuclei of long ascending tracts	Groups of neurons receiving the axons of the long ascen-ding tracts from the spinal cord	No equivalent structures	By definition the fibers of the long ascending tracts	No equivalent structure	The axons of the neurons ascend to the thalamus as parts of the sensory systems	No equivalent structure
Precerebellar nuclei	Groups of neurons the axons of which terminate in the cerebellar cortex and cerebellar nuclei	Clarke's column and neurons of the ventral spino-cerebellar tract in the intermediate zone	These nuclei are the site of termination of numerous, mostly descending tracts	Unlike precerebellar nuclei in the brain stem, equivalent nuclei in the spinal cord receive direct connections from sensory neurons	By definition the axons of these neurons course into the cerebellum through one of the cerebellar peduncles	Anterior and posterior spinocerebellar tracts

Table III. Types of nuclei in the brain stem (cont.'d)

Name	Definition	Equivalent structure in the spinal cord	Afferent connectivity	Equivalent connectivity in the spinal cord	Efferent connectivity	Equivalent connectivity in the spinal cord
Sensory nuclei in the acoustic system	Groups of neurons receiving the sensory nerve fibers of the acoustic nerve	No equivalent structures	By definition the central branches of the bipolar acoustic sensory neurons located in the spiral ganglion	No equivalent structures	The axons of the neurons in the sensory nuclei course to one of the relay nuclei	No equivalent structures
Relay nuclei in the acoustic system	Groups of neurons at various hierarchical levels of the acoustic system	No equivalent structures	Relay nuclei receive the axons of the sensory and lower order relay nuclei.	No equivalent structures	The axons of the relay nuclei course to the higher order relay nucleus	No equivalent structures
Vestibular sensory nuclei	Groups of neurons receiving the sensory nerve fibers of the vestibular nerve	No equivalent structures	By definition the central branches of the bipolar vesti-bular sensory neurons located in the vestibular ganglia	No equivalent structures	The axons of the neurons in the vestibular sensory nuclei form several tracts the most important among them is the medial longitudinal fasciculus	No equivalent structures
Relay nuclei of the long descending tracts	Groups of neurons the axons of which descend into the spinal cord	No equivalent structures	Axons of various sources.	No equivalent structures	By definition the axons descend and terminate in the spinal cord	No equivalent structures

Table IV. Summary table of the brain stem nuclei

Name	Definition	Examples
Sensory nuclei of the cranial nerves (branchiogen subdivision)	Group of neurons receiving the central branches of the cranial nerves	Somatosensory nuclei: spinal nucleus of the trigeminal nerve, main sensory nucleus of the trigeminal nerve Viscerosensory nuclei: solitary tract
Motor nuclei of the cranial nerves	Group of neurons (motoneurons) the axons of which leave the brain stem and innervate striated muscles.	Ventrolateral group: motor nuclei of the trigeminal and facial nerves, nucleus ambiguus; Dorsomedial group: motor nuclei of the oculomotor, trochlear, abducens and hypoglossal nerves
Autonomous nuclei of the cranial nerves	Group of neurons the axons of which leave the brain stem and terminate in autonomous ganglia (preganglionic neurons)	Edinger-Westphal nucleus, superior and inferior salivatory nucleus, dorsal motor nucleus of the vagus nerve
Mesencephalic nucleus of the trigeminal nerve	Pseudounipolar sensory neurons displaced into the midbrain	Mesencephalic nucleus of the trigeminal nerve
Relay nuclei of long ascending tracts	Groups of neurons receiving the axons of the long ascending tracts from the spinal cord	Gracile and cuneate nuclei
Precerebellar nuclei	Groups of neurons the axons of which terminate in the cerebellar cortex and cerebellar nuclei	Inferior olivary nucleus, external cuneate nucleus, nuclei pontis, nuclei in the reticular formation
Sensory nuclei in the acoustic system	Groups of neurons receiving the sensory nerve fibers of the acoustic nerve	Dorsal and ventral cochlear nuclei
Relay nuclei in the acoustic system	Groups of neurons at various hierarchical levels of the acoustic system	Superior olivary nucleus, nuclei of the trapezoid body, nucl. of the lateral lemnisci, inferior colliculus
Vestibular sensory nuclei	Groups of neurons receiving the sensory nerve fibers of the vestibular nerve	Lateral (Deiters), medial, superior and inferior vestibular nuclei
Relay nuclei of the long descending tracts	Groups of neurons the axons of which descend into the spinal cord	Red nucleus, nuclei in the reticular formation, superior colliculus (partially)

Table V. Summary table of the cranial nerve nuclei

Cranial nerve	Origin of the motor fibers	Termination of the sensory fibers	Origin of the preganglionic parasympathetic fibers	Notes
Oculomotor nerve (III.)	Motor nucleus of the oculomotor nerve (midbrain)	-	Edinger-Westphal nucleus (midbrain)	
Trochlear nerve (IV.)	Motor nucleus of the trochlear nerve (midbrain)	-	-	
Trigeminal nerve (V.)	Motor nucleus of the trigeminal nerve (pons)	Large diameter sensory fibers: main sensory nucleus (pons) Fine sensory fibers: spinal nucleus of the trigeminal nerve (pons and medulla)	-	Mesencephalic nucleus of the trigeminal nerve (midbrain): perikarya of sensory neurons inner-vating muscle spindles
Abducens nerve (VI.)	Motor nucleus of the abducens nerve (ponto-medullary junction)	-	-	
Facial nerve (VII.)	Motor nucleus of the facial nerve (ponto-medullary junction)	-	-	
Intermediate nerve (later part of the facial nerve)	-	Somatosensory fibers: spinal nucleus of the trigeminal nerve (pons and medulla) Viscerosensory fibers: solitary nucleus (medulla)	Superior salivatory nucleus (pons)	

Table V. Summary table of the cranial nerve nuclei (cont.'d)

Cranial nerve	Origin of the motor fibers	Termination of the sensory fibers	Origin of the preganglionic parasympathetic fibers	Notes
Vestibulocochlear nerve (VIII.)	-	Cochlear nerve sensory fibers: ventral and dorsal cochlear nuclei (ponto-medullary junction) Vestibular nerve sensory fibers: vestibular nuclei (ponto-medullary junction)	-	
Glossopharyngeal nerve (IX.)	Nucleus ambiguus (medulla)	Somatosensory fibers: spinal nucleus of the trigeminal nerve (pons and medulla) Viscerosensory fibers: solitary nucleus (medulla)	Inferior salivatory nucleus (ponto-medullary junction)	
Vagus nerve (X.)	Nucleus ambiguus (medulla)	Somatosensory fibers: spinal nucleus of the trigeminal nerve (pons and medulla) Viscerosensory fibers: solitary nucleus (medulla)	Dorsal motor nucleus of the vagus nerve (medulla)	
Accessory nerve (XI.)	Nucleus ambiguus (medulla)	-	-	Motor fibers originate also from the upper cervical segments (spinal root of the accessory nerve)
Hypoglossal nerve (XII.)	Motor nucleus of the hypoglossal nerve (medulla)	-	-	

Table VI. Connections and functional significance of the thalamic nuclei

Source of the main afferent connection	**Nucleus**	Main efferent connection	Functional significance
Mammillary body (mammillothalamic tract)	**Anterior nucleus (A)**	Cingulate gyrus	See Limbic system
Dentate nucleus (cerebellum), pallidum	**Ventralis anterior (VA), ventralis lateralis (VL) nucleus**	Precentral gyrus	See Motor system
Spinal cord (spinothalamic tract), dorsal column nuclei (medial lemniscus)	**Ventralis posterolateralis (VPL) nucleus**	Postcentral gyrus	See Sensory system
Spinal and main trigeminal nuclei (trigeminal lemniscus), asending fibers from the solitary nucleus	**Ventralis posteromedialis (VPM) nucleus**	Postcentral gyrus	See Sensory system and Gustatory pathway
Amygdaloid nucleus	**Dorsomedial (DM) nucleus**	Frontal lobe	See Limbic system
Spinal cord (spinothalamic tract), spinal trigeminal nucleus (spinal trigeminal lemniscus)	**Centromedian, parafascicular nuclei**	Frontal lobe	See Limbic system
Cerebral cortex	**Nucleus lateralis posterior, pulvinar thalami**	Cerebral cortex	See Cerebral cortex
Thalamus	**Reticular thalamic nucleus**	Thalamus	Uncertain
Inferior colliculus	**Medial geniculate body (MGB)**	Superior temporal gyrus	See Acoustic system
Retina (optic nerve and tract)	**Lateral geniculate body (LGB)**	Striate cortex (occipital lobe)	See Visual system

Table VII. Summary table of the sensory pathways

	Dorsal column medial lemniscus	**Trigeminal lemniscus**	**Spinothalamic tract**	**Spinal trigeminal lemniscus**
Type and location of the **sensory receptors**	Mechanoreceptors (encapsulated nerve endings) in the skin, joints, muscles; **specific stimulus**: touch, pressure		Mechanoreceptors, thermoreceptors, chemoreceptors, nociceptors (free nerve endings) in the skin, joints, muscles, periosteum and viscera; specific stimuli: touch, warm, cold, chemicals, change in pH, tissue damaging (noxious) stimuli	
Sensory neuron				
- location of the perikaryon	One of the spinal ganglia	Trigeminal (Gasserian) ganglion	One of the spinal ganglia	Trigeminal (Gasserian) ganglion, sensory ganglia of the VIIth, IXth and Xth nerves
- character and location of the peripheral branch	Thick, myelinated (Aβ type), in one of the branches of a spinal nerve	Thick, myelinated (Aβ type), in one of the branches of the trigeminal nerve	Fine myelinated (Aδ type) or unmyelinated (C type), in one of the branches of a spinal nerve	Fine myelinated (Aδ type) or unmyelinated (C type), in one of the branches of the Vth, VIIth, IXth or Xth nerves
- termination of the central branch	Dorsal column nuclei (nucleus gracilis, nucleus cuneatus)	Main sensory nucleus of the trigeminal nerve	Lamina I and V of the spinal gray matter	Spinal nucleus of the trigeminal nerve
Interneurons between the sensory neuron and the ascen-ding tract neuron	No	No	Several, in the spinal dorsal horn	Several, in the spinal nucleus of the trigeminal nerve

Table VII. Summary table of the sensory pathways (cont.'d)

	Dorsal column medial lemniscus	Trigeminal lemniscus	Spinothalamic tract	Spinal trigeminal lemniscus
Ascending tract neuron				
- location of the perikaryon	Dorsal column nuclei	Main sensory nucleus of the trigeminal nerve	Spinal dorsal horn and intermediate zone	Spinal nucleus of the trigeminal nerve
- course of the axon	Decussation in the medulla, followed by ascending course (medial lemniscus)	Decussation in the pons, followed by ascending course	Decussation in the spinal cord, followed by ascen-ding course	Decussation in the medulla, followed by ascending course
- termination of the axon	thalamus, VPL	thalamus, VPM	thalamus, VPL, intralaminar nucleus	thalamus, VPM, intralaminar nucleus
Thalamocortical neuron				
- location of the perikaryon	VPL	VPM	VPL	VPM
- projection of the axon	postcentral gyrus, dorsal-medial part	postcentral gyrus, ventral-lateral part	postcentral gyrus, dorsal-medial part, orbitofrontal cortex	postcentral gyrus, ventral-lateral part, orbitofrontal cortex
Function	Discriminative touch, recognition of shape and texture		Crude touch, temperature (warm, cold), pain	

Table VIII. Types of the neurons in the cerebellar cortex

	Granule neurons	Golgi neurons	Purkinje neurons	Basket neurons
Size and location of the perikaryon	Small perikarya, densely distributed in the granular layer	Medium size perikaryon scattered in the granular layer	Large perikaryon irregularly spaced in the Purkinje cell layer	Medium size neurons in the inner molecular layer
Axon terminals synapsing on the perikaryon	No synapses on the perikaryon	No significance	Axons of the basket cells establish inhibitory synapses	No significance
Dendritic tree	Three to four dendrites in the vicinity of the perikaryon	Straight dendrites in the granular and molecular layers	The superficially directed main dendrite branches into 7 to 8 secondary branches in the molecular layer. The dendritic tree of a Purkinje neuron is restricted to the sagittal plane. The dendrites carry spines.	Four to six dendrites in the molecular layer
Axon terminals synapsing on the dendrites	Mossy fiber terminals synapse with the dendrites in the form of complex synapses (cerebellar glomeruli, excitatory synapses). Axons of the Golgi cells form inhibitory synapses with the dendrites within the glomeruli.	Mossy fibers and parallel fibers (both are excitatory synapses)	Parallel fibers synapse with the dendritic spines. Climbing fibers synapse with the dendrites (both are excitatory synapses)	Parallel fibers (excitatory synapses)

Table VIII. Types of the neurons in the cerebellar cortex (cont.'d)

	Granule neurons	**Golgi neurons**	**Purkinje neurons**	**Basket neurons**
Course and termination of the axon	The fine axon courses towards the molecular layer where it bifurcates and both branches take a medio-lateral course (parallel fibers, excitatory synapses)	The axon synapses with the dendrites of the granule cells in the glomeruli (inhibitory synapses)	The axons leave the cerebellar cortex and course in the white matter towards the cerebellar nuclei where they form inhibitory synapses with the neurons. The axons of a few Purkinje neurons leave the cerebellum for the vestibular nuclei	The axons arborize in the molecular and Purkinje neuron layers and surround the perikarya of the Purkinje neurons with a basket-like terminal structure (inhibitory synapse)

Table IX. Afferent cerebellar connections

	Posterior spinocerebellar tract	**Anterior spinocerebellar tract**	**Cuneo-cerebellar tract**	**Pontocerebellar tract**	**Olivocerebellar tract**	**Vestibulo-cerebellar tract**	**Reticuloerebellar tract**
Origin	Clarke's column	Intermediate zone of the spinal cord	External cuneate nucleus	Nuclei pontis	Inferior olive	Medial and inferior vestibular nuclei	Brain stem reticular formation
Course	Inferior cerebellar peduncle	Superior cerebellar peduncle	Inferior cerebellar peduncle	Middle cerebellar peduncle	Inferior cerebellar peduncle	Inferior cerebellar peduncle	Inferior cerebellar peduncle
Termi-nation	Vermis, mossy fibers	Vermis, mossy fibers	Vermis, mossy fibers	Hemisphere, mossy fibers	Vermis and hemispheres, climbing fibers	Nodulus and flocculus, mossy fibers	Vermis and hemispheres, mossy fibers

Table X. Efferent cerebellar connections originating from the cerebellar nuclei

	Dentate nucleus	Emboliform nucleus	Globose nucleus	Fastigial nucleus
Location of the Purkinje neurons synapsing with the neurons of the nucleus	Cerebellar hemispheres	Intermediate zone between vermis and hemispheres		Vermis
Course of the fibers	Superior cerebellar peduncle			Inferior cerebellar peduncle
Termination of the fibers	Thalamus, VA and VL.	Red nucleus		Reticular formation, vestibular nuclei

Table XI. Connections and cell types of the basal ganglia

	Striatum	**Globus pallidus**
Afferent connections	1. Corticostriate fibers from all four lobes. 2. Thalamostriate fibers from the intralaminar nuclei. 3. Nigrostriate fibers from the pars compacta of the substantia nigra	1. Striopallidal fibers
Types of neurons	Medium size neurons as projection neurons and interneurons	
Efferent connections	1. Striopallidal fibers to the globus pallidus. 2. Strionigral fibers to both parts of the substantia nigra.	1. Pallidothalamic fibers (ansa lenticularis) to the thalamus (VA, VL nuclei). 2. Lenticular fasciculus to the subthalamus.

Table XII. Corticospinal- and corticonuclear tracts

	Corticospinal tract	Corticonuclear tract
Location of the perikarya	The perikarya of both tracts are located in the motor cortex (precentral gyrus, Brodmann 4), in the Vth layer (large size pyramidal neurons, Betz cells). The cells of origin are arranged reflecting the spinal segment in which the axon terminates (somatotopical arrangement).	
Course of the fibers in the hemisphere	Internal capsule, caudal to the knee. Fibers directed to the caudal spinal segments are located posteriorly, fibers to the cranial spinal segments and to the cranial nerve motor nuclei are located anteriorly	
Course of the fibers in the midbrain	Middle portion of the cerebral peduncle. Fibers directed to the caudal spinal segments are located laterally, while fibers directed to the cranial cervical segments and cranial nerve motor nuclei are located medially. The corticonuclear fibers to the motor nuclei of the IIIrd and IVth cranial nerves are detached from the bundle and course towards the appropriate nucleus.[10]	
Course of the fibers in the pons	Basis pontis in several smaller bundles. The corticonuclear fibers to the motor nuclei of the Vth, VIth[10] and VIIth cranial nerves are detached from the bundle and course towards the appropriate nucleus.	
Course of the fibers in the medulla	Pyramid, forming a compact bundle. Eight to five percent of the fibers decussate and follow the descending course in the lateral portion of the medulla	The corticonuclear fibers to the nucleus ambiguus are detached from the bundle.
Course of the fibers in the spinal cord	Lateral (crossed) and ventral (uncrossed) corticospinal tracts (see Table II). In the lateral tract the axons directed to the cranial segments are located in a central, whereas axons directed to the caudal segments are located in a peripheral position.	-
Termination of the fibers	Synapsing directly with the **contralateral** $A\alpha$ and $A\gamma$ motoneurons, and with interneurons in the ventral horn and intermediate zone.	Synapsing with motoneurons of the cranial nerve nuclei. The connection is mostly **contralateral**, but **ipsilateral** termination also occurs (e.g. motoneurons of the facial nerve innervating the muscle of the periocular and frontal musculature).
Significance	Control of finely tuned voluntary movements.	

[10] Corticobulbar neurons to the IIIrd, IVth and VIth cranial nerve motor nuclei originate from the frontal eye field, an area in the inferior frontal gyrus (Brodmann 8).