The Sensory Systems of the Human Body

The sensory organs enable us to interact with our surroundings and perceive things outside our bodies. Their functions are fascinating, but the topic seems vast and complex during medical studies. However, all sensory organs follow a few fundamental principles in their structure and function.



The Fundamentals of Sensory Perception

An adequate stimulus (i.e. a threshold energy input that causes a reaction of the sensory organ) triggers the stimulation of the organ, such as light in the eye. The stimulation is relayed via peripheral pathways (in this example, the eye and optic nerve) and processed in the respective brain areas optic nerve and corpus geniculatum laterale). This means that there are 2 central processes:

Transduction: the conversion of a stimulus into a receptor potential

- Transformation: the conversion of receptor potentials into action potentials
- for forwarding to the processing brain areas

Here, 4 **traditional senses**—sight, hearing, smell, and taste—, as well as the sense of balance, will be discussed.

Sensory adaptation

Sensory adaptation is defined as the change over time in the responsiveness of the sensory system to a constant stimulus. This allows the brain to tune out unimportant information. The system is designed to respond to changing, not constant, information. Nociceptors (pain receptors) do not adapt under any circumstances.

Sensory Pathways

Sensory receptors are sensory nerves that are either cells or nerve endings. They can detect both internal (interoceptor) and external (exteroceptor) stimuli. Activation initiates signal transduction by creating graded or action potentials. Sensory pathways begin with the receptor and continue through to ganglion cells and, finally, to the spinal cord.



Types of Sensory Receptors

Sensory receptors are specific to only 1 sensory modality.

Type of sensory receptor	Description
Mechanoreceptors	Auditory hair cells detect mechanical movement of cells
	from fluid in the ear.
Chemoreceptors	Olfactory receptors detect airborne chemicals, allowing
	smell
	Taste (gustatory receptors) detect chemicals on the
	tongue.
Nociceptors	Receptors that respond to tissue injury, leading to pain
Thermoreceptors	Receptors that respond to temperature
Photoreceptors	Activation of rod and cone cells in the eye

The Sense of Sight

The optical apparatus



Image: Structures of the Eye, by Phil Schatz.

An object has to be projected onto the ocular fundus for us to see it. For this purpose, light is refracted at the air–ocular border of the globe, and the image of the object is projected on the retina upside down and scaled down. The total refractive power of the eye is 58.8 diopters (D; distance-accommodating power of cornea, anterior chamber, and lens).

A higher refraction can be achieved with greater curvature of the lens, and thus, the refractive power can be adjusted according to the distance from the object. The distance between near and far-off objects (i.e. between the minimum and maximum distances that allow for a sharp image) is also referred to as the range of accommodation.

The difference between the respective diopter values forms the amplitude of accommodation. This value cannot exceed a maximum of 14 D. In addition, the pupil contributes to the intensification of the projected object by blanking out marginal rays.

The retina

The retina lines the ocular bulb. The pars optica, which consists of the stratum pigmentosum and the stratum nervosum, is located in the rear area of the bulb. The pars caeca is located in the anterior area and consists of stratum pigmentosum only. From outside to inside, the retina can be divided into the following 10 layers:

Stratum pigmentosum

Pigment epithelium: supply of retinal cells

Stratum nervosum

- Photoreceptors: transduction of light signals
- External glia limitans

- External granular layer: cell nuclei of photoreceptors (first neuron)
- External plexiform layer: first synapse
- Internal granular layer: cell nuclei of bipolar cells (second neuron)
- Internal plexiform layer: second synapse
- Ganglion cell layer: cell nuclei of ganglia (third neuron)
- Nerve fiber layer
- Internal glia limitans

The internal granular layer contains additional horizontal cells, amacrine cells, and Müller glia cells, which have a modulating effect on the processing of signals and can amplify the contrast.

Photoreceptors - rods and cones

There are 2 types of photoreceptors. The rods are responsible for providing light/dark vision, also referred to as scotopic vision, and the cones are responsible for color vision, also called photopic vision. The cones can be divided into 3 subtypes according to the 3 spectral colors. The human eye has approximately 120 million rods and approximately 6 million cones.

Phototransduction of the eye

The sensory cells contain the visual pigment 11-*cis* retinal, which absorbs light and changes its conformation to all-trans-retinal. As a result, the sodium channels of the cell membrane close, leading to a hyperpolarized signal at the glutamate photoreceptor synapses.



Image: Retinal Isomers, by Phil Schatz. License: CC BY 4.0

The signals are processed in a network of bipolar cells, amacrine cells, and horizontal cells and are interconnected with ganglion cells. Therefore, rods and cones are secondary sensory cells.

The macula lutea is a yellow oval spot at the center of the retina. It is the part of the retina that is responsible for sharp, detailed central vision (also called visual acuity), and it contains a very high concentration of cones. The **fovea centralis**, the center of the macula lutea, consists only of cones. This is the site of clearest vision.

The papilla **nervi optici** is located medial to the **macula lutea** and marks the exit of the optic nerve. Because of missing photoreceptors in this area, vision is not possible here. Therefore, this area is also referred to as the 'blind spot.' This spot is located laterally in the field of vision.

The visual pathway

The efferent fibers of the ganglion cells form the **optic nerve**. This nerve exits the eye at the papilla **nervi optici**, passes through the orbital foramen, and enters the cranial cavity. The optic nerves of both eyes join in the chiasma opticum.

Here, the medial parts of the retina cross to the opposite side. The temporal parts remain ipsilateral. Therefore, the ipsilateral temporal fibers and the contralateral medial fibers run together starting from the chiasma opticum.

The tractus opticus projects onto the corpus geniculatum laterale inside the thalamus.

From here, the visual pathway then proceeds to the visual cortex via the **broad radiatio optica.** The visual cortex is divided into primary and secondary visual cortex. The primary visual cortex is responsible for making us conscious of visual impulses, which are then analyzed in the secondary visual cortex.

Paresis of the visual pathway

Symptoms can often lead to conclusions about the location of lesions of the visual pathway. The following examples illustrate this:

- Blindness in 1 eye: The lesion is probably located in the nervus opticus because this nerve houses all fibers of 1 eye.
- **Homonymous hemianopia**: The same side of the visual field is affected in

both eyes; the lesion is located behind the chiasma opticum.

Heteronymous hemianopia: The opposite sides of both eyes are affected,

i.e. the patient has a vision as if he had blinkers on, meaning that both temporal visual fields are defected; the lesions are located inside the chiasma opticum.

Hemianopia with intact optical reflexes: A lesion of the corpus

geniculatum laterale. The collaterals of the reflex pathways in the mesencephalon exit before the corpus; thus, the reflexes remain intact despite the loss of vision.

Minor scotomas: The lesion is probably located in the optic radiation because

only particular areas are damaged due to the broad fragmentation.

The Auditory System

The auditory sense converts acoustic waves—meaning fluctuations in pressure in our surroundings—into electrical signals and, consequently, perceives tones, sounds, and noises.

Sound pressure level and volume level

The most important measurement unit in this context is the **sound pressure level**, measured in decibels (dB). This describes the acoustic pressure in relation to the auditory threshold.

The **auditory threshold** is the minimal acoustic pressure at which a tone of a specific frequency can be heard. The relationship of the sound pressure level to a specific value (auditory threshold) makes it a measurable value that can be calculated as follows:

sound pressure level = $20 \times \log (p1 / p)$,

where *p* is the reference value meaning the auditory threshold.

The **volume level** is not the same as the sound pressure level. The volume level describes the subjective perception of the sound volume and is based on the phon scale. The phon value equals the sound pressure level at a frequency of 1 kHz. This means that, for instance, values of lower frequency need a higher sound pressure level than 1 kHz to be perceived as equally loud. These differences are shown with the help of isophones.

Structure of the ear



Image: Structures of the Ear, by Phil Schatz. License: CC BY 4.0

The ear is divided into the outer ear, middle ear, and inner ear. Sound passes through the outer ear to the tympanic membrane. There, the auditory ossicles-malleus, incus, and stapes relay the sound to the oval window of the inner ear.

The middle ear is responsible for impedance adjustment, which allows a sound transmission of 60%. Without this adjustment, 98% of the sound would be reflected. The adjustment occurs via 3 mechanisms:

- 1. The leverage effect of the ossicles amplifies the sound force onto the oval window, contrary to the force on the tympanic membrane.
- 2. The smaller area of the stapes compared with the tympanic membrane leads to an increase in pressure.
- 3. Compared with the oscillations of the tympanic membrane, the stapes moves more slowly. Because impedance = pressure/velocity, a decrease of velocity results in an increased impedance.



The inner ear – Structure of the cochlea

The cochlea is the part of the inner ear responsible for hearing. The cochlea consists of several tubes (scala tympani, scala media, and scala vestibuli) and the organ of Corti, which are coiled into the cochlea.

The scala tympani and scala vestibuli are filled with sodium-rich perilymph. The scala media contains potassium-rich endolymph, and it is bordered by the Reissner membrane at the scala vestibuli and by the basilar membrane at the scala tympani, as well as by the **stria vascularis**.

The organ of Corti contains the actual sensory cells, the outer and inner hair cells, and is covered by the tectorial membrane. There are 3 rows of outer hair cells that touch the tectorial membrane with their longest stereocilia, as well as 1 row of inner hair cells whose stereocilia do not touch the membrane but, rather, are deflected by the displacement of the endolymph (hydrodynamic coupling) and are thus stimulated.

Transduction of the cochlea

The traveling wave inside the scala vestibuli caused by the stapes leads to a frequencyspecific maximum deflection of the basilar membrane at the corresponding location of the cochlea. This results in a shearing motion of the tectorial membrane against the organ of Corti and the hair cells. High-pitched tones are reflected near the oval window, low-pitched tones in the direction of the helicotrema.

The deflection of stereocilia creates a receptor potential and leads to mechanoelectrical transduction. The endocochlear potential, which is created through the higher potassium concentration of the endolymph compared with the perilymph, is essential for the creation of potential. This potential is built by the stria vascularis, which actively transports potassium ions into the endolymph.

The deflection of the stereocilia opens potassium channels. Potassium from the endolymph flows into the cell and depolarizes it. Thereafter, calcium channels open, and the calcium influx results in a glutamatergic synaptic transmission of the potential to the first neuron of the sound conduction system.

The auditory pathway

The perikaryon of the first neuron is located inside the ganglion spiral. These bipolar cells transmit the potentials to the cochlear nuclei of the medulla oblongata. Their extensions form an important part of the vestibulocochlear nerve. The tonotopic organization of the cochlear coil is preserved.

Part of the fibers cross inside the trapezoid body, while another part continues on uncrossed. The crossed part is interconnected in the nuclei olivares superiores, which is essential for directional hearing. Contralaterally, both strands continue together to the inferior colliculi as the lemniscus lateralis. After dispensing with some of the smaller branches and back-crossings, the main part of the fibers continues to the corpus geniculatum mediale and, from there, to the primary auditory cortex as acoustic waves.

Therefore, the auditory cortex receives information from both cochleae. This has a positive effect in the case of unilateral injury of the auditory pathway and on directional hearing. The primary auditory cortex is responsible for making us conscious of sounds. The meaningful connection to words or melodies takes place in the secondary auditory cortex.

The Vestibular System

The vestibular apparatus, which is responsible for the sense of balance or sense of equilibrium, is located in the inner ear along with the cochlea. It consists of 3 semicircular ducts and 2 otolith organs, which together facilitate spatial orientation and registration of movements.

Structure of the Vestibular Apparatus

The structure of the vestibular apparatus is similar to that of the cochlea. The ducts of the vestibular apparatus are also filled with endolymph, and the sensory cells are also hair cells. However, unlike the hair cells of the cochlear, these develop cilia and several stereocilia that are connected via tip links.

They are covered by a gelatinous mass. Inside the semicircular ducts, this mass, which contains mucopolysaccharide, is called the cupula. In addition, this mass contains small calcium carbonate crystals inside the otolith organ and is, therefore, called the otolithic membrane.

Transduction of the vestibular apparatus

The tough cupula/otolithic membrane is shifted against the sensory cells through acceleration, deceleration, or rotating of the head. Just like inside the cochlea, the shifting leads to shear movement and a deflection of cilia and stereocilia and causes a receptor potential.

The transduction process is the same in the semicircular ducts and the otolith organs. However, because of their anatomic differences, the 2organs measure different movements.

Translational motion: Otolith organs measure acceleration and deceleration. Macula sacculi measure vertical translational motions, and macula utriculi measure horizontal motions.



Image: Linear Acceleration Coding, by Phil Schatz. License: CC.BY 4.0

Rotational motion: The endolymph in the semicircular ducts is usually arranged circularly. Because of inertia, the fluid is shifted against the sensory epithelium during rotations, and thus the cilia of the cells are deflected. Cilia are built in a way that, if deflected medially toward the utricle, they will cause a potential. This means that when the head is rotated to the left side, the fluid in the horizontal semicircular ducts shifts to the right, which leads to activity in the left semicircular ducts and afferent nerves.



Image: Rational Coding by Semicircular Canals, by Phil Schatz. License: CC.BY 4.0

Vestibular pathway

The generated potentials are transferred from the first neuron as part of the **vestibulocochlear nerve** to the **vestibular nuclei** inside the rhombencephalon and to the second neuron. From this point on, the crossed and uncrossed pathways continue on to the **nucleus ventralis posterior** of the thalamus. The impulses are then transmitted to the vestibular areas of the cerebrum.

The central vestibular system

The information from the vestibular apparatus is continuously offset by somatosensory information from the brain and neck area, as well as from other joints, for the central nervous system to acquire information about the posture of the entire body.

The 4 vestibular nuclei involved are the nucleus superior of Bechterew, nucleus inferior of Roller, nucleus medalis of Schwalbe, and nucleus laterals of Deiters. This is also true for muscular reflexes activated to maintain body balance.

Particularly interesting are the vestibulo-ocular reflexes, which connect the vestibular apparatus with the eye muscles. This is, for instance, important for rotational movements. Vestibular nystagmus is a slow, vestibular-induced eye movement followed by a fast return movement.

Example: If a person sitting in a chair turns to the right, the sensory cells in the right semicircular duct are activated. They project via vestibular nuclei to the nuclei of the eye muscle and cause an eye movement to the left. Vision stabilization follows. The fast return movement is mediated centrally and follows the turning movement.

The Olfactory Sense

Structure and function of the olfactory mucosa

This area of olfactory perception (**regio olfactoria**) is strongly underdeveloped in humans and covers only the upper nasal concha and nasal septum. The stratified olfactory epithelium consists of 3 cell populations.

Supporting cells, basal cells and olfactory cells

Resting on the basal lamina of the olfactory epithelium, basal cells are stem cells capable of division and differentiation into either supporting or olfactory cells. The constant divisions of the basal cells lead to the olfactory epithelium being replaced every 2–4 weeks.

The olfactory cells are the primary bipolar sensory cells of the olfactory organ. They form long cilia (**olfactory cilia**) that bind molecules of breathable air with the help of chemoreceptors and thereby stimulate the sensory cells.

Each sensory cell can perceive only 1 olfactory quality, such that 1 olfactory quality can be perceived by tens of thousands of sensory cells. Humans have approximately 350 different receptors and can differentiate between 7 typical kinds of smells.

Primary sensory cells transmit the stimulation directly to the central nervous system via their axons and without any interconnection. The axons, or **fila olfactoria**, are bundled in the **olfactory nerve** and pass directly into the bulbus olfactorius through the lamina cribrosa of the ethmoid bone plate. The **bulbus olfactorius** is considered a part of the central nervous system located in front of it. The first interconnections take place here.

Bulbus olfactorius

The endings of the fila olfactoria, together with the dendrites of the **mitral** cells, form **glomeruli** inside the **bulbus olfactorius**, which are the smallest functional units of the olfactory organ. The first synapse of the olfactory system is located there. During this

process, convergence occurs: More than 1000 axons of sensory cells project onto the dendrites of 1 mitral cell.

Periglomerular cells and granular cells of the glomeruli can modulate the signal. A lateral inhibition facilitates periglomerular cells to amplify the signal of the stimulated glomerulus and to define it better against weaker neighboring signals.

The olfactory pathway - tractus olfactorius

Approximately 30,000 axons of mitral cells exit the bulbus as the so-called **tractus olfactorius**, which splits into a main branch and a side branch. The main branch crosses at the anterior commissure to the bulbus of the opposite side of the brain, whereas the side branch projects onto the olfactory bulb.

The olfactory bulb is located in the paleocortex and consists of many olfactory projection fields. Information is sent from here to the neocortex and the **cortex praepiriformis**, as well as to the limbic system. From the limbic system, it is sent to the nuclei areas of the hypothalamus and the **formatio reticularis**.



Image: The Olfactory System, by Phil Schatz. License: CC BY 4.0

The Sense of Taste

Structure of the organ of taste

Taste is perceived via the tongue, on which the appropriate structures are located. There are 3 different types of taste papillae:

- Papillae fungiformes: 200-400, distributed on the entire surface
- Papillae foliatae: 15-20, located on the posterior margin in consecutive rows
- **Papillae vallatae:** 7–12, located at the border to the tongue base

The taste papillae contain the taste buds. There are 2,000–4,000 buds, each having approximately 10–50 sensory cells. The taste buds develop a cavity filled with fluid. The sensory cells and their microvilli extend into this cavity. The microvilli contain the actual taste receptors.

Transduction of taste

Here, a chemical stimulus is converted into an electrical signal. The chemical substances/relationships always cause a depolarization of the sensory cell through different receptors or channels, which leads to the release of transmitters and the activation of innervating nerves. Therefore, sensory cells of taste are secondary sensory cells.

We can differentiate between 4 different qualities of taste: sweet, sour, salty, bitter.

A sensory cell can perceive just 1 quality of taste or all 4 of them but with a predefined ranking order of the 4 qualities.

Gustatory pathway

The papillae are innervated by the **nervus glossopharyngeus** and the **nervus vagus**. These nerves proceed to the **nucleus tractus solitarii** of the brain stem. The information is switched over to the second neuron and transferred ipsilaterally to the third neuron in the **nucleus parabrachialis** of the **formatio reticularis**.

This neuron projects into the contralateral **nucleus ventralis posterior** of the thalamus. The thalamus transfers the information to different areas of the brain. There, we become conscious of the taste and of links to other perceptions, i.e. the sense of smell.