The Sensory Systems of the Human Body

The sensory organs enable us to interact with our surroundings and perceive things outside our body. As fascinating as their function is, as complex and vast seems the topic during medical studies. Despite the large variety of sensory organs, they all follow a few fundamental principles in their structure and function. From the fundamentals to the necessary detailed knowledge of the different sensory perceptions is only a short way.

The Fundamentals of Sensory Perception

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

Below, the four most important classic senses - sight, hearing, smell, and taste - as well as the sense of balance will be discussed.

There are different ways to measure the sensitivity of the same receptor. One receptor will have a measurable absolute threshold value AND a measurable difference.
Absolute Threshold | Difference Threshold
--- | ---
Sight in low light | Hear
Hear slightest noise | Taste
Taste 3 sugar cubes in 100 l water | Smell
 | Feel
 | See

Weber’s Law

Two stimuli must differ by a constant proportion in order for their difference to be perceived. Proportion varies by stimulus (weight vs. light vs. sound).

Proportion by sense for humans

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Weight</td>
<td>2 %</td>
</tr>
<tr>
<td>Light</td>
<td>8 %</td>
</tr>
<tr>
<td>Sound</td>
<td>0.3 %</td>
</tr>
</tbody>
</table>

Weber’s Law:

\[
\frac{\Delta I}{I} = k
\]

\(\Delta I\) represents the difference threshold. \(I\) represents the initial stimulus intensity. \(k\) is the Weber constant.
Example of Weber’s law

Can detect the difference between a 25 lb bag of groceries and a 30 lb bag of groceries. If he is helping another customer which one of these bags would he be able to differentiate by weight?

- 2 lbs and 3 lbs?
- 20 lbs and 22 lbs

\[
JND = \frac{(30 - 25) \text{ lbs}}{25 \text{ lbs}}
\]

\[
= \frac{5 \text{ lbs}}{25 \text{ lbs}}
\]

\[
= 0.2 \text{ (20 \% difference)}
\]

2 and 3 lbs

**right:**

\[
JND = \frac{(3 - 2) \text{ lbs}}{2 \text{ lbs}}
\]

\[
= \frac{1 \text{ lbs}}{2 \text{ lbs}}
\]

\[
= 0.5 \text{ (50 \% difference)}
\]

20 and 22 lbs

**wrong:**

\[
JND = \frac{(22 - 20) \text{ lbs}}{20 \text{ lbs}}
\]

\[
= \frac{2 \text{ lbs}}{20 \text{ lbs}}
\]

\[
= 0.1 \text{ (10 \% difference)}
\]

Signal Detection Theory

Predicts how and when an individual will detect the presence of stimulus amongst background noise.

Detection is influenced by four psychological states:

- Active vs. passive process
- Based on detection and influencing factors there are four possible outcomes:

<table>
<thead>
<tr>
<th>stimulus not detected</th>
<th>stimulus detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>stimulus present</td>
<td>miss, hit</td>
</tr>
<tr>
<td>stimulus absent</td>
<td>correct rejection</td>
</tr>
</tbody>
</table>
Sensory adaptation

Defined as the change over time in the responsiveness of the sensory system to a constant stimulus. Allows the brain to tune out “unimportant” information. The system is designed to respond to changing and not constant information. Nociceptors (pain) do not adapt under any circumstance.

Psychophysics – Fechner’s Law

Psychophysics quantitatively investigate the relationship between physical stimuli and the sensations and perceptions they affect. Fechner describes a logarithmic relationship between perceived intensity of a stimulus and the actual physical stimulus intensity.

Sensory Pathways

Sensory receptors are sensory nerves that are either cells or nerve endings. 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, through to ganglion cells and end in the spinal cord.
Types of Sensory Receptors

Sensory receptors are specific to only one sensory modality.

<table>
<thead>
<tr>
<th>Type of Sensory Receptor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanoreceptors</td>
<td><strong>Auditory hair cell</strong> — mechanical movement of cells from fluid in the ear</td>
</tr>
<tr>
<td></td>
<td><strong>Olfactory receptors</strong> detect airborne chemicals allowing smell</td>
</tr>
<tr>
<td></td>
<td><strong>Taste (gustatory receptors)</strong> detect chemicals on tongue</td>
</tr>
<tr>
<td>Chemoreceptors</td>
<td>Respond to tissue injury leading to <strong>pain</strong></td>
</tr>
<tr>
<td>Nociceptors</td>
<td>Respond to <strong>temperature</strong></td>
</tr>
<tr>
<td>Thermoreceptors</td>
<td>Activation of rod and cone cell in the <strong>eye</strong></td>
</tr>
<tr>
<td>Photoreceptors</td>
<td></td>
</tr>
</tbody>
</table>
The Sense of Sight

The optical apparatus

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 dpt or diopters (distance-accommodating power of cornea, anterior chamber and lens).

A higher refraction can be achieved due to the 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, in other words the minimal and maximal distance still allowing 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 dpt. In addition, the pupil contributes to the intensifying of the projected object by blanking out annoying 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 ten layers:

**Stratum pigmentosum:**
- Pigment epithelium – supply of retinal cells

**Stratum nervosum:**
- Photoreceptors – transduction of light signals
- External glia limitans
- External granular layer – photoreceptors cell nuclei (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 two types of photoreceptors. The rods are responsible for providing light-dark vision, also referred to as scotopic vision, the cones are responsible for color vision or photopic vision. The cones can be divided into three subtypes according to the three spectral colors. The human eye has approximately 120 million rods and about 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.
The signals are processed in a network of bipolar cells, amacrine cells, and horizontal cells and 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 contains a very high concentration of cones. The fovea centralis, the center of the macula lutea only consists of cones. This is the site of clearest vision.

The papilla n. optici is located medial to the macula lutea and marks the exit of the optic nerve. Due to missing photoreceptors in this area, vision is not possible here. Therefore it is also referred to as blind spot. Within the field of vision, this spot is located laterally.

The visual pathway

The efferent fibers of the ganglion cells form the optic nerve. This nerve exits the eye at the papilla n. 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 the 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 allow conclusions about the location of lesions of the visual pathway. The following examples illustrate this:

- **Blindness in one eye**: the lesion is probably located in the **n. opticus**, since this nerve houses all fibers of one 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 defect – 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 prior to the corpus, thus the reflexes remain intact despite the loss of vision.
- **Minor scotomas**: the lesion is probably located in the optic radiation since only particular areas are damaged due to the broad fragmentation.

**The Auditory System**

Our 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 decibel (dB). It 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 measureable value. It is calculated as follows:

\[
\text{sound pressure level} = 20 \times \lg \left( \frac{p_1}{p} \right)
\]

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

The **volume level** has to be differentiated from the sound pressure level. The volume level describes the subjective perception of the sound volume with the help of the phon scale. The phon values equal 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 in order to be perceived as equally loud. These differences are shown with the help of isophones.
The ear is divided into the outer ear, the middle ear, and the inner ear. The 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. Said adjustment occurs via three 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 to the tympanic membrane leads to an increase in pressure.
3. Compared to the oscillations of the tympanic membrane, the stapes move slower. Since 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) as well as 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. It is bordered by the Reissner’s 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 three rows of outer hair cells which touch the tectorial membrane with their longest stereocilia as well as one row of inner hair cells whose stereocilia do not touch the membrane but are rather deflected by the displacement of the endolymph (hydrodynamic coupling) and are thus stimulated.

Transduction of the cochlea

The travelling wave inside the scala vestibule caused by the stapes leads to a frequency-specific, 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 a mechanoelectrical transduction. The endocochlear potential which is created through the higher potassium concentration of the endolymph in comparison to 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.

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

Therefore, the auditory cortex receives information from both cochleae. This has a positive effect in 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 three semicircular ducts and two otolith organs which together facilitate spatial orientation and registration of movements.

Structure of the Vestibular Apparatus

The structure is similar to the cochlea. The ducts of the vestibular apparatus are also filled with endolymph. The sensory cells are hair cells as well. However, contrary to the hair cells of the cochlear, they develop cilia and several stereocilia which are connected via tip-links.

They are covered by a gelatinous mass. Inside the semicircular ducts, this mass which contains mucopolysaccharide is called cupula. In addition, this mass contains small calcium carbonate crystals inside the otolith organ and is therefore called 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, a deflection of cilia and stereocilia and causes a receptor potential (refer to section on hearing).

The transduction process is the same in the semicircular ducts and the otolith organs. However, due to their anatomic differences the two organs measure different movements.

**Translational motion**: Otolith organs measure acceleration and deceleration. Macula sacculi measure vertical translational motions, macula utriculi horizontal motions.
Rotational motion: The endolymph in the semicircular ducts is usually arranged circularly. Due to 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 rotating the head to the left side, the fluid in the horizontal semicircular ducts shifts to the right which leads to an activity of the left semicircular ducts and its afferent nerves.

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 pathway 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 of the vestibular apparatus are continuously offset against somatosensory information from the brain and neck area as well as from other joints in order for the CNS to acquire information about the posture of the entire body.

The four vestibular nuclei involved are: nucleus superior of Bechterew, ncl. inferior of Roller, ncl. medalis of Schwalbe, and ncl. 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. A vestibular nystagmus is a slow vestibular-induced eye movement followed by a fast return movement.

Example: If a person sitting in a chair is turned 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 only covers the upper nasal concha as well as the nasal septum. The stratified olfactory epithelium consists of three 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 leads 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) which bind molecules of the breathable air with the help of chemoreceptors and thereby stimulate the sensory cells.

Each sensory cell can only perceive one olfactory quality whereby one olfactory quality can be perceived by tens of thousands of sensory cells. Humans have approximately 350 different receptors and can differentiate between seven typical kinds of smells.

Primary sensory cells transmit the stimulation directly to the CNS 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 CNS 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 one thousand axons of sensory cells project onto the dendrites of one 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 from neighboring, weaker signals.

The olfactory pathway – Tractus olfactorius

Approximately 30,000 axons of mitral cells exit the bulbus as 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**.
The Sense of Taste

Structure of the organ of taste

Taste is perceived via the tongue in which the appropriate structures are located. There are three 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 about 10-50 sensory cells. The taste buds develop a porus filled with fluid. The sensory cells and their microvilli extend into this porus. 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 four different qualities of taste: sweet, sour, salty, bitter
A sensory cell can either perceive just one quality of taste or all four of them, but with a predefined ranking order of the four qualities.

**Gustatory pathway**

The papillae are innervated by the *n. glossopharyngeus* and the *n. 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 *ncl. parabrachialis* of the *formatio reticularis*.

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

**Review Questions**

The answers can be found below the references.

1. **Which of the following statements is true?**
   
   A. Photoreceptors are primary sensory cells.
   B. The blind spot is located medially in the visual field.
   C. The closing of sodium channels leads to a depolarization of photoreceptors.
   D. The opening of potassium channels leads to a depolarization of photoreceptors.
   E. The closing of sodium channels leads to a hyperpolarization of photoreceptors.

2. **Which anatomical structure is not part of the auditory pathway?**
   
   A. Corpus geniculatum laterale
   B. Ganglion spirale
   C. Corpus trapezoideum
   D. vestibulocochlearis
   E. Lemniscus lateralis

3. **Which statement concerning the hair cells of the vestibular organ is true?**
   
   A. They are entirely covered by an otolithic.
   B. They are identical to the hair cells of the cochlea.
   C. They are primary sensory cells.
   D. They have one cilium and several stereocilia.
   E. They have different cell types that are responsible for different directions of movement

**References**


Correct answers: 1E, 2A, 3D

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