Auditory and vestibular system

Sensory organs on the inner ear

- inner ear: audition (exteroceptor) and vestibular apparatus (proprioceptor)
- bony and membranous labyrinths within the temporal bone (os temporale)
- both sensory organs contain hair cells: secondary receptor cells
- these sensory systems are related evolutionary with the lateral-line organ (fish, amphibians) - acousticolateral organ
- structure of hair cells is similar everywhere
- hair cells are flanked by supporting cells - tight junctions: perilymph and endolymph separated
- perilymph: extracellular space, high Na\(^+\), low K\(^+\)
- endolymph: transcellular fluid, high K\(^+\), low Na\(^+\)
- endolymph is positive compared to perilymph - 150 mV compared to the intracellular space
- at the tip of the stereocilia mechanosensitive K\(^+\) channels, 10-15% open - 90 Hz firing rate on primary axons - changes depend on direction of bending
Structure of hair cells

- endolymph high K⁺
- perilymph high Na⁺
- supporting cell
- actin
- hair cell
- transmitter
- Na⁺ K⁺
- ATP
- Ca⁺ K⁺ Na⁺
- + 80 mV
- - 70 mV
- + 0 mV

Cilia on hair cells

Eckert: Animal Physiology, W.H.Freeman and Co., N.Y., 2002, Fig. 7-24
Vestibular system I.

- Vestibular apparatus consists of two parts:
  - 3 semicircular canals - detect angular acceleration
  - otolith organs (utricle, sacculus) - detect position of the head, linear acceleration
- Semicircular canals are approximately perpendicular to each other
  - Horizontal one is tilted downwards by 25°, the two vertical ones have an angle of 41° and 56°, respectively with the sagittal plane
- Sensory epithelium with the hair cells is called crista ampullaris, it is located at one end of the canal in the ampulla
  - Hair cells are covered by the cupula that almost blocks the flow of the endolymph
- Lateral-line organ works similarly
- Kinocilia are uniformly oriented in the crista
- Semicircular canals are in pairs within the same plane - complementary pairs - when one is excited, the other is inhibited

Vestibular system II.

- Hair cells are located in maculas within the utricle and sacculus
- Macula is horizontal in the utricle, while it is vertical in the sacculus
- Hair cells are covered by otolith membrane containing otoliths (calcium carbonate)
- Kinocilia in maculas (maculae) are oriented with respect to an undulating line, the striola
- Any position of the head causes a specific firing pattern in the primary afferents
- Linear acceleration (lift) is also detected because of the inertia of the otoliths
- Primary sensory neurons are located in the ganglia vestibulare
- Central axons run to the four vestibular nuclei in the brainstem
Vestibular centers

- Deiters' nucleus (nucl. vestibularis lateralis)
  - strong, tonic excitatory effect on spinal motor neurons – tractus vestibulospinalis lateralis
  - crucial for the maintenance of straight posture
  - opposite effects: cerebellar inhibition on Deiters' nucleus, cortical (in tetrapods rubral) inhibition on spinal motor neurons
  - decerebration rigidity
- nucl. vestibularis medialis
  - brief, short lasting input from semicircular canals – control of neck muscles
- nucl. vestibularis superior
  - similar input – control of eye movements
- nucl. vestibularis inferior
  - less known, it integrates inputs with cerebellar information and provides ascending pathways

Audition

- ear is one of the most important telereceptive organ – vision is limited by darkness, olfaction depends on the direction of the wind
- audition is functioning even during sleep – weak sounds made by the baby awake the mother
- audition is very important for communication too
- sounds are longitudinal waves
- human ear is sensitive to sounds between 20 Hz and 20 kHz, some animals hear ultrasounds (rat after coitus); infrasound is annoying
- intensity in given as the logarithm of the ratio to a reference value (20 µPa – threshold at 2 kHz) because the range of intensities is wide
- in practice tenth of Bel, decibel (dB) is used, thus the logarithm should be multiplied by 10
- if voltage or current is used, then the second power of these values should be entered in the equation – that's why we use 20 and not 10 in the equation
The organ of audition

- Human ear consists of 3 parts: external, middle, and inner ear.
- **External ear:**
  - Pinna (can be moved in some animals)
  - Auditory canal
  - Tympanic membrane - closing external ear
- **Middle ear:**
  - Ossicles (malleus, incus, stapes) - 22-fold increase in pressure because of the different surface size and the lever system
  - Eustachian tube to the pharynx - equalization of pressure in the external and middle ears (flying, yawning, candy)
- **Inner ear:**
  - Bony and membranous labyrinth with three canals
  - Scala media (ductus cochlearis) surrounded by membrana basilaris (with the organ of Corti) and Reissner's membrane
  - Above: scala vestibuli, below: scala tympani

Mechanism of audition I.

- Ossicles forward sound stimuli to the perilymph (scala vestibuli) through fenestra ovale
- Cochlea has 2.5 turns - sound waves reach the top of the cochlea, then return through scala tympani to fenestra rotunda
- Total length of the cochlea is about 32-33 mm
- Sound waves also reach inner ear by bone conduction - it is less important, except when listening to our own sound record, or when middle ear is damaged and hearing aid is needed
- The site of maximal oscillation of the membrana basilaris depends on frequency - tonotopy
- Movement of membrana basilaris stimulates hair cells
  - Membrana basilaris is narrow and tight at the base (100µ), and wide and loose at the top (500µ)
- Helmholtz suggested, György Békésy proved that high pitch tones are detected at the base, low pitch tones at the top of the cochlea.
Mechanism of audition II.

- function of inner and outer hair cells is different
- inner hair cells - sensation, outer hair cells - setting sensitivity
- activation induces shortening of outer hair cells due to activation of their cytoskeleton - amplitude of maximal oscillation increases
- threshold of inner hair cells is higher, it reaches normal detection limit only due to amplification
- noise-induced hearing loss: (Walkman), and certain medicines (streptomycin) destroy outer hair cells
- stereocilia are also shorter and tighter at the base of the cochlea - contributes to tonotopy
- outer hair cells reach tectorial membrane, inner ones not - turbulently flowing perilymph stimulates them

Mechanism of audition III.

- mechanosensitive channels of stereocilia respond with time resolution in the µs range - K⁺ enters, because of the 150 mV potential difference
- depolarization causes Ca++ influx - shape change in outer hair cells, increased glutamate (?) release in inner hair cells
- primary sensory neurons are located in the ganglion spirale - 1 hair cell 10 afferents, 1 afferent - 1 hair cell
- there are approx. 3500-3500 hair cells, i.e. 60-70000 afferents on the two sides together
- afferents cannot follow 20 kHz frequency, spikes appear phase-locked
- intensity is coded partly in frequency, partly in the number of cells activated (population code) depending on recruitment of neighboring and high-threshold hair cells
- sensitivity is set by the lateral (inner hair cells and primary dendrites) and medial (outer hair cells) olivocochlear bundle
Central auditory pathway I.

- onset and termination of sounds, location of the source, and stimulus pattern should be analyzed by the central apparatus
- anatomy is known, physiology is less well
- general characteristics: parallel ascending fibers, two-directional connections, tonotopy
- first relay stations are the cochlear nuclei (anteroventral, posteroventral and dorsal) – strictly ipsilateral
- deafness restricted to one side is either because of damage to this nuclei or disruption at the periphery
- primary afferents related to one hair cell (approx. 10 axons) terminate in one layer
- fibers originating in these nuclei, join ipsi- and contralateral lemniscus lateralis and go to inferior colliculus, or reach superior olivary nucleus – second relay station

Central auditory pathway II.

- oliva receives bilateral projection, it localizes sound source – based on differences in phase [below 2 kHz], or in intensity [above 2 kHz]
- 1° difference in direction can be detected
- fibers from oliva join lemniscus lateralis and run to the third relay station, inferior colliculus
- inferior colliculus is also important in detection of sound direction – e.g. owls
- output to non-auditory areas as well
- fourth station is corpus geniculatum mediale (medial geniculate body) – tonotopic representation, input from other sensory areas as well
- the end station is the primary auditory cortex, Br. 41-42 in the temporal lobe – several areas arranged in a tonotopic way
**Structure of the inner ear**

![Diagram of the inner ear](image)

**Crista ampullaris and macula**

![Diagram of cristae ampullares and maculae](image)
The lateral-line system

Structure of the labyrinth