The last two special senses are located within the organ we call the ear. Those two special senses are:

- Hearing
- Equilibrium

The special structures in charge of these functions are found within the ear and protected by an osseous surrounding. The outer aspect of the ear are used to enhance the function of hearing but have no influence on the function of equilibrium.
The ear can be divided into 3 specific areas:

- **The External or Outer ear**: collect soundwaves and direct them to the Middle Ear
- **The Middle ear**: Transmits and directs soundwaves to specific portion of the Inner Ear
- **The Inner ear**: contains sensory organs for hearing and equilibrium

The External Ear

- Contains the fleshy Auricle
- It surround the external acoustic canal
- This canal ends at the Tympanic Membrane (eardrum)
- Ceruminous glands secrete waxy substance
THE MIDDLE EAR

The MIDDLE Ear

- Communicates with the nasopharynx via the pharyngotympanic tube or Eustachian Tube
- Contains 3 auditory ossicles that connect the tympanic membrane with the inner ear
  - **Malleus** or Hammer: connects at three points with the eardrum
  - **Incus** or Anvil: connect Malleus to Stapes
  - **Stapes** or Stirrup: is connected to the oval window of the inner ear

THE MIDDLE EAR

The MIDDLE Ear

- Sound waves result in a vibrating eardrum. These vibrations are passed on via these ossicles and focused onto the oval window
- Since the tympanic membrane is 22x larger than the oval window, considerable amplification occurs
- Damage to the tympanic membrane and ossicles is partially prevented by two muscles
  - **Tensor tympani**: stiffens the eardrum by pulling on the malleus
  - **Stapedius muscle**: prevents excessive movement of stapes on the oval window
The INNER Ear

- Contains the receptors for hearing and equilibrium

- These receptors lie within fluid filled tubes referred to as the membraneous labyrinth: the fluid is called the endolymph
- The endolymph is atypical in that it has a high potassium and low sodium concentration.

- The bony labyrinth surrounds and protects this membraneous labyrinth. Between bony and membraneous labyrinth flows a fluid called the perilymph.

The Bony labyrinth is divided into

- Cochlea
- Vestibule
- Semicircular canals
THE INNER EAR

The INNER Ear

- The Vestibule consist out of saccule and utricle: they contain receptors that are important for sensation of gravity and linear acceleration.

- Receptors in the semicircular canals sense rotation of the head.

- Together, Vestibule and semicircular canals are called the vestibular complex.

- The cochlea is a spiral-shaped bony chamber that houses the cochlear duct and the receptors for hearing.

- The sensory receptors of the inner ear are called hair-cells.

THE INNER EAR HAIR CELLS
THE INNER EAR HAIR CELLS

- Hair cells have a tall kinocilium and many stereocilia (decreasing in length)
- They are all connected to each other by links
- Movement of stereocilia towards the kinocilium, pulls ion channels open (K+ channels)

THE INNER EAR

Movement of stereocilia towards the kinocilium thus creates a change in membrane potential and increases the number of action potentials in the afferent nerve (the vestibular or cochlear nerve depending on where we are).
### The Sense of HEARING

- The organs for hearing are located within the **Cochlear duct**, within the cochlea
- The cochlear duct, filled with endolymph, itself is sandwiched between the **vestibular duct** and the **tympanic duct (filled with perilymph)**
- The receptor Hair cells of the cochlear duct are organized within the **Spiral Organ of Corti**

They pick up the sound vibrations which have been transmitted from Tympanic membrane via the middle ear ossicles to the oval window and transformed into waves in the perilymph.
The Sense of HEARING

- Even though the cochlea is spiral-shaped, it is actually a tube.
- We can visualize the organization of the cochlear duct better if we imagine it being rolled out.
- Oval window connects to the Scala Vestibuli.
- This wraps around at the end into the Scala Tympani, which ends at the Round window.
- In the middle is the Scala media, which contains the hair cells and spiral organ of Corti.

The Sense of HEARING

- The organ of Corti sits on the basilar membrane within the Scala Media.
- Basilar membrane separates S. Media from S. Tympani.
- Vestibular membrane separates S. Vestibuli from S. media.
- S. vestibuli and S. tympani form one continuous duct, filled with perilymph.
- S. media is filled with endolymph.
- Endolymph is rich in K⁺ and similar to intracellular fluid.
The Sense of HEARING

- The organ of Corti with the hair cells is the actual organ of hearing.
- They respond to the pressure waves generated in the endolymph by the action of the tympanic membrane on the perilymph.
The Sense of HEARING

Organ of Corti contains:
- Tectorial Membrane
- Hair cells

The hair cells are organized in outer hair cells and inner hair cells. The inner hair cells are connected to afferent nerve fibers while the outer hair cells are connected to mostly efferent fibers.

This thus implies that hearing is comes mostly from the inner hair cells while the outer hair cells are important in modulation.

The Sense of HEARING

- Hearing is the detection of sound; sound travels in pressure waves
- The wavelength of a sound wave determines the frequency.

\[
\text{Wavelength} = \frac{\text{Speed of sound}}{\text{Frequency of sound}}
\]

- Frequency is expressed in terms of Hertz: number of waves per second (Hz = Freq/sec)
The Sense of HEARING

**Low Frequency Wave**

- The pitch of a sound relates to the Freq.
  - High pitch = high frequency, short wavelength
  - Low pitch = low frequency, high wavelength

**Examples**:
For sound in air (1235 km/hr)

\[ (= \frac{1235000 \text{ m}}{3600 \text{ sec}}) \text{ or } (= \frac{343 \text{ m}}{\text{sec}}) \]

Wavelength = speed/Freq

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<tr>
<th>Frequency (Hertz, or cycles / second)</th>
<th>Wavelength (meters)</th>
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<tr>
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**The Sense of HEARING**

The wave’s amplitude is the change in pressure as the sound wave passes by.

The amplitude of a wave is related to the amount of energy it carries.

- A high amplitude wave carries a large amount of energy (louder)
- A low amplitude wave carries a small amount of energy (quieter)

As the amplitude of the sound wave increases, the intensity of the sound increases.

Relative sound intensities are often given in units named decibels (dB).
The Sense of HEARING

Decibel is a logarithmic scale
10 times the log of the ratio of the sound intensity (L1) to the reference intensity L0

\[ dB = 10 \log \left( \frac{L_1}{L_0} \right) \]

<table>
<thead>
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<th>Decibel</th>
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</tr>
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The Physiology of HEARING

Step 1: (Outer ear Process)
Sound waves travel toward tympanic membrane, which vibrates

Step 2: (Middle ear process)
Auditory ossicles conduct the vibration into the inner ear
- Eardrum resonates with frequencies between 20 and 20,000 Hz
- Tensor tympani and stapedius muscles contract to reduce the amount of movement when loud sounds arrive
• The middle ear acts as an impedance-matching device.
• Sound waves travel much easier through air (low impedance) than water (high impedance).

• If sound waves were directed at the oval window (water) almost all of the acoustic energy would be reflected back to the middle ear (air) and only 1% would enter the cochlea.

• This would be a terribly inefficient mechanism.

• To increase the efficiency of the system, the middle ear acts to transform the acoustic energy to mechanical energy which then stimulates the cochlear fluid.

• The middle ear also acts to increase the acoustic energy reaching the cochlea by essentially two mechanical phenomenon.

  • **First,** the area of the tympanic membrane is much greater than that of the stapes footplate (oval window) causing the force applied at the footplate per square area to be greater than the tympanic membrane.

  • **Second,** the ossicles act as a lever increasing once again the force applied at the stapes footplate. Overall, the increase in sound energy reaching the cochlea is approximately 22 times.
Step 3: Inner Ear process

- The cochlea consists of a fluid filled bony canal within which lies the cochlear duct containing the sensory epithelium.
- Energy enters the cochlea via the stapes bone at the oval window and is dissipated through a second opening (which is covered by a membrane) the round window.
- Vibrations of the stapes footplate cause the perilymph to form a wave. This wave travels the length of the cochlea. It takes approximately 5 msec to travel the length of the cochlea.

Step 4: Basilar membrane distortion

- As it passes the basilar membrane of the cochlear duct, the fluid wave causes the basilar membrane to move in a wave-like fashion (i.e. up and down). The wave form travels the length of the cochlea and is dissipated at the round window.
- Due to changes in the mechanical properties of the basilar membrane, the amplitude of vibration changes as one travels along the basilar membrane. Low frequency stimuli cause the greatest vibration of basilar membrane at its apex, high frequency stimuli at its base.
The Physiology of HEARING

- The hair cells make tight contact with the tectorial membrane.
- The longest hair, the kinocilium, influences the mechanically gated ion channels of the stereocilia.
- Movement in one direction causes opening of K+ channels and depolarization; the other way and it closes the channels resulting in hyper-polarization.

Step 5: Hair cells and Tectorial membrane interact

- As the basilar membrane is displaced superiorly by the perilymph wave, the kinocilium and stereocilia at the apex of each inner and outer hair cell, which are imbedded in the tectorial membrane undergo a shearing force (i.e. they are bent).

- The bending of these hair cells against the tectorial membrane in a certain direction causes ion channels to open, and a change in the resting membrane potential of the hair occurs.

- In this case, inward K+ and Ca2+ currents cause the depolarization.
The Physiology of HEARING

Step 5: Hair cells and Tectorial membrane interact

- The depolarization results in the opening of calcium channels, which results in the release of neurotransmitters (glutamate) at the base of the hair cells.

Step 6:

- The hair cell synapse with a bipolar neuron (see next image)

- This causes depolarization of the bipolar neuron nerve fiber, which transmits this neural impulse towards the auditory centers of the brain.
The Pathway of HEARING

- Sound activates the hair cells
- These activate bipolar cells of the spiral ganglion of the cochlear nerve
- The afferent fibers form the cochlear branch of the CN VIII
- CN VIII synapses in the cochlear nucleus in the medulla oblongata
- Crosses over to the olivary nuclei and informs the inferior colliculi as well as motor tracts (reflexes to noise)
- Additional connections are made via the geniculate nucleus of the thalamus to the auditory complex in the temporal lobe (contains a frequency map for conscious awareness of sound).
- Not all fibers cross over, so each auditory receives info from both ears.
HEARING Imbalances

Deafness

- Conduction deafness: Due to sound conduction problems
  - Wax, perforated eardrum
  - Otosclerosis (hardening of the ear ossicles)
- Sensorineural deafness: damage to neural structures
  - Damage to hair cells (broken cilia)
  - Damage to cochlear nerve or auditory cortex.

Meniere’s Syndrome

- Labyrinth disorder and affects all 3 parts of inner ear
- Person has repeated attacks of vertigo, nausea, vomiting and balance problems.
- Tinnitus (ringing sounds in the ear) is common as well.

The Sense of EQUILIBRIUM

The vestibular complex provides information about equilibrium. Semicircular canals relate rotational movement of the head, the saccule and utricle relate information with respect to gravity and sudden acceleration.

The Semicircular Canals

- The bony part houses the semicircular ducts, filled with endolymph fluid.
- Each semicircular duct has at its base an ampulla
- The ampulla contains a raised structure, the crista, to which the hair cells are attached to.
- The hair cells are embedded in the cupula, a gelatinous structure
The Sense of EQUILIBRIUM

The semicircular canals detect angular acceleration/deceleration of the head.

When you turn your head in the plane of the canal, the inertia of the endolymph causes it to push against the cupula, deflecting the hair cells and creating action potentials in the vestibulocochlear nerve.

Thus these semicircular canals act as rotation detectors. However if the rotational movement of the head continues, eventually the fluid will get to be moving at the same speed as the canal, and there will be no more pressure on the cupula.

Naturally, you have the same arrangement (mirrored) on both sides of the head.

Each tuft of hair cells is polarized - if you push it one way, it will be excited, but if you push it the other way, it will be inhibited. This means that the canals on either side of the head will generally be operating in a push-pull system; when one is excited, the other is inhibited.

When you stop rotating after having adapted to the rotation the cupula that was excited now switches off, and the one that was switched off now switches on. Thus you feel as though you are turning in the opposite direction. This is the explanation for the phenomenon of giddiness.
The Sense of EQUILIBRIUM

- It is important that both sides agree as to what the head is doing. If there is disagreement, if both sides push at once, then you will feel debilitating vertigo and nausea.

- This is the reason that infections of the endolymph or damage to the inner ear can cause vertigo.

- However, if one vestibular nerve is cut, the brain will gradually get used to only monitoring one side - this can actually be a treatment for intractable vertigo.

- Drugs such as Dramamine tend to depress the activity of the vestibular nuclei.

The Sense of EQUILIBRIUM

The Vestibule

- The utricle and saccule are located in the vestibule.

- They detect linear acceleration and the pull of gravity.

- Each organ has a sheet of hair cells (the macula) whose cilia are embedded in a gelatinous mass, just like the semicircular canals.

- Unlike the canals, however, this gel has a clump of small crystals embedded in it, called the **otoliths**.
The Sense of EQUILIBRIUM

The Vestibule

The otoliths provide the inertia, so that when you move to one side, the otolith-gel mass drags on the hair cells.

Once you are moving at a constant speed, such as in a car, the otoliths come to equilibrium and you no longer perceive the motion.

The Sense of EQUILIBRIUM

The hair cells in the utricle and saccule are polarized, but they are arrayed in different directions so that a single sheet of hair cells can detect motion forward and back, side to side. Each macula can therefore cover two dimensions of movement.

In addition to that:

1. The utricle lies horizontally in the ear, and detects motion in the horizontal plane.
2. The saccule is oriented vertically, so detects motion in the sagittal plane (up and down, forward and back).
The Pathway to EQUILIBRIUM

- Vestibular receptors activate sensory neurons of the vestibular ganglia
- Axons form the vestibular branch of cranial nerve VII
- Synapses within the vestibular nuclei at the boundary between pons and medulla
- These relay information to the cerebellum and motor nuclei of brain stem, Spinal cord.
- Additional information is projected to the superior colliculi in order to keep eyes focused on one point despite body movements
- **Nystagmus** = trouble controlling eye movements