Physiology

Modified no. 10

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المدقق: مريم علي و سديل مأمون

الدكتور: فاطمة ريالات

Neurophysiology

Hearing

Fatima Ryalat, MD, PhD

Assistant Professor, Department of Physiology and Biochemistry
School of Medicine, University of Jordan

Color code

(black)	Slides
(dark blue)	Doctor
(light blue)	Additional info
(red)	Important

Sound waves

As we all know, the stimulus for hearing is sound waves

- Sound waves are alternating high- and low-pressure regions traveling in the same direction through a medium. They originate from a vibrating object.

- The higher the **frequency** of vibration, the higher is the pitch. (Measured in hertz)

The difference between different sounds is their frequency, the higher the frequency the higher the pitch, and the lower the frequency the lower the pitch

Sound waves

- The larger the **intensity (or amplitude**) of the vibration, the louder is the sound. Sound intensity is measured in decibels (dB).

- An increase of one decibel represents a tenfold increase in sound intensity.

The other feature of sound is its amplitude (intensity), the higher the amplitude the louder the sound is.

Numbers are not for memorization

Sound waves

- Most sounds are mixtures of pure tones. The human ear is sensitive to tones with frequencies between 20 and 20,000 Hz (a cycle/sec) and is most sensitive between 2000 and 5000 Hz.

- The usual range of frequencies in human speech is between 300 and 3500 Hz, and the sound intensity is about 65 dB.

- Sound intensities greater than 100 dB can damage the auditory apparatus, and those greater than 120 dB can cause pain.

Numbers are <u>not</u> for memorization

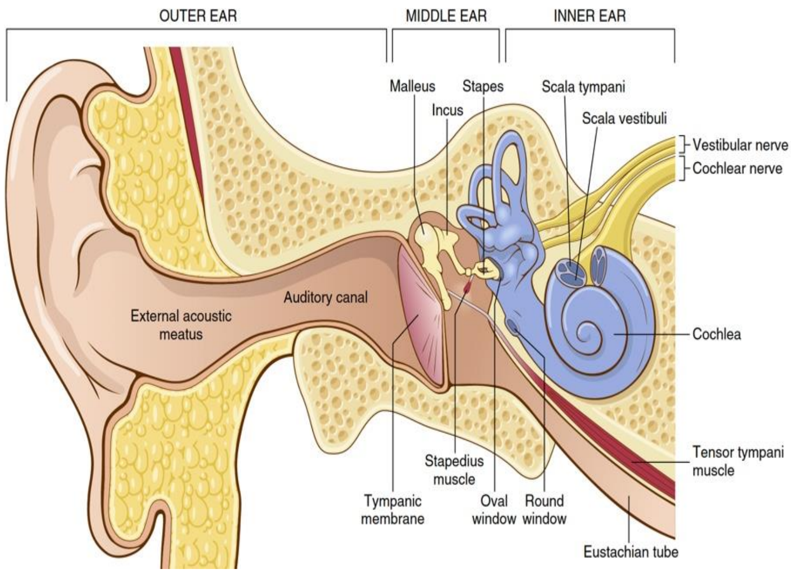
Sound	Loudness in Decibels (dB)	Comparison to Faintest Audible Sound (Hearing Threshold)
Rustle of leaves	10 dB	10 times louder
Ticking of watch	20 dB	100 times louder
Whispering	30 dB	1 thousand times louder
Normal conversation	60 dB	1 million times louder
Food blender, lawn mower, hair dryer	90 dB	1 billion times louder
Loud rock concert, ambulance siren	120 dB	1 trillion times louder
Takeoff of jet plane	150 dB	1 quadrillion times louder

Very loud sound (like takeoff of jet plane sound) will cause pain and if it's sustained it will cause damage to the ear.

Hearing

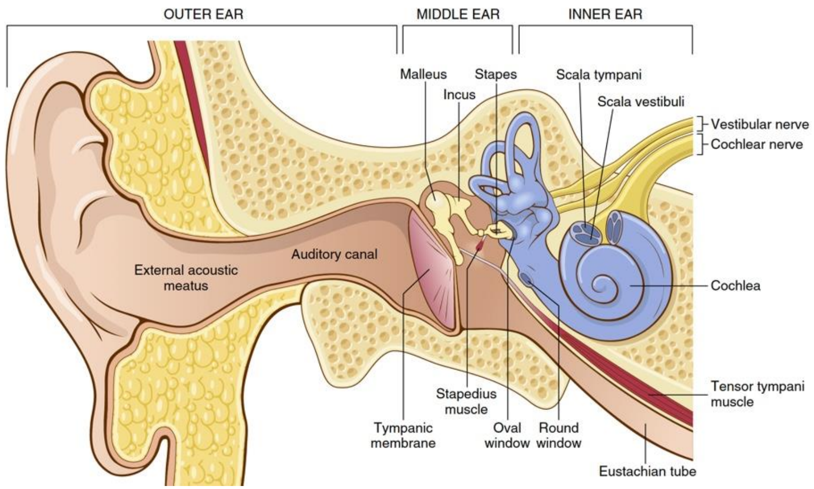
- Hearing is the ability to perceive sounds.

- The ear is divided into three main regions:
- (1) the external ear, which collects sound waves and channels them inward.
- (2) the middle ear, which conveys sound vibrations to the oval window.
- (3) the internal ear, which houses the receptors for hearing and equilibrium.



An overview of the ear :

- The external ear is responsible for collecting sounds to reach the middle ear
- What separates the external ear from the middle ear is the eardrum (tympanic membrane), what is special about it is its **strength** and **elasticity,** this gives it the ability to move. When sound gets to the external ear it gets collected to reach the tympanic membrane, this causes the tympanic membrane to oscillate which transports the sound waves from the external ear to the middle ear.
- The middle ear has 3 of the smallest bones in humans, they transfer sound waves to the inner ear.
- The inner ear is the place where we actually feel sound, it is also responsible the feel of balance (vestibular part of inner ear), but for hearing we are only concerned about the cochlear part (القوقعة), that is why it is called (vestibulocochlear system).



Middle ear

- The middle ear is a small, air-filled cavity in the petrous portion of the temporal bone. It is separated from the external ear by the tympanic membrane and from the internal ear by a thin bony partition that contains two small openings: the oval window and the round window.

- Extending across the middle ear and attached to it by ligaments are the three smallest bones in the body, the auditory ossicles. The bones are the malleus, incus, and stapes.

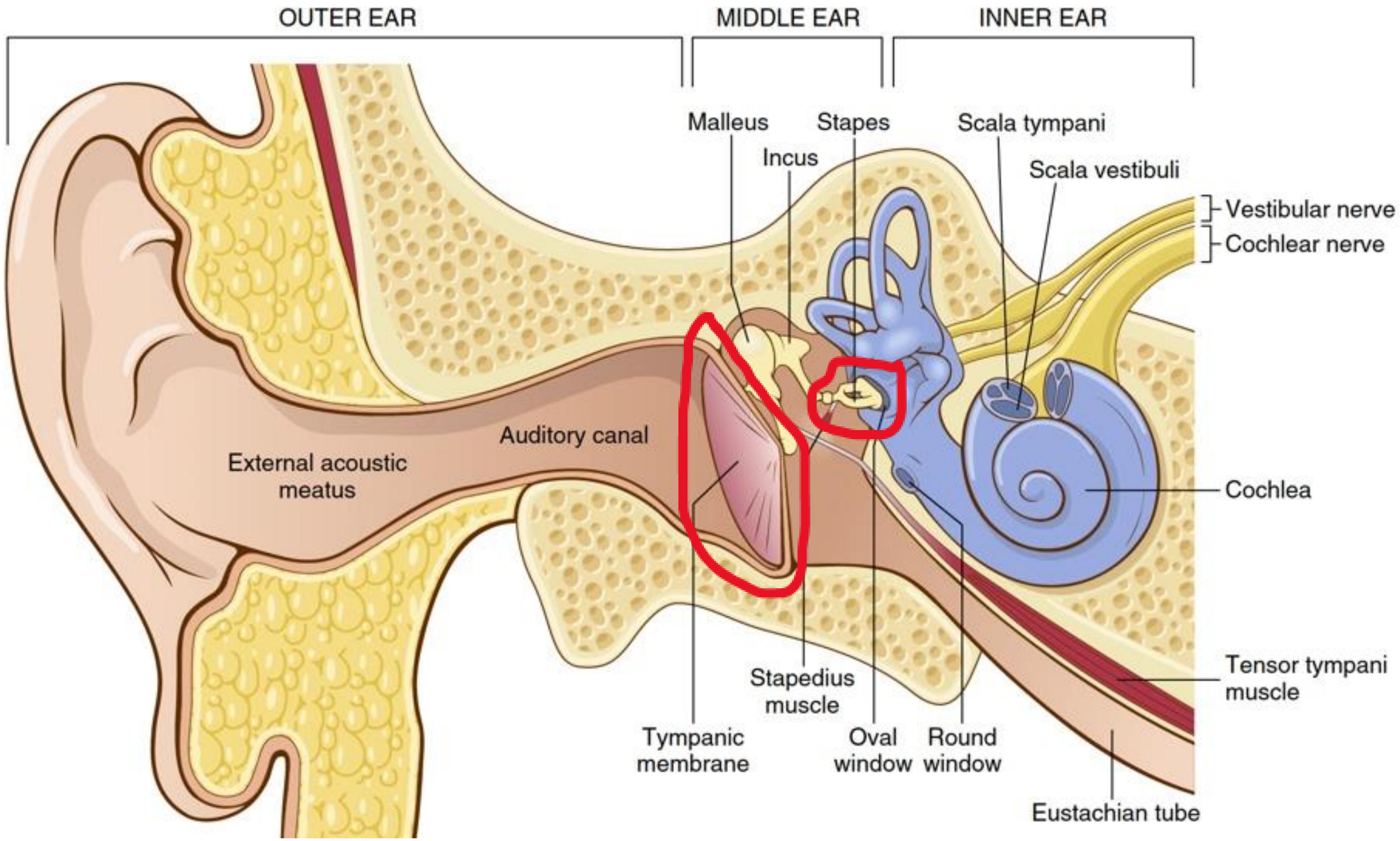
If the place that senses the sound is the middle ear, why do we need the tympanic membrane and middle ear?

The cochlea is fluid-filled, but the medium in which sound travels is the air, so when sound waves are transported from air to this fluid we will face a problem called impedance mismatch which will prevent the conduction of sound, for that, we have the middle ear to fix that problem and be an amplifier and impedance matcher between the sound in air and the fluid in the inner ear.
More on acoustic impedance : link

Auditory transduction

- The external and middle ears are air filled, and the inner ear, which contains the organ of Corti, is fluid filled.
- Thus before transduction can occur, sound waves traveling through air must be converted into pressure waves in fluid.
- The acoustic impedance of fluid is much greater than that of air.
- The combination of the tympanic membrane and the ossicles serves as an **impedance-matching device** that makes this conversion.

Notice the significant difference in surface area between the tympanic membrane and the stapes ossicle; this difference is crucial for amplifying sound waves and aiding impedance matching.



Middle ear

- Besides the ligaments, two tiny skeletal muscles also attach to the ossicles.
- The **tensor tympani muscle**, which is supplied by the mandibular branch of the trigeminal (V) nerve, limits movement and increases tension on the eardrum to prevent damage to the inner ear from loud noises.
- This tension allows sound vibrations on any portion of the tympanic membrane to be transmitted to the ossicles.
- The **stapedius muscle**, which is supplied by the facial (VII) nerve, is the smallest skeletal muscle in the human body. By dampening large vibrations of the stapes due to loud noises, it protects the oval window.

Middle ear

- When loud sounds are transmitted through the ossicular system and from there into the central nervous system, a reflex occurs after a latent period of only 40 to 80 milliseconds to cause contraction of the stapedius muscle and, to a lesser extent, the tensor tympani muscle.
- <u>The tensor tympani muscle pulls the handle of the malleus inward while the stapedius muscle pulls the stapes outward.</u>
- <u>These two forces cause the entire ossicular system to develop increased rigidity</u>.

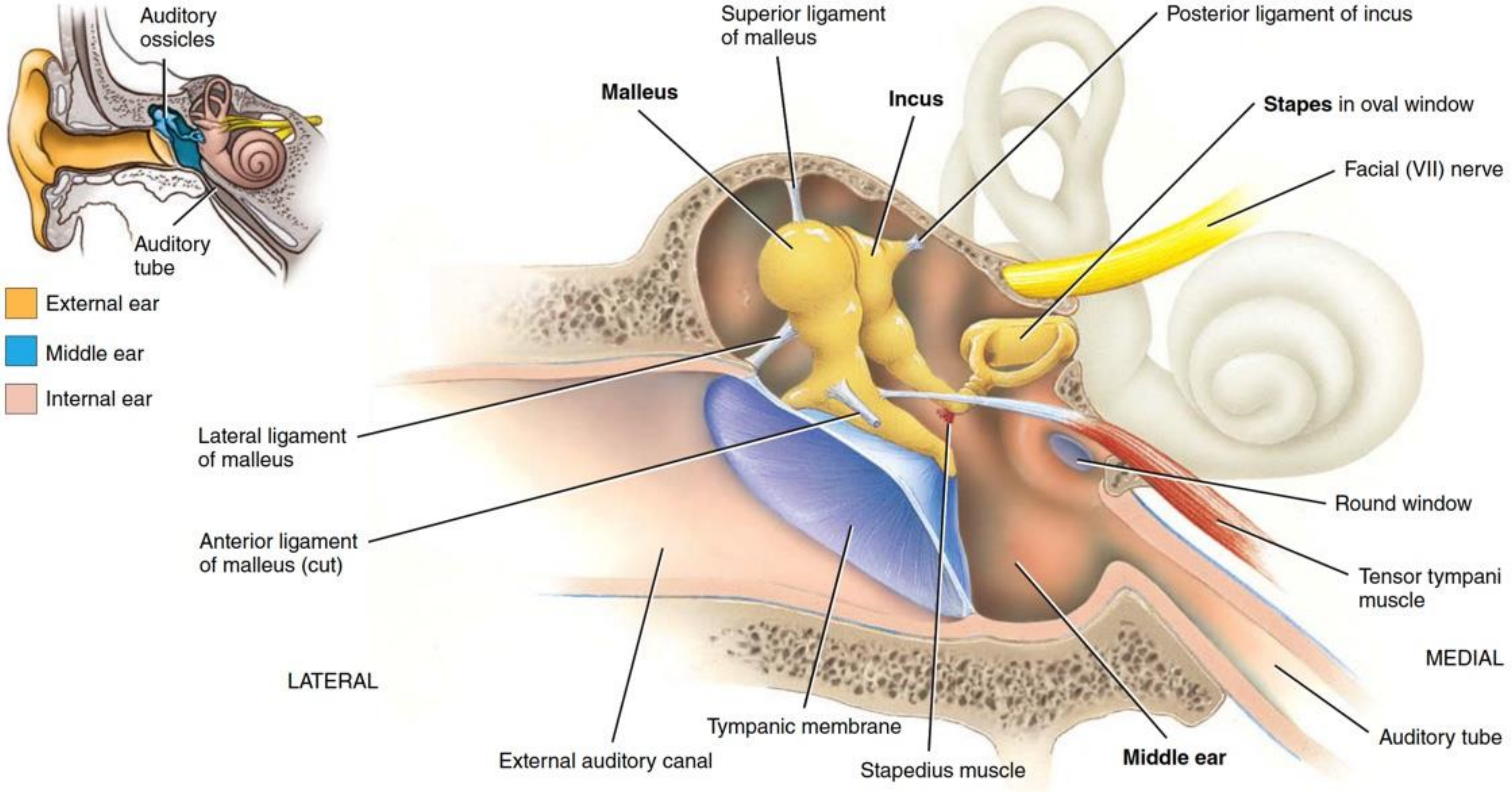
This rigidity restricts the movement of the ossicles, dampening sound. This protective mechanism is known as the attenuation reflex.

The parts responsible for this reflex are the two muscles : tensor tympani and stapedius muscle

Attenuation reflex

- This reflex can reduce the intensity of lower frequency sound transmission by 30 to 40 decibels, which is about the same difference as that between a loud voice and a whisper.
- The function of this mechanism is:
- 1.to protect the cochlea from damaging vibrations caused by excessively loud sound and to mask low-frequency sounds in loud environments, and allows a person to concentrate on sounds above 1000 cycles/sec, where most of the pertinent information in voice communication is transmitted.
- 2.to decrease a person’s hearing sensitivity to his or her own speech.

Unfortunately ,this reflex does not respond to sudden loud sounds; it only activates in response to sustained loud sounds. This is due to some latency in the reflex.



Auditory ossicles
Auditory tube
External ear
Middle ear
Internal ear
Superior ligament of malleus
Posterior ligament of incus
Malleus
Incus
Stapes in oval window
Facial (VII) nerve
Lateral ligament of malleus
Anterior ligament of malleus (cut)
Round window
Tensor tympani muscle
MEDIAL
LATERAL
Tympanic membrane
External auditory canal
Stapedius muscle
Middle ear
Auditory tube

Inner ear

- The inner ear is also called the labyrinth. Structurally, it consists of two main divisions: an outer bony labyrinth that encloses an inner membranous labyrinth.

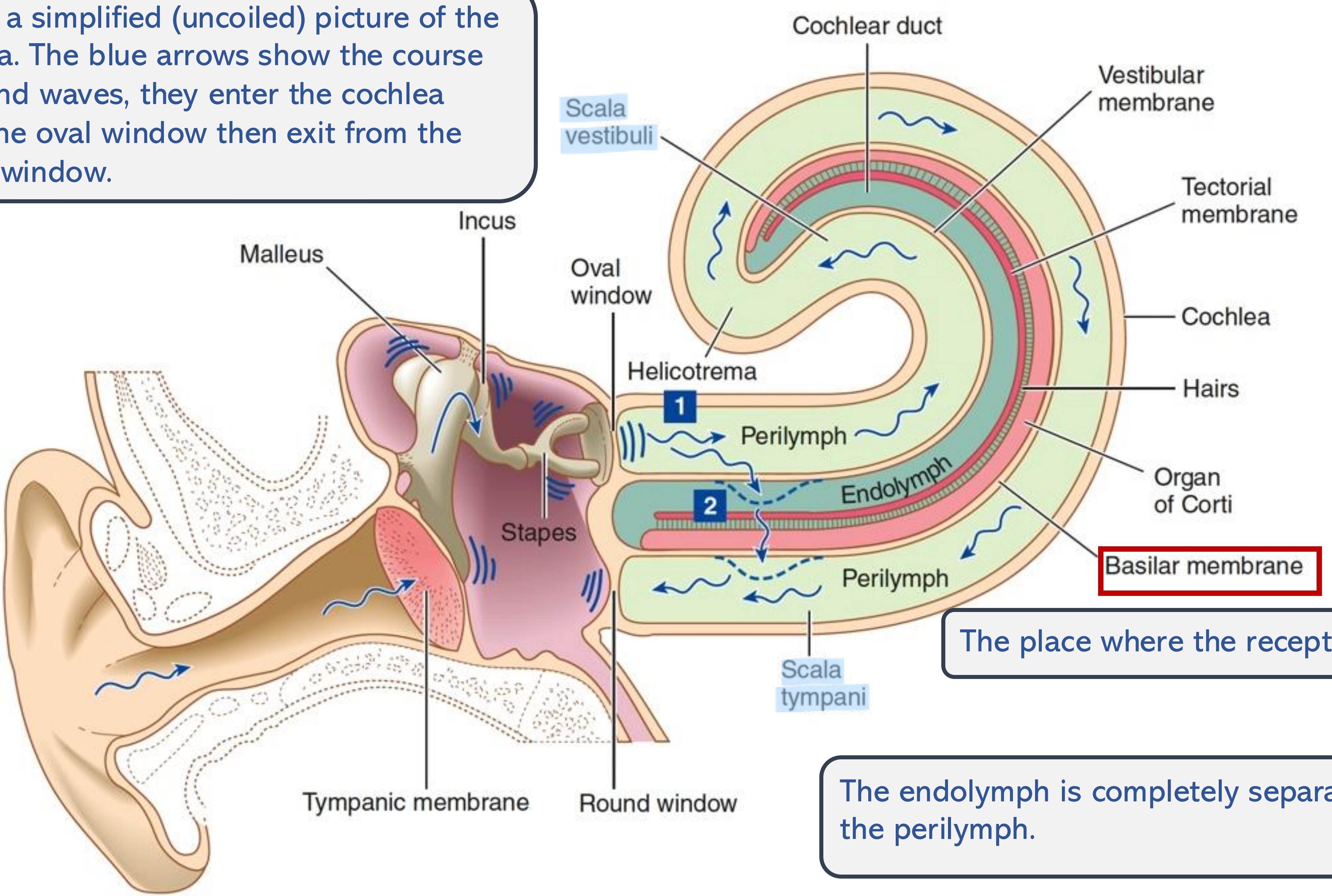
- The **bony labyrinth** is a series of cavities in the petrous portion of the temporal bone divided into three areas: (1) the semicircular canals, (2) the vestibule, and (3) the cochlea.

- The **membranous labyrinth**, a series of epithelial sacs and tubes inside the bony labyrinth that have the same general form as the bony labyrinth and house the receptors for hearing and equilibrium.

Inner ear

- The **cochlea**, which is a spiral-shaped structure composed of three tubular canals or ducts, contains the organ of Corti.
- The **organ of Corti contains the receptor cells** and is the site of auditory transduction.
- The inner ear is **fluid filled**, and the fluid in each duct has a different composition.

This is a simplified (uncoiled) picture of the cochlea. The blue arrows show the course of sound waves, they enter the cochlea from the oval window then exit from the round window.



The place where the receptor cells are

The endolymph is completely separated from the perilymph.

Inner ear

- The fluid in the scala vestibuli and scala tympani is called **perilymph**, which is similar to extracellular fluid (CSF).
- The fluid in the scala media is called **endolymph**, which has a high potassium (K+) concentration.

This is important for the formation of signal

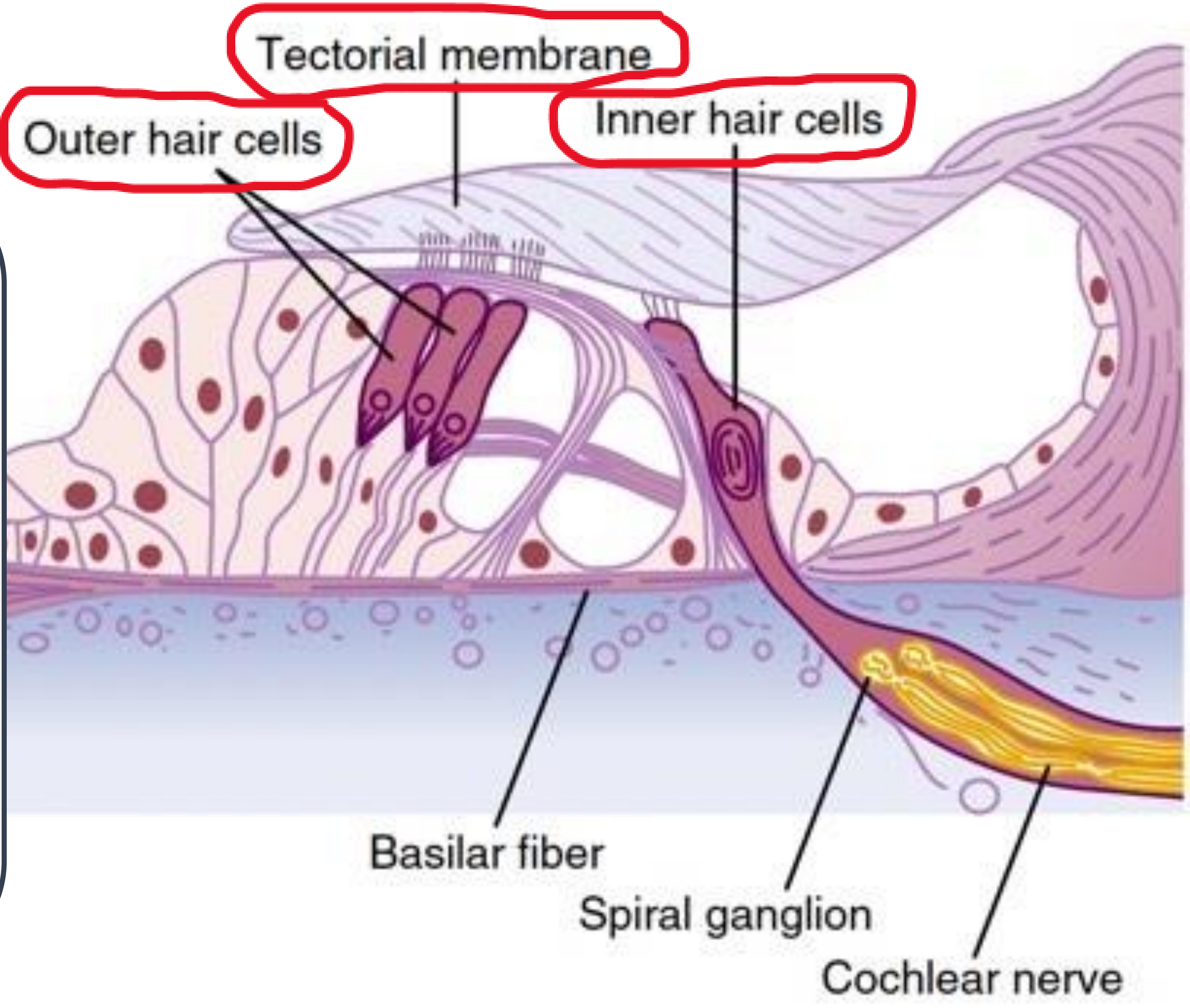
- Thus endolymph is unusual in that its composition is similar to that of intracellular fluid, even though, technically, it is extracellular fluid.

The basilar membrane

Inner hair cells are the receptors of sound, they are called hair cells because they have cilia, the cilia are touching a membrane called the tectorial membrane, which is important for the hearing process.

On the other hand, we have outer hair cells, their function is still not fully understood.

This composition of cells is called the **Organ of Corti.**



Inner ear

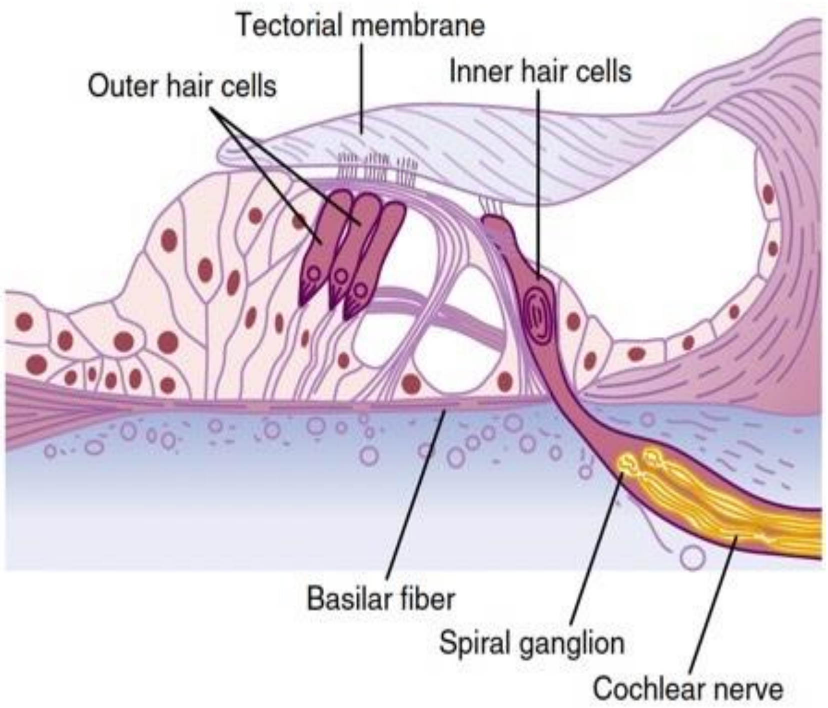
- The lengths of the basilar fibers increase progressively, beginning at the oval window and going from the base of the cochlea to the apex.

- The diameter of the fibers, however, decrease from the oval window to the helicotrema, so their overall stiffness decreases more than 100-fold.

- As a result, the stiff, short fibers near the oval window of the cochlea vibrate best at a very high frequency, whereas the long, limber fibers near the tip of the cochlea vibrate best at a low frequency.

Organ of Corti

- <u>The organ of Corti lies on the basilar membrane of the cochlea and is bathed in the endolymph contained in the scala media.</u>
- <u>Auditory hair cells in the organ of Corti are the sites of auditory transduction.</u>
- <u>The organ of Corti contains two types of receptor cells: **inner hair cells and outer hair cells.**</u>
- There are fewer inner hair cells, which are arranged in single rows. Outer hair cells are arranged in parallel rows and are more numerous.



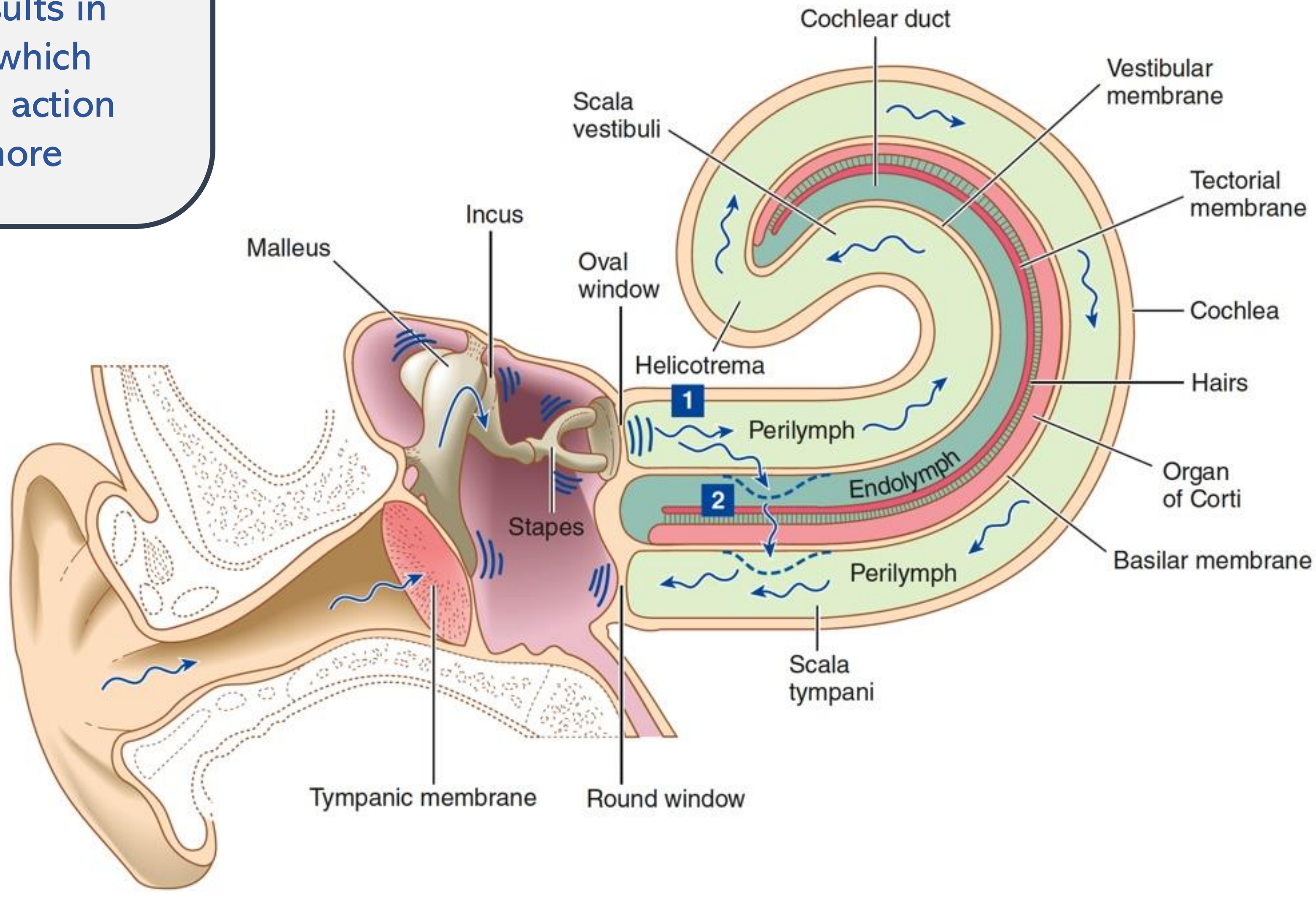
Organ of Corti

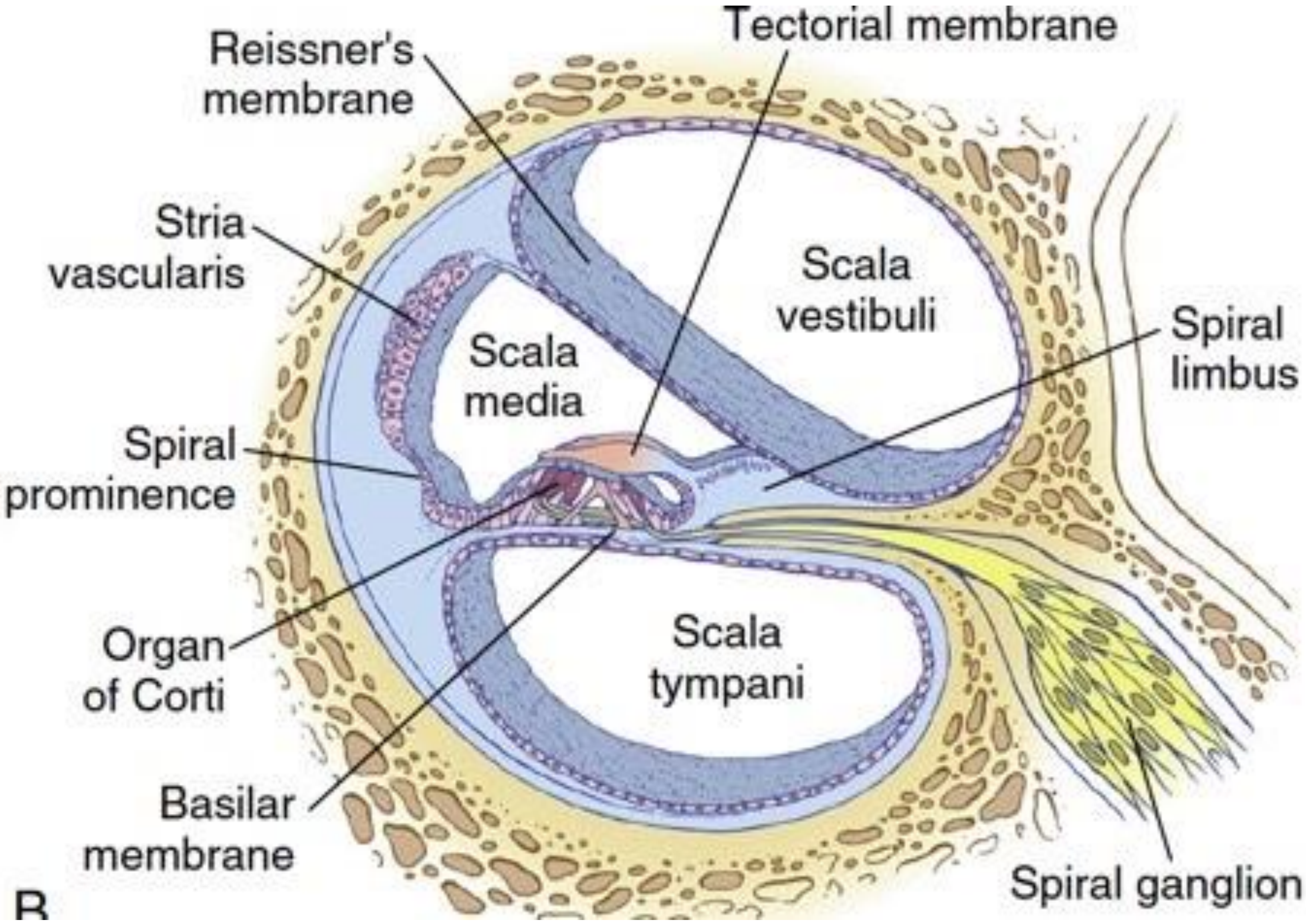
- Cilia, protruding from the hair cells, are touching/embedded in the tectorial membrane.

- Thus the bodies of the hair cells are in contact with the basilar membrane, and the cilia of the hair cells are in contact with the tectorial membrane.

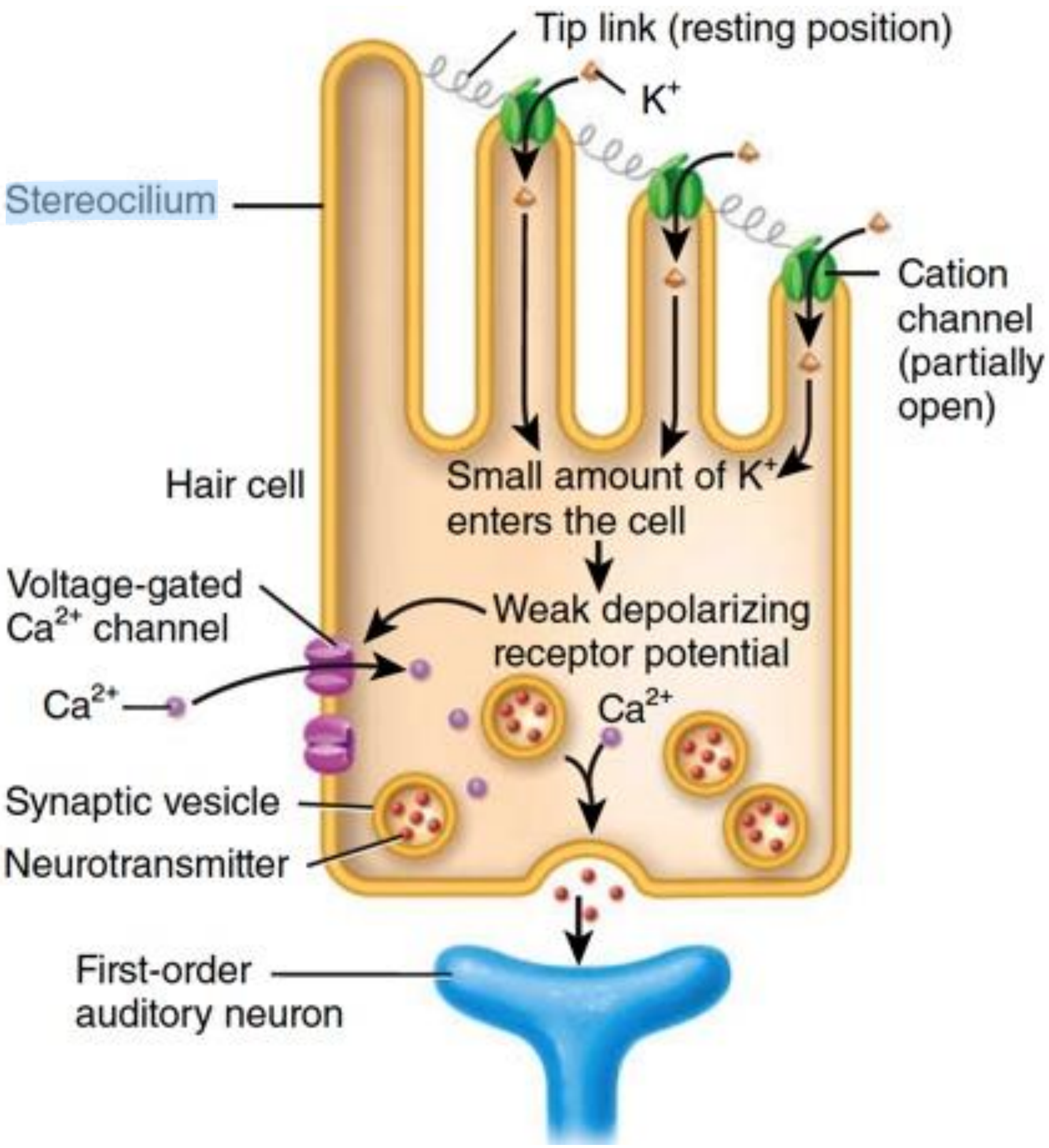
- The nerves that serve the organ of Corti are contained in the vestibulocochlear nerve (CN VIII). The cell bodies of these nerves are located in spiral ganglia, and their axons synapse at the base of the hair cells.

The cilia of inner hair cells touch the tectorial membrane. When sound waves are present, these cells vibrate, pushing the hair cells and their cilia against the tectorial membrane, causing them to bend. This bending results in potassium ions (K+) entering the cells, which ultimately leads to the generation of an action potential. The next slides will provide more details.




Reissner's membrane
Tectorial membrane
Stria vascularis
Scala vestibuli
Scala media
Spiral limbus
Spiral prominence
Organ of Corti
Scala tympani
Basilar membrane
Spiral ganglion
B

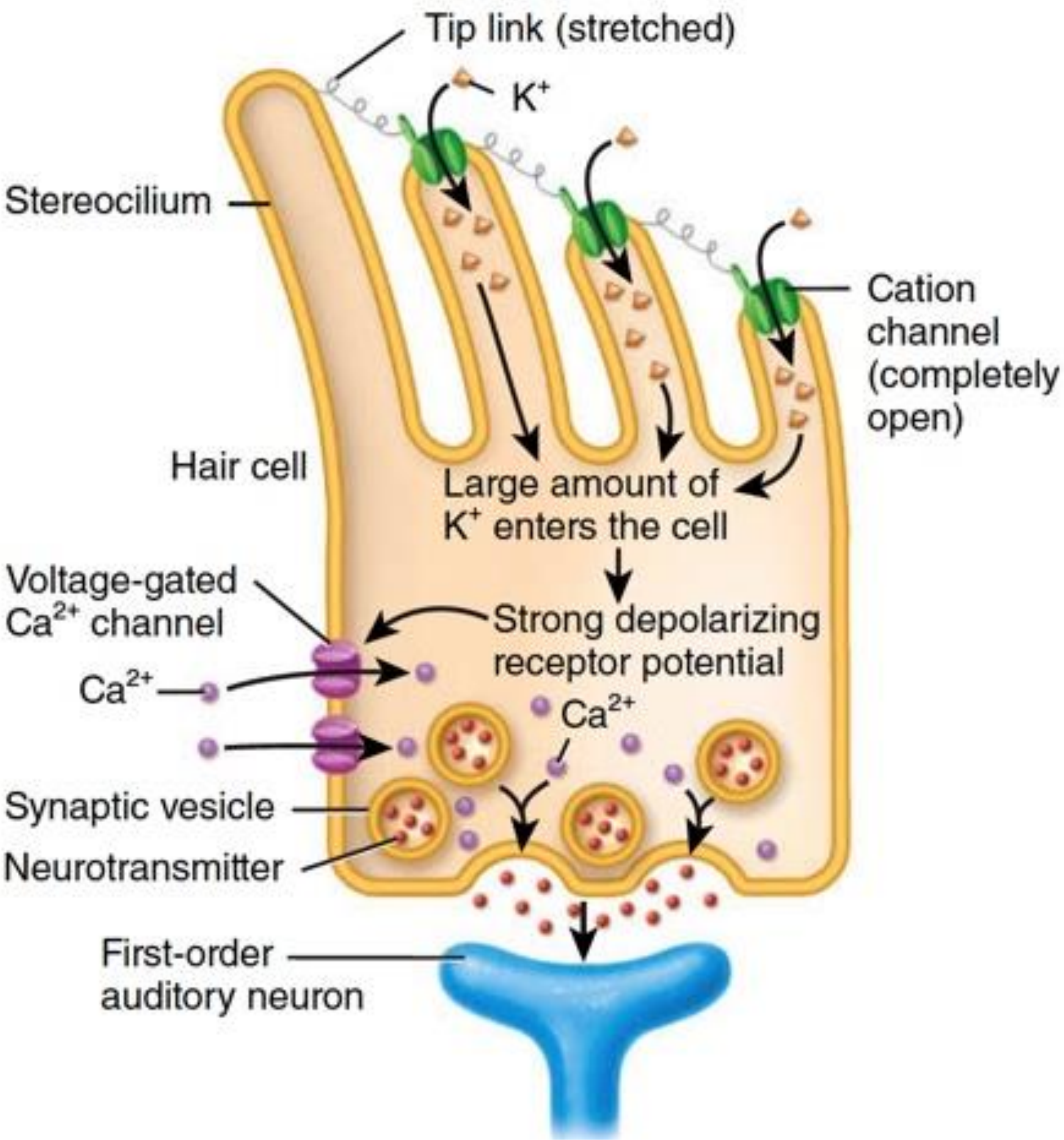
A hair cell is a distinct type of cell that communicates with the first-order neuron. These cells have tiny hair-like structures called cilia, which vary in length and gradually increase to the longest ones known as stereocilia. At the tips of these cilia, there are ion channels connected to spring-like structures that anchor each cilium to the next longer cilium.



In <u>resting state</u>, ion channels on hair cells are **partially** open so some **potassium** will enter causing slight depolarization which activates the voltage gated calcium channels that will cause the vesicles to open releasing the neurotransmitter, mainly **glutamate**.

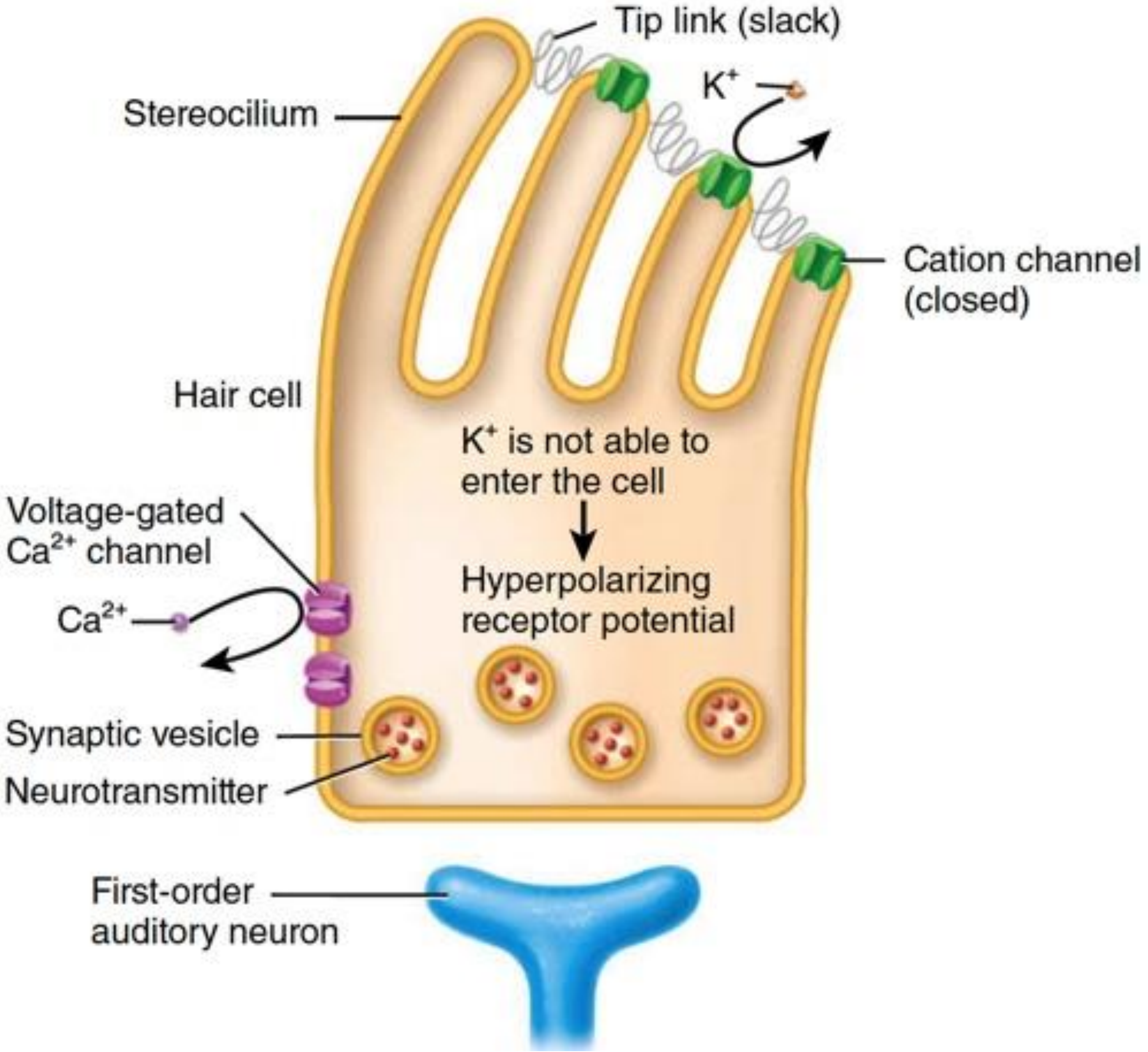
So slight amounts of glutamate means there's no signal.

When a signal reaches, the basilar membrane moves up and down causing bending of the cilia. Bending is ether towards the longest cilia or away from it. If it moves towards it, the spring-like structure will pull the gates and open them to the fullest causing more potassium to enter therefore more depolarization, more open of voltage gated calcium channels, and more release of neurotransmitters.



When more action potential is detected from a certain hair cell that detects a specific frequency from a specific direction, the auditory cortex will interpret this sound

When the cilia move away from the longest stereocilia, the spring closes the channels, preventing potassium from entering. This causes hyperpolarization, so no action potential is produced, indicating that the sound differs from the previous one.



The basilar membrane has a unique structure that allows the sensory system to encode auditory information. Its design is not uniform along its entire length, enabling it to distinguish between different frequencies and intensities of sound.

Starting from the oval window, the basilar membrane is called the base and the cells here are short and wide. As we go to the helicotrema, it’s called the apex and the cells get longer and thinner.

Encoding of frequency

- Encoding of sound frequencies occurs because different auditory hair cells are activated by different frequencies.
- The frequency that activates a particular hair cell depends on the position of that hair cell along the basilar membrane.
- The base of the basilar membrane is nearest the stapes and is narrow and stiff. Hair cells located at the base respond best to high frequencies.

Encoding of frequency

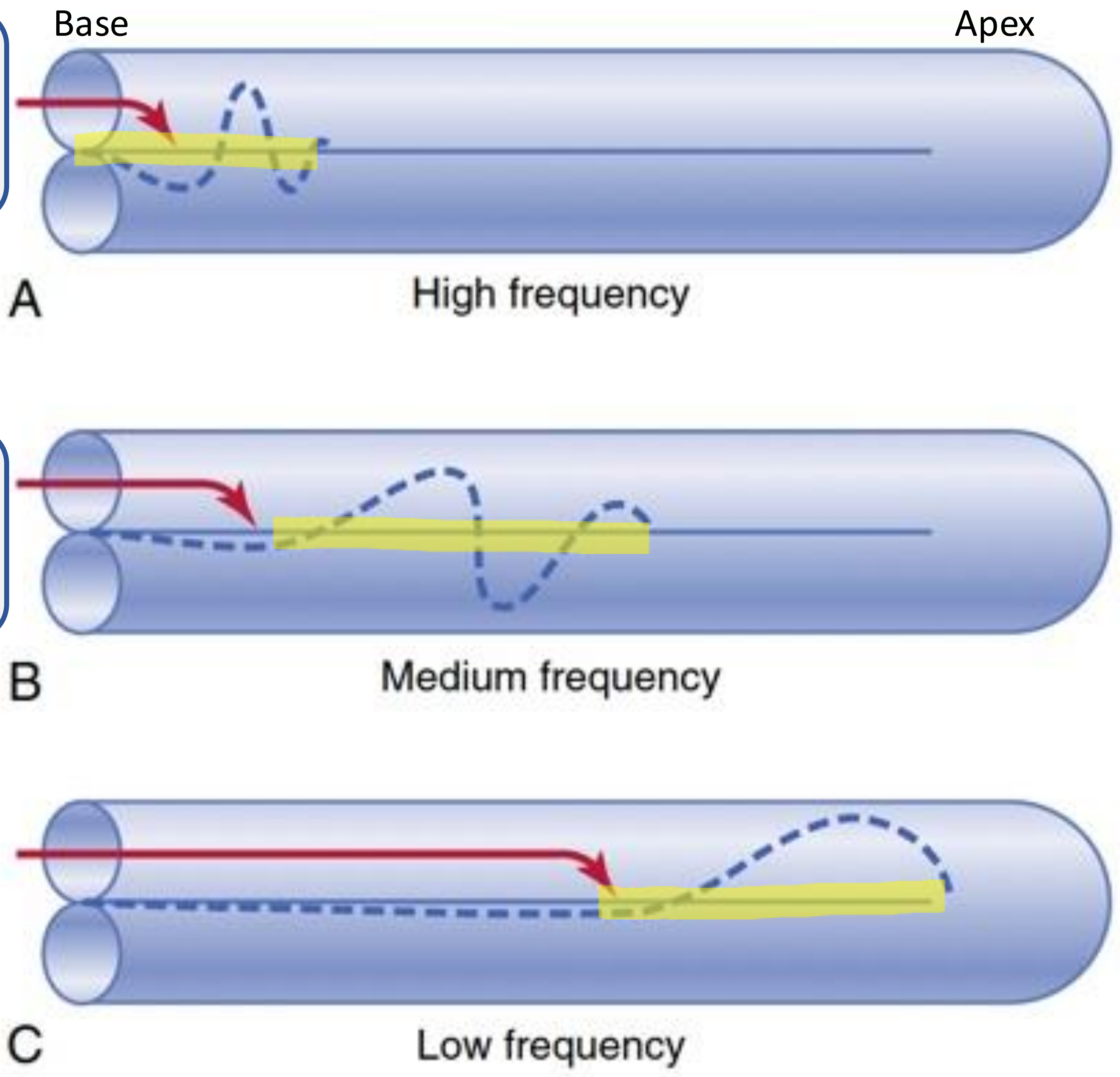
- The **apex of the basilar membrane is wide and compliant**. Hair cells located at the apex respond best to low frequencies.

- Thus the **basilar membrane acts as a sound frequency analyzer**, with hair cells positioned along the basilar membrane responding to different frequencies.

- This **spatial mapping of frequencies generates a tonotopic map**, which then is transmitted to higher levels of the auditory system.

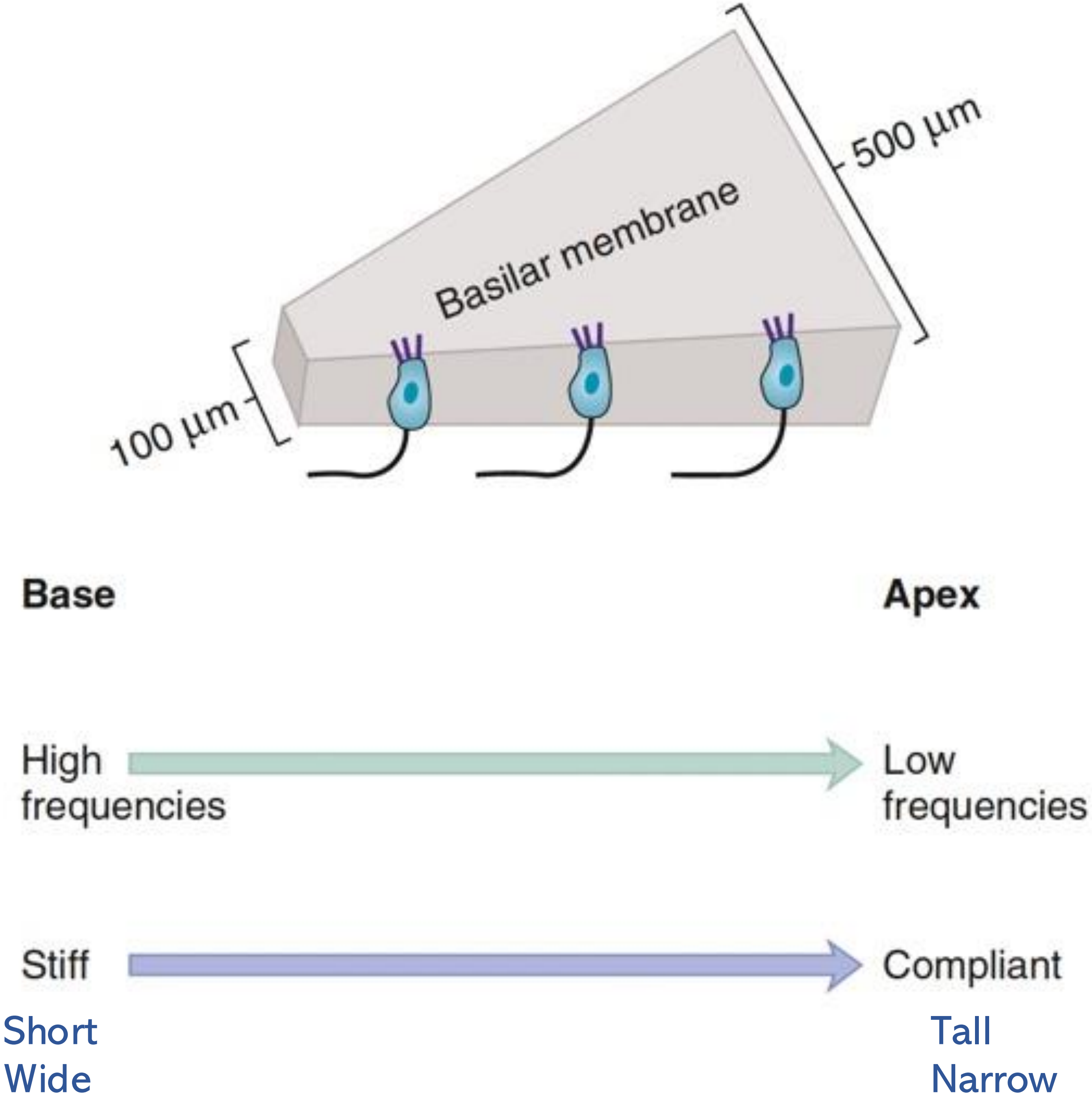
Because the cells here are wide and stiff, they can detect high frequency waves.

When the signal comes from this area to the brain, it will know that it's high frequency. (In high frequency it's further divided to sub frequencies)



Cells here are narrower and taller than the base.

Cells here are thin and tall.


Basilar membrane
500 µm
100 µm
Base
Apex
High frequencies
Low frequencies
Stiff
Compliant
Short
Wide
Tall
Narrow

We want to understand how different sound intensities are detected. When the sound is more intense, it causes greater movement in the basilar membrane, leading to more bending. This bending creates a stronger receptor potential, resulting in a higher frequency of action potentials.

Therefore, an intense sensory signal will result in:

.1Temporal summation, which leads to a higher frequency of action potentials.
.2Spatial summation, which results in a greater number of activated sensory receptors.

encoding of loudness

- First, as the sound becomes louder, the amplitude of vibration of the basilar membrane and hair cells also increases so that the hair cells excite the nerve endings at **more rapid rates**.

- Second, as the amplitude of vibration increases, it causes more and more of the hair cells on the fringes of the resonating portion of the basilar membrane to become stimulated, thus causing **spatial summation** of impulses.

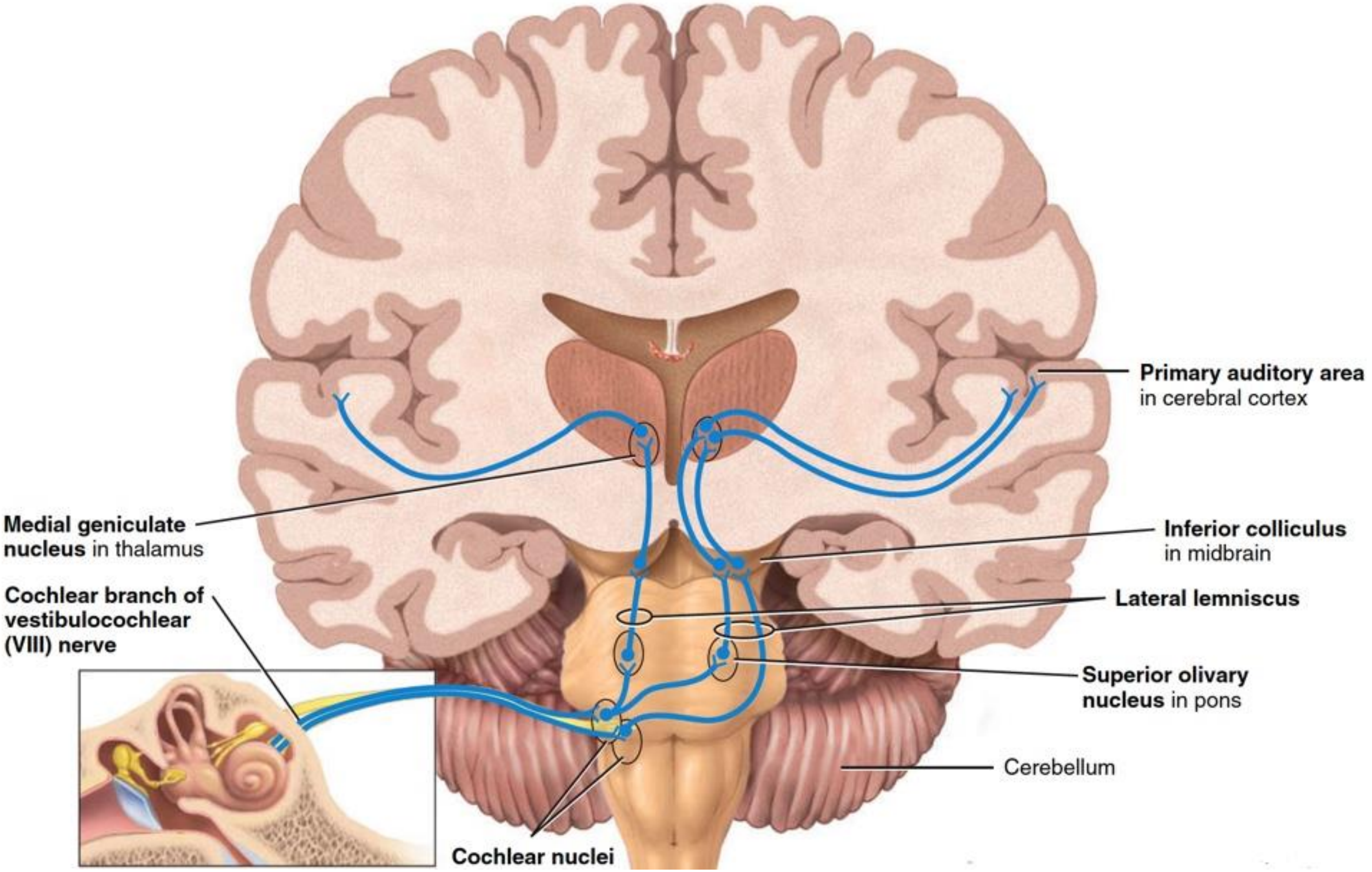
- Third, the **outer hair cells** do not become stimulated significantly until vibration of the basilar membrane reaches high intensity, and stimulation of these cells presumably apprises the nervous system that the sound is loud.

The auditory signal travels from the cochlear branch of the vestibulocochlear nerve to the brainstem, where it synapses with second-order neurons in either the dorsal or ventral cochlear nuclei. Some of these second-order neurons will cross to the opposite side of the brain, while others will continue to the superior olivary nucleus, where another synapse occurs. From there, the signal passes through the lateral lemniscus to the inferior colliculus, which plays an important role in reflexes, such as the auditory reflex that occurs in response to loud sounds. After reaching the inferior colliculus, the auditory signal ascends to the medial geniculate nucleus in the thalamus. Finally, it travels to the primary auditory area in the cerebral cortex, and then to secondary and association areas, **where the sound is integrated and given meaning.**

There is a map for different frequencies of sounds in the superior olivary nucleus and in the primary auditory area.

Auditory pathway

- Nerve fibers from the spiral ganglion of Corti enter the **dorsal and ventral cochlear nuclei** located in the medulla.
- At this point, all the fibers synapse, and second-order neurons pass mainly to the opposite side of the brain stem to terminate in the **superior olivary nucleus**.
- A few second-order fibers also pass to the superior olivary nucleus on the same side.


Primary auditory area
in cerebral cortex
Medial geniculate
nucleus in thalamus
Inferior colliculus
in midbrain
Cochlear branch of
vestibulocochlear
(VIII) nerve
Lateral lemniscus
Superior olivary
nucleus in pons
Cerebellum
Cochlear nuclei

- **Signals from both ears are transmitted through the pathways of both sides of the brain**, with a preponderance of transmission in the contralateral pathway.

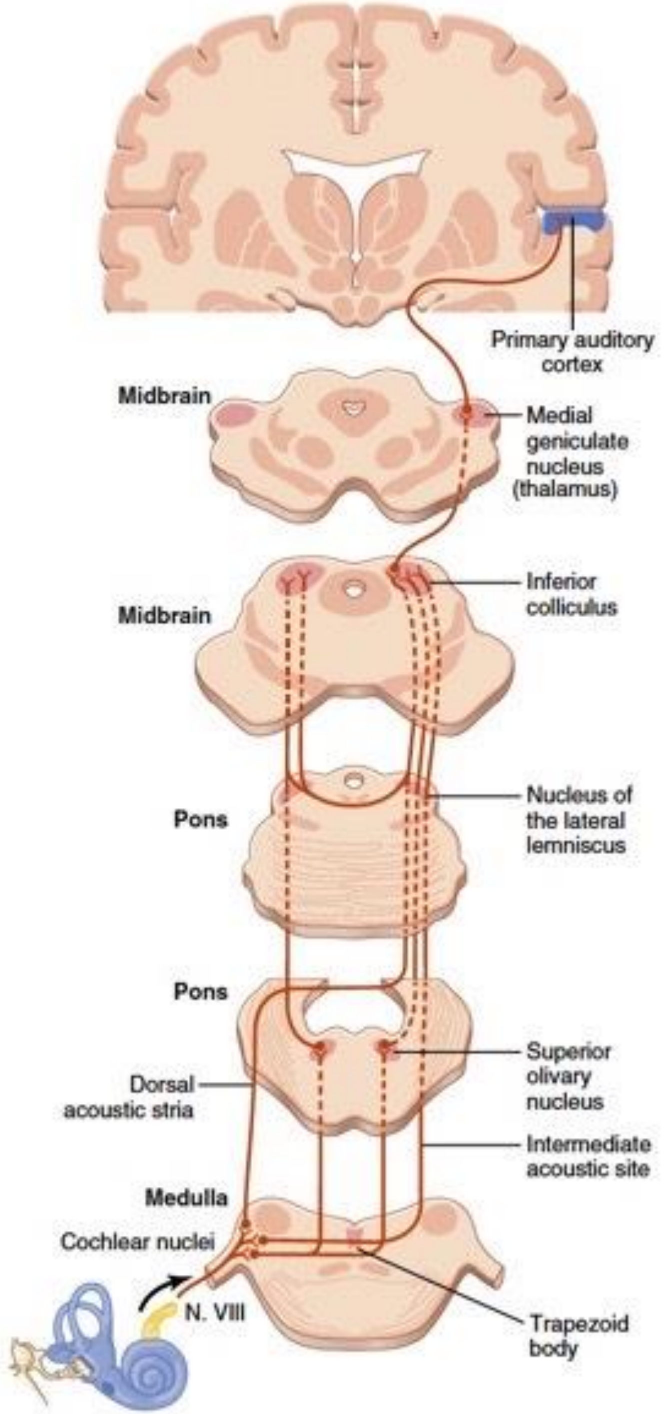
- Many **collateral fibers** from the auditory tracts pass directly into the **reticular activating system** of the brain stem. This system projects diffusely upward in the **brain stem** and downward into the **spinal cord** and activates the entire nervous system in response to loud sounds.

So if you hear a loud sound you're going to wake up from sleep.

- <u>Other **collaterals** go to the vermis of the c**erebellum**, which is also activated instantaneously in the event of a sudden noise.</u>

If you hear a sudden loud sound you may lose balance.

- A high degree of spatial orientation is maintained in the fiber tracts from the cochlea all the way to the cortex.



Primary auditory cortex
Midbrain
Medial geniculate nucleus (thalamus)
Midbrain
Inferior colliculus
Pons
Nucleus of the lateral lemniscus
Pons
Superior olivary nucleus
Dorsal acoustic stria
Intermediate acoustic site
Medulla
Cochlear nuclei
N. VIII
Trapezoid body

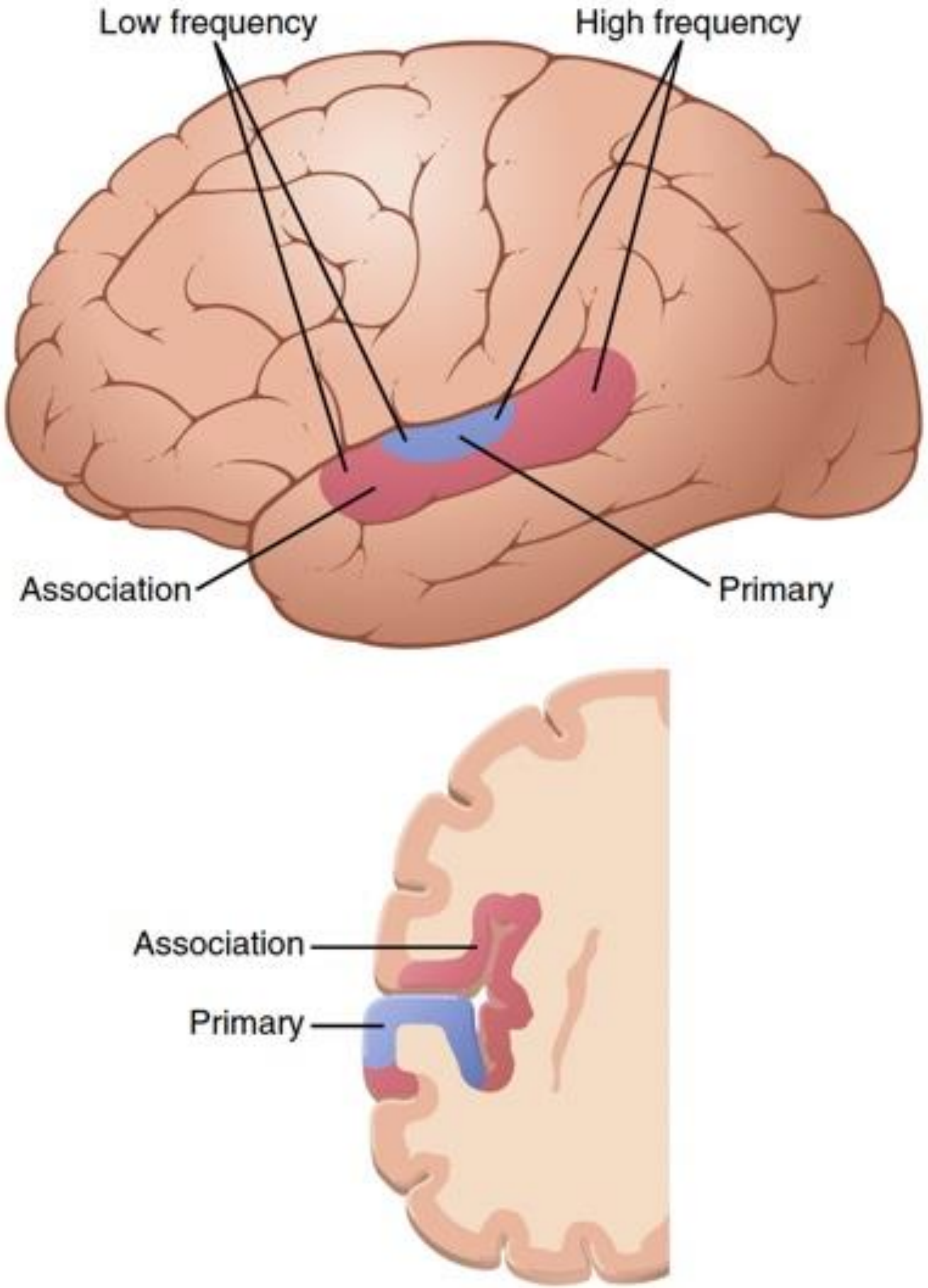
Auditory cortex

- **Destruction of both primary auditory cortices** in the human being greatly reduces one's sensitivity for hearing.

> It will be significantly impaired but There will not be complete hearing loss because the subcortical regions will play a role in processing the sound however, those sounds will be meaningless without the cortex.

- **Destruction of one side** only slightly reduces hearing in the opposite ear; it does not cause deafness in the ear because of many crossover connections from side to side in the auditory neural pathway.

- However, it does affect one's ability to localize the source of a sound because comparative signals in both cortices are required for sound localization.



Low frequency
High frequency
Association
Primary
Association
Primary

- **Lesions that affect the auditory association are**as but not the primary auditory cortex do not decrease a person’s ability to hear and differentiate sound tones.

- However, the person is often **unable to interpret the meaning** of the sound heard (ex. Wernicke’s area).

Determination of the direction of sound

- A person determines the horizontal direction from which sound comes by two principal means:
- (1) the **time lag** between the entry of sound into one ear and its entry into the opposite ear.

When a sound with the same frequency and loudness comes from the right ear before the left ear, you know that the sound is coming from the right side.

- (2) the difference between the **intensities** of the sounds in the two ears.

Determination of the direction of sound

- These two mechanisms cannot tell whether the sound is emanating from in front of or behind the person or from above or below.

- This discrimination is achieved mainly by the **pinnae** (auricle) , which act as funnels to direct the sound into the two ears.

- The shape of the pinna changes the quality of the sound entering the ear, depending on the direction from which the sound comes.

Determination of the direction of sound

- The neural analyses for the direction detection process begin in the **superior olivary nuclei** in the brain stem, even though the neural pathways all the way from these nuclei to the cortex are required for interpretation of the signals.

Actually the sounds are conducting through the air (air conductance) , there is another type of conductance called **bone conductance** .

Bone conductance

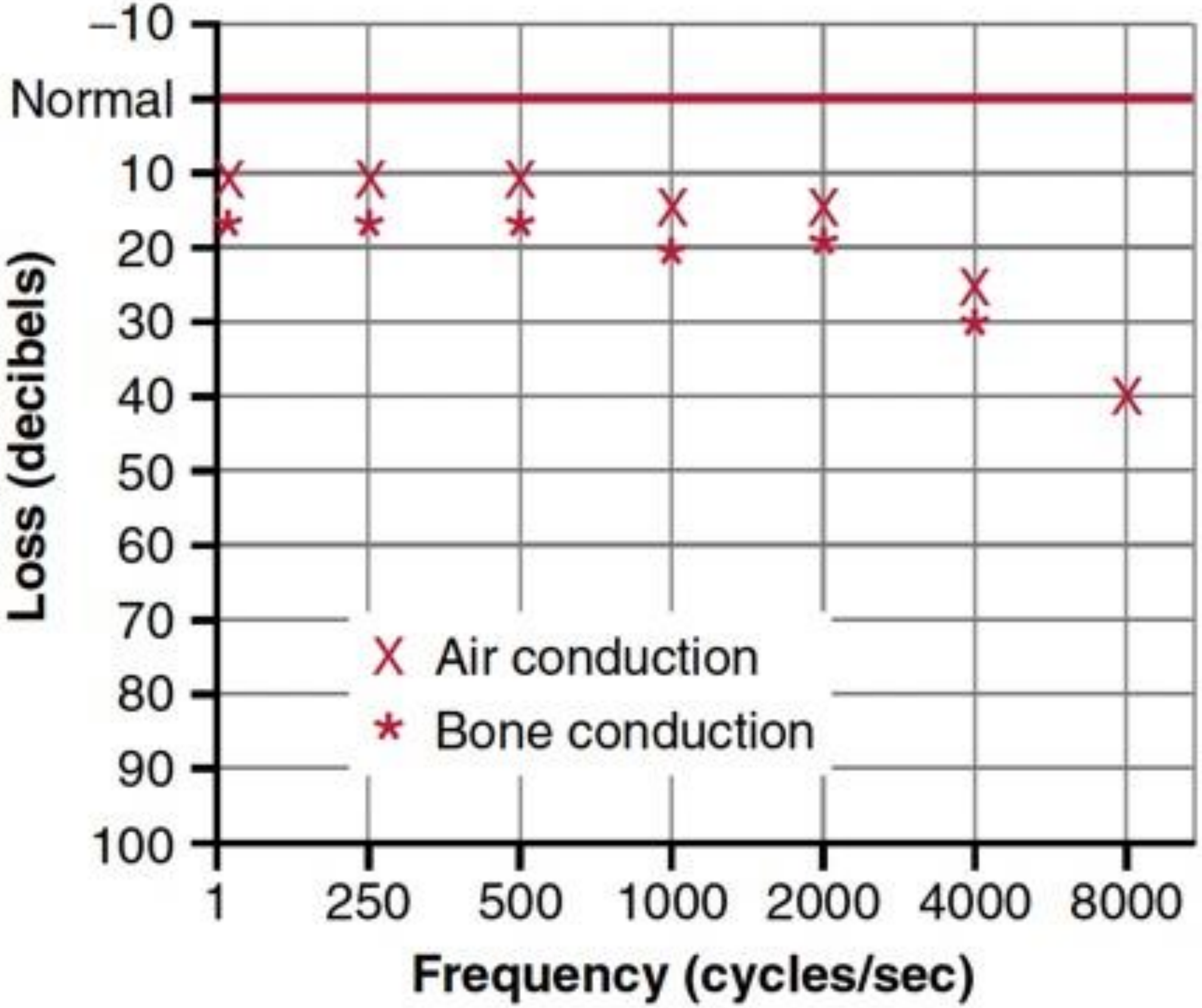
- Because the inner ear, the cochlea, is embedded in a bony cavity in the temporal bone, called the bony labyrinth, vibrations of the entire skull can cause fluid vibrations in the cochlea.

Normally, air conduction is better than bone conduction. However, in certain conditions, bone conduction may become better than air conduction, such as in conductive hearing loss, otitis media, eardrum rupture,…

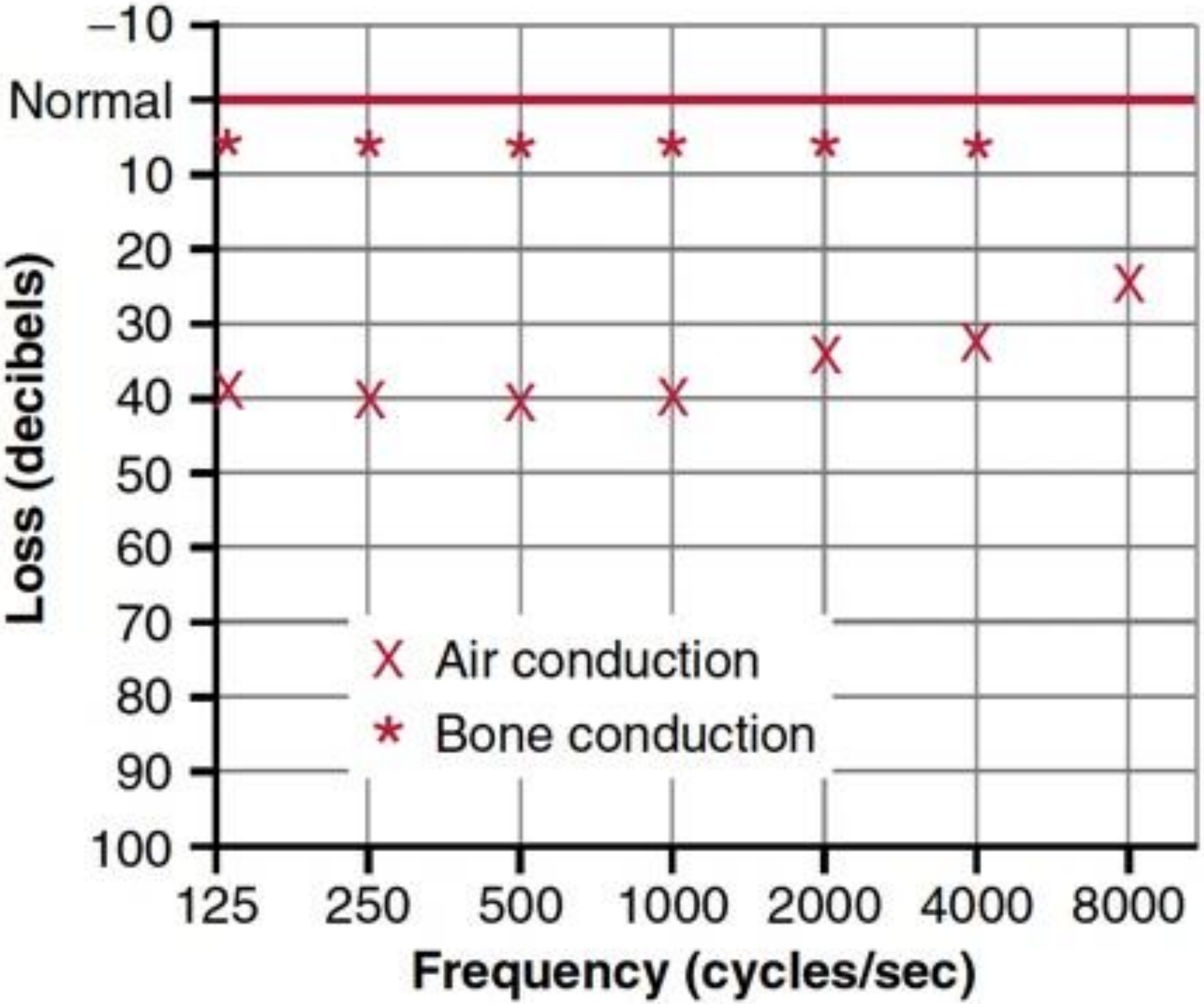
- Therefore, under appropriate conditions, a tuning fork or an electronic vibrator placed on any bony protuberance of the skull, but especially on the mastoid process near the ear, causes the person to hear the sound.

Audimetry :
The patient enters a soundproof room, where they will hear sounds at various frequencies and intensities. The patient has a button to press whenever they hear a sound. This test is essential for determining if there is any hearing impairment or loss.

Hearing loss can be conductive or neurosensory:
1-conductive: there’s a problem in the coduction from the external to the middle ear.
2-neural: there’s a problem in the receptor cells, in neurons, or the pathway



After the frequency of 2000 Hz, both air conduction and bone conduction declined, indicating a neural problem. This characteristic is associated with aging, as hair cells for higher frequencies, located in the basal part of the cochlea, are lost over time.



Bone conduction is fine as the neural part is fine, however, the air conduction is decreased when the frequency is low because maybe there's an infection in the middle ear, the tympanic membrane is perforated, or there is a disease in the ausicles. So that this is conductive impairment.

(إِنَّ السَّمْعَ وَالْبَصَرَ وَالْفُؤَادَ كُلُّ أُولئِكَ كَانَ عَنْهُ مَسْؤُولاً) سورة الإسراء: 36

﴿ وَاللَّهُ أَخْرَجَكُمْ مِنْ بُطُونِ أُمَّهَاتِكُمْ لَا تَعْلَمُونَ شَيْئًا وَجَعَلَ لَكُمُ السَّمْعَ وَالْأَبْصَارَ وَالْأَفْئِدَةَ لَعَلَّكُمْ تَشْكُرُونَ ﴾ سورة النحل: 78

VERSIONS	SLIDE #	BEFORE CORRECTION	AFTER CORRECTION
V1→ V2			
V2→V3			

امسح الرمز و شاركنا بأفكارك لتحسين أدائنا !!