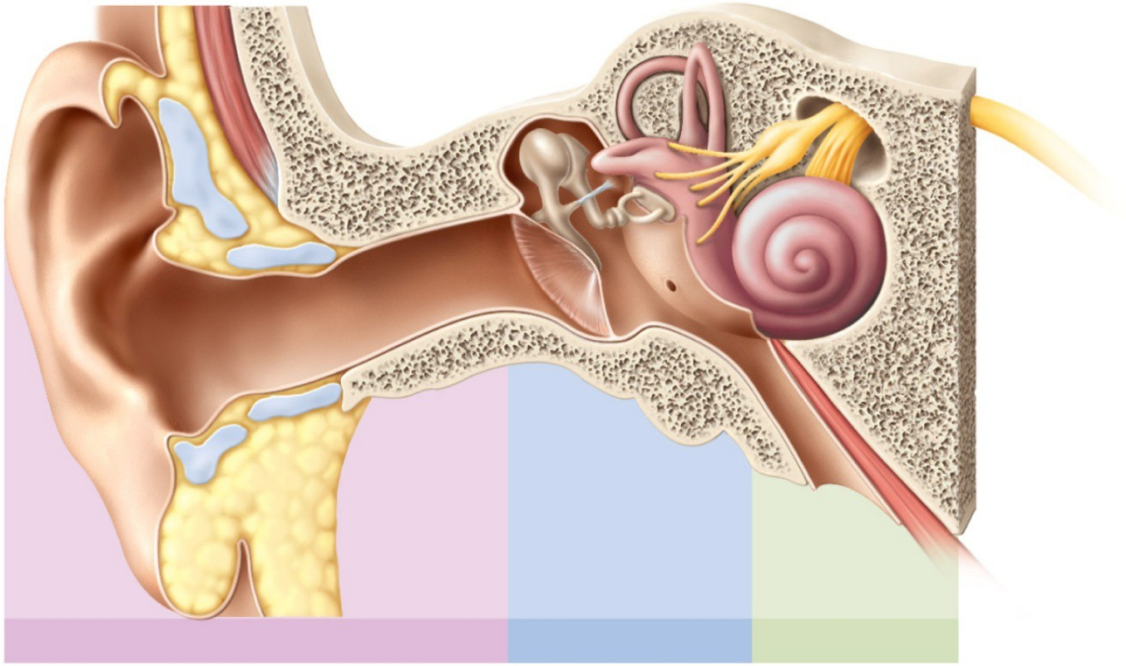
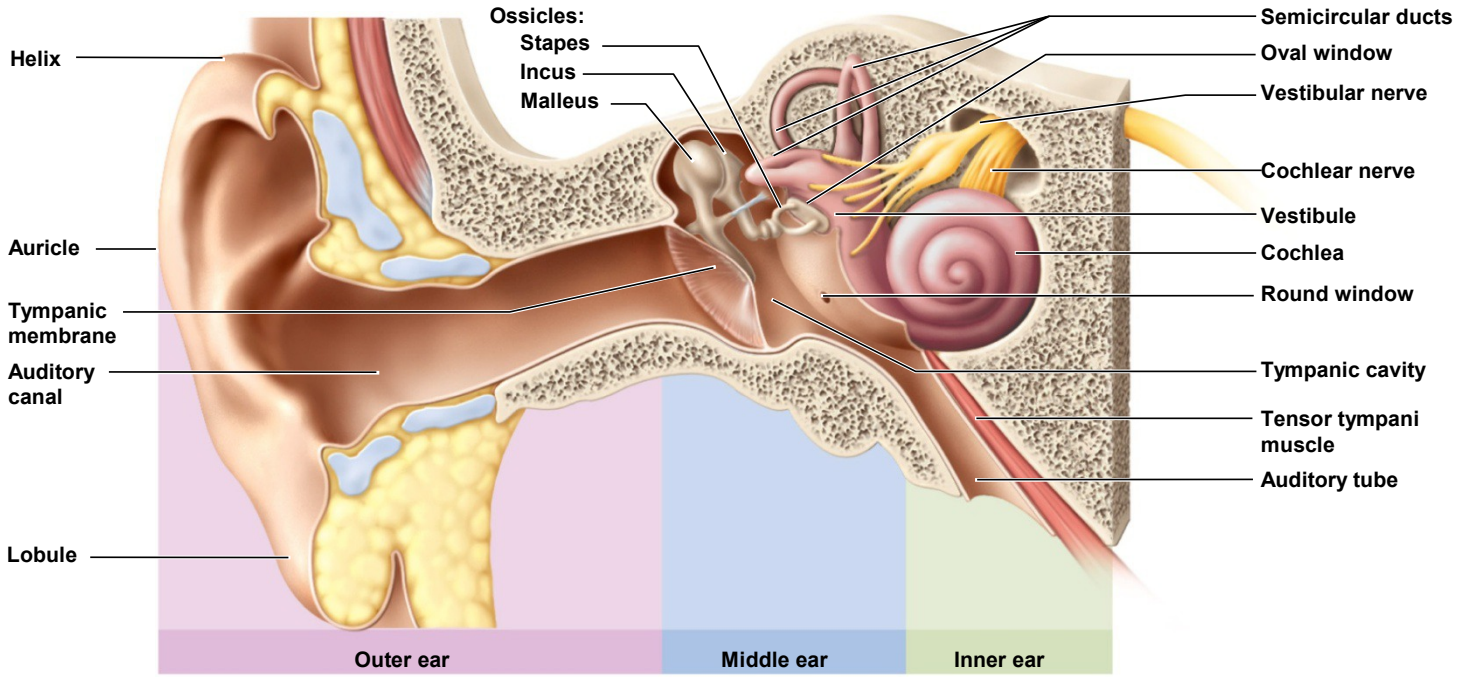
Chapter 16.3

Hearing and Equilibrium



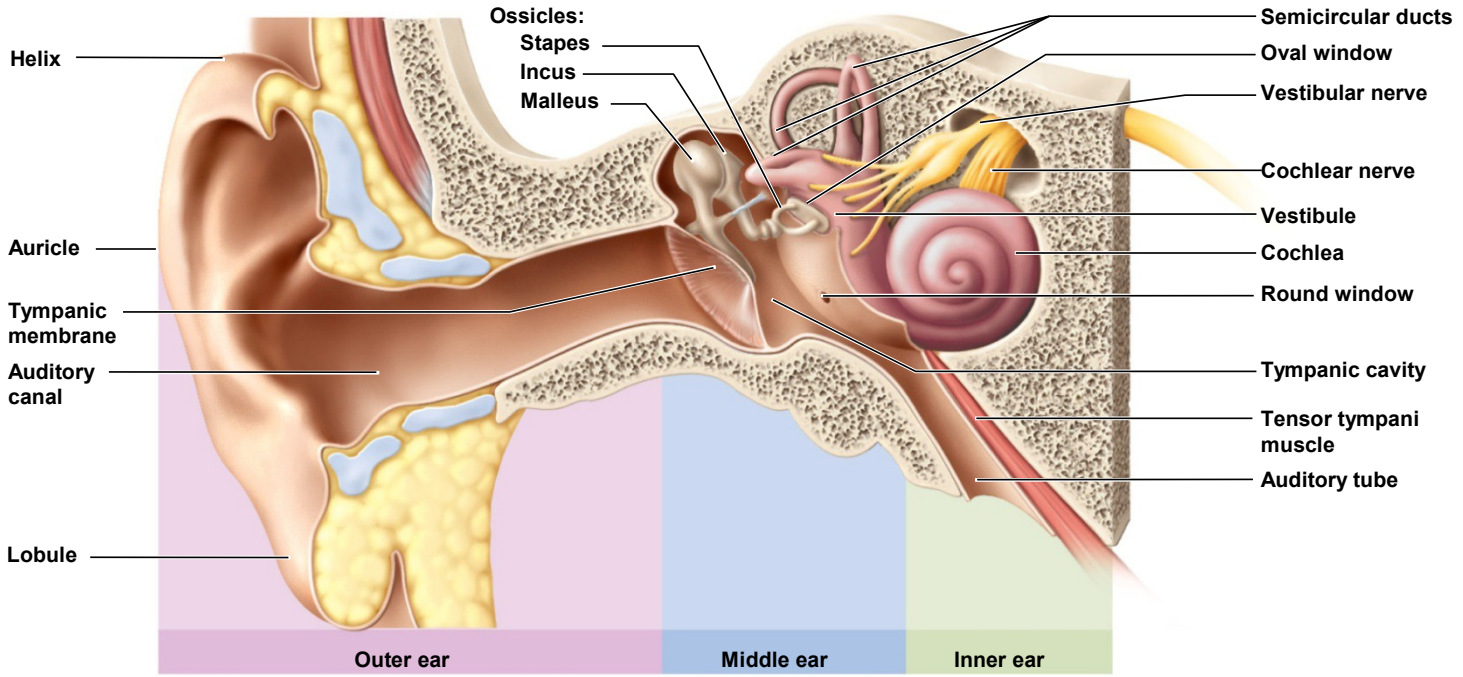
The Nature of Sound

- **Sound** – *an audible experience caused by a vibration that moves molecules*
  - a vibrating object pushes on air molecules to create "waves of pressure"
  - air molecules in turn push on other air molecules
  - eventually, air molecules hitting eardrum then causes another vibration

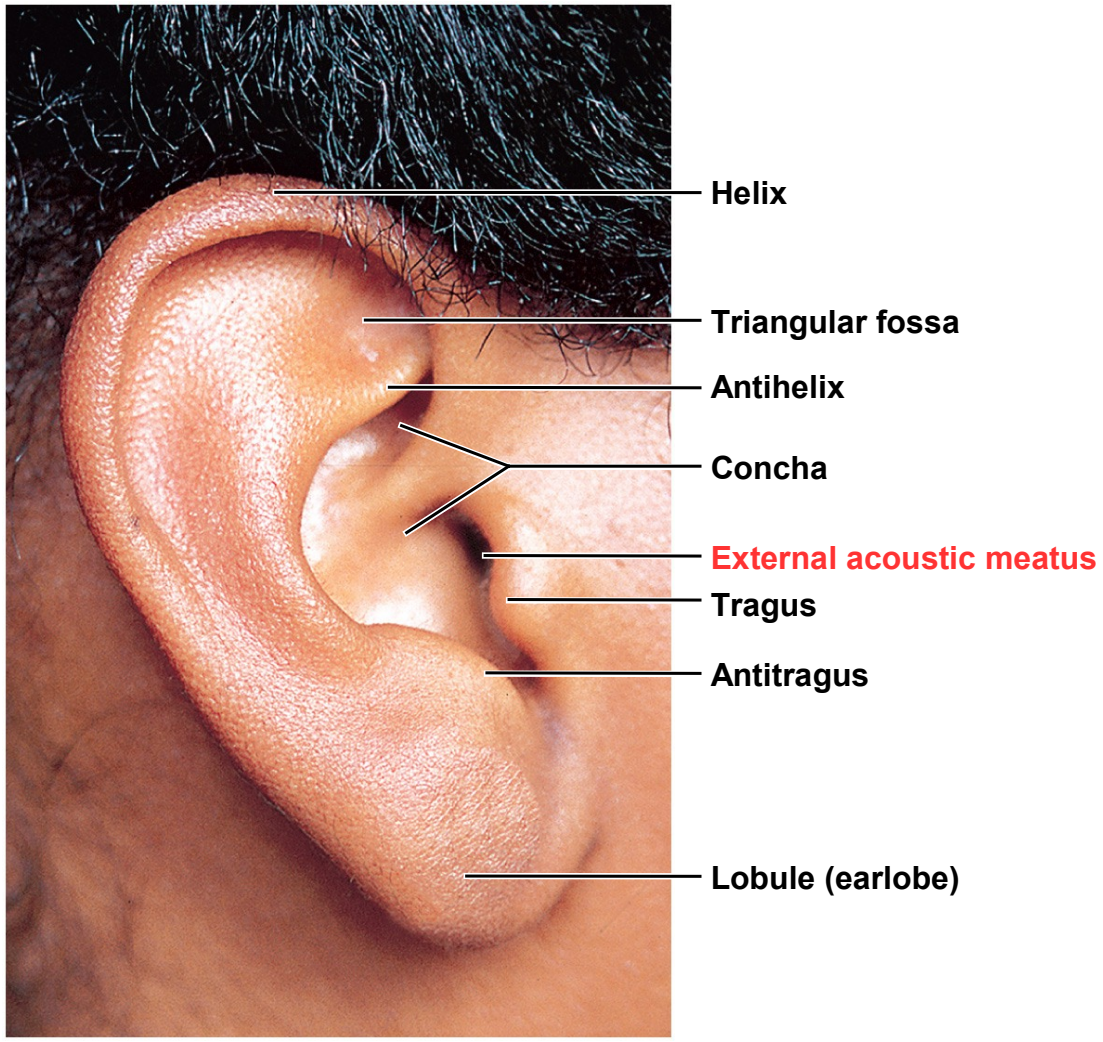


Anatomy of Ear

- **Ear** has three sections **outer, middle, and inner ear**
  - first two are concerned only with the transmission of sound to the inner ear
  - inner ear – where vibrations are converted to fluid waves then converted to nerve action potentials



Outer Ear



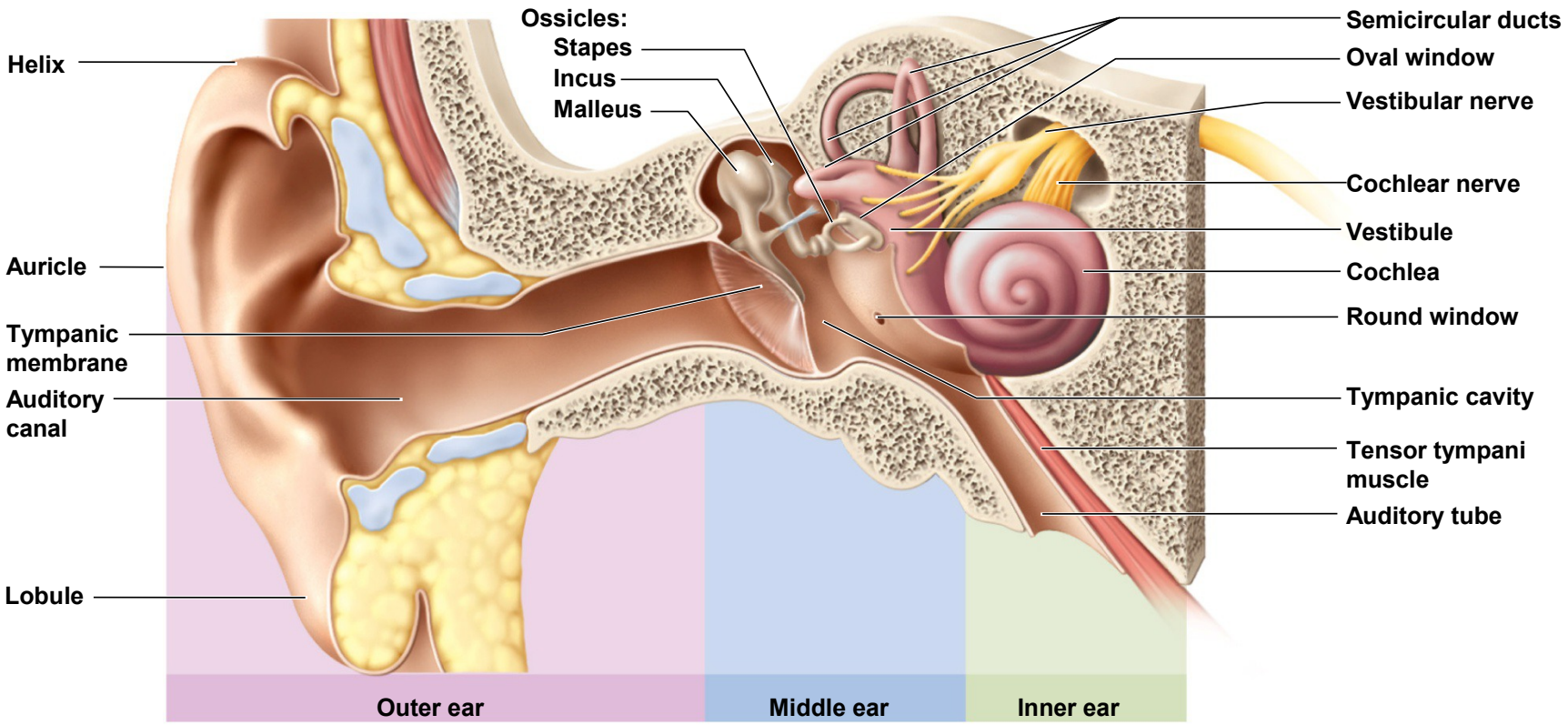
Outer (External) Ear

- Function as a funnel for conducting vibrations to the **tympanic membrane** (eardrum)
  - **auricle** (pinna) directs sound down the auditory canal
    - shaped and supported by elastic cartilage
  - **auditory canal** – passage leading through the temporal bone to the tympanic membrane

Outer (External) Ear

- **external acoustic meatus** – slightly s-shaped tube that begins at the external opening and courses for about 3 cm
  - **guard hairs** protect outer end of canal
  - **cerumen** (earwax) – mixture of secretions of ceruminous glands and sebaceous glands plus mixed with dead skin cells
    - sticky and coats guard hairs
    - contains lysozyme with low pH that inhibits bacterial growth
    - water-proofs canal and protects skin
    - keeps tympanic membrane pliable

Anatomy of Middle Ear (Lab Objectives)



Middle Ear

- **middle ear** - located in the air-filled tympanic cavity in temporal bone (between typmpanic membrane and oval window)
  - **tympanic membrane** (eardrum) – closes the inner end at the auditory canal
    - separates it from the middle ear
    - about 1 cm in diameter
    - suspended in a ring-shaped groove in the temporal bone
    - vibrates freely in response to sound
    - innervated by sensory branches of the vagus and trigeminal nerves
    - highly sensitive to pain
  - **tympanic cavity** is continuous with mastoid air cells
    - space only 2 to 3 mm wide between outer and inner ears
    - contains auditory ossicles

Middle Ear

- auditory (eustachian) tube connects middle ear cavity to nasopharynx
  - Allows equalize air pressure on both sides of tympanic membrane
  - normally flattened and closed
  - swallowing and yawning opens it
  - allows throat infections to spread to the middle ear
- auditory ossicles (smallest synovial joints in body!)
  - malleus - attached to inner surface of tympanic membrane
  - incus - articulates in between malleus and stapes
  - stapes - footplate rests on oval window – inner ear begins
- stapedius and tensor tympani muscles // attach to stapes and malleus

Middle-Ear Infection

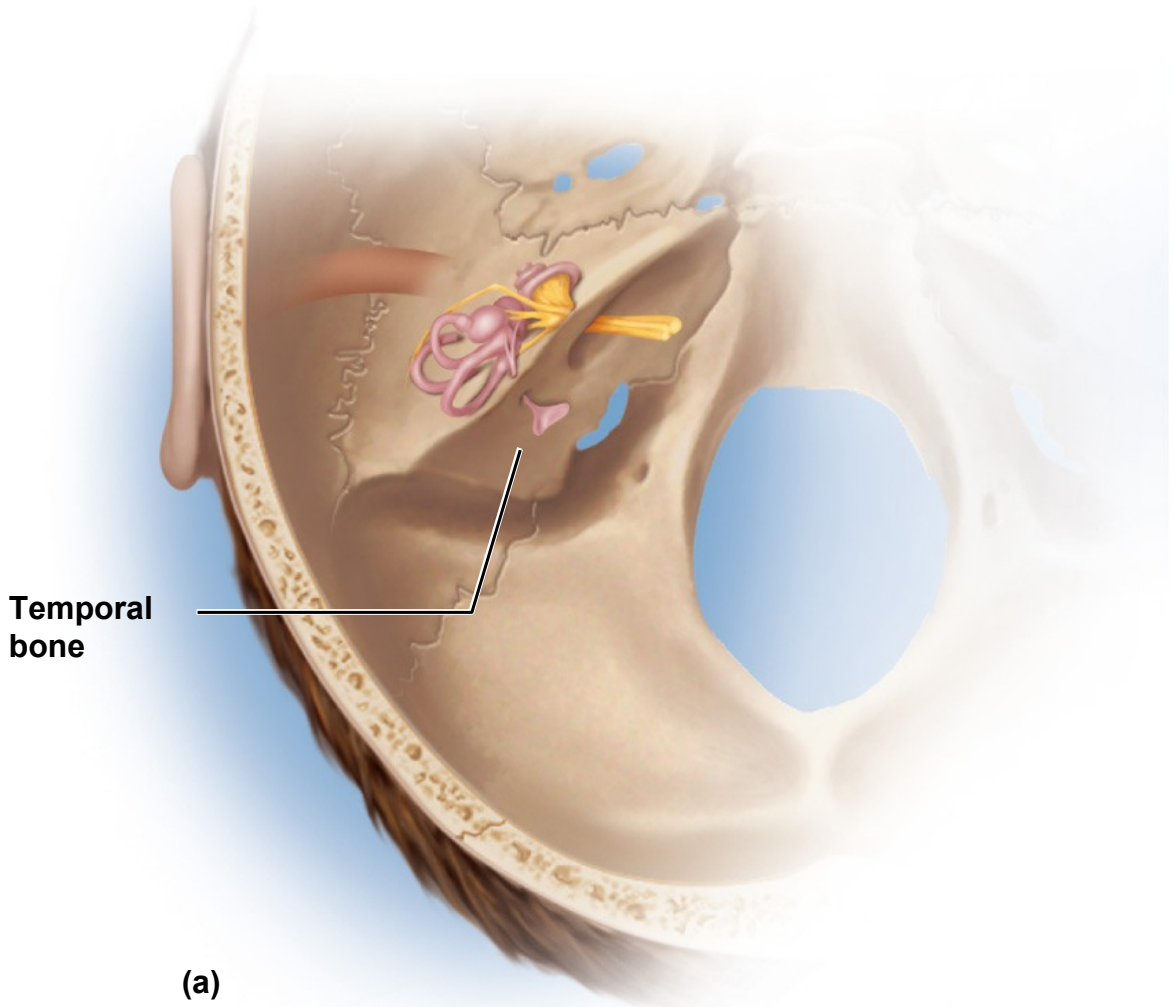
- **Otitis media** (middle ear infection) is common in children

- auditory tube is short and horizontal in new born /// this allows infections to easily spread from throat to tympanic cavity and mastoid air cells // as child grows the shape of head changes and auditory tube becomes longer and more verticle

- symptoms:
  - fluid accumulates in tympanic cavity producing pressure, pain, and impaired hearing
  - can spread leading to meningitis
  - can cause fusion of ear ossicles and hearing loss

- **tympanostomy** – lancing tympanic membrane and draining fluid from tympanic cavity /// inserting a tube to relieve the pressure and allow infection to heal

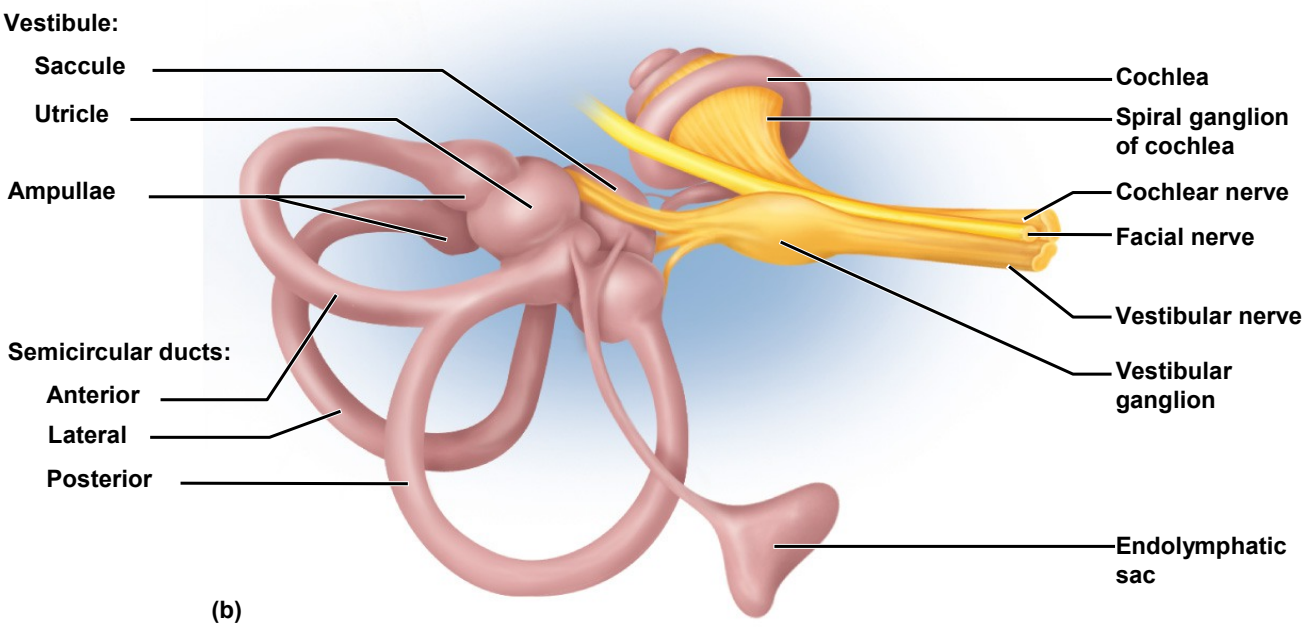
The Inner Ear



Two Functions of the Inner Ear

- 1) hearing – a response to vibrating air molecules // waves of different pressure
- 2) equilibrium – the senses of motion, body orientation, and balance
- the organs for hearing and equilibrium are located deep within the temporal bone // region called the inner ear
- Inner ear = maze of fluid-filled passages and sensory cells
- In both hearing and equilibrium
  - fluids are set into motion by somatic movement or air pressure on tympanic membrane
  - fluid "bends" cilia that open mechanical regulated ion gates
  - sensory cells convert these motions into action potentials

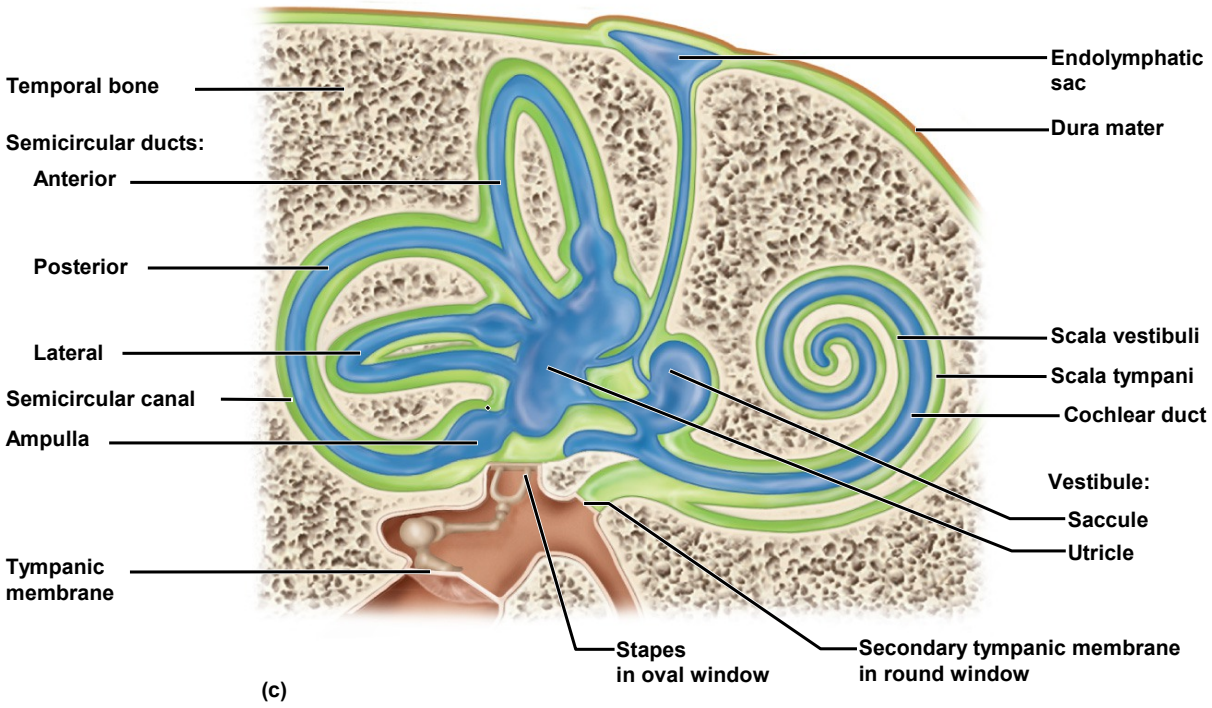
Inner Ear Structure



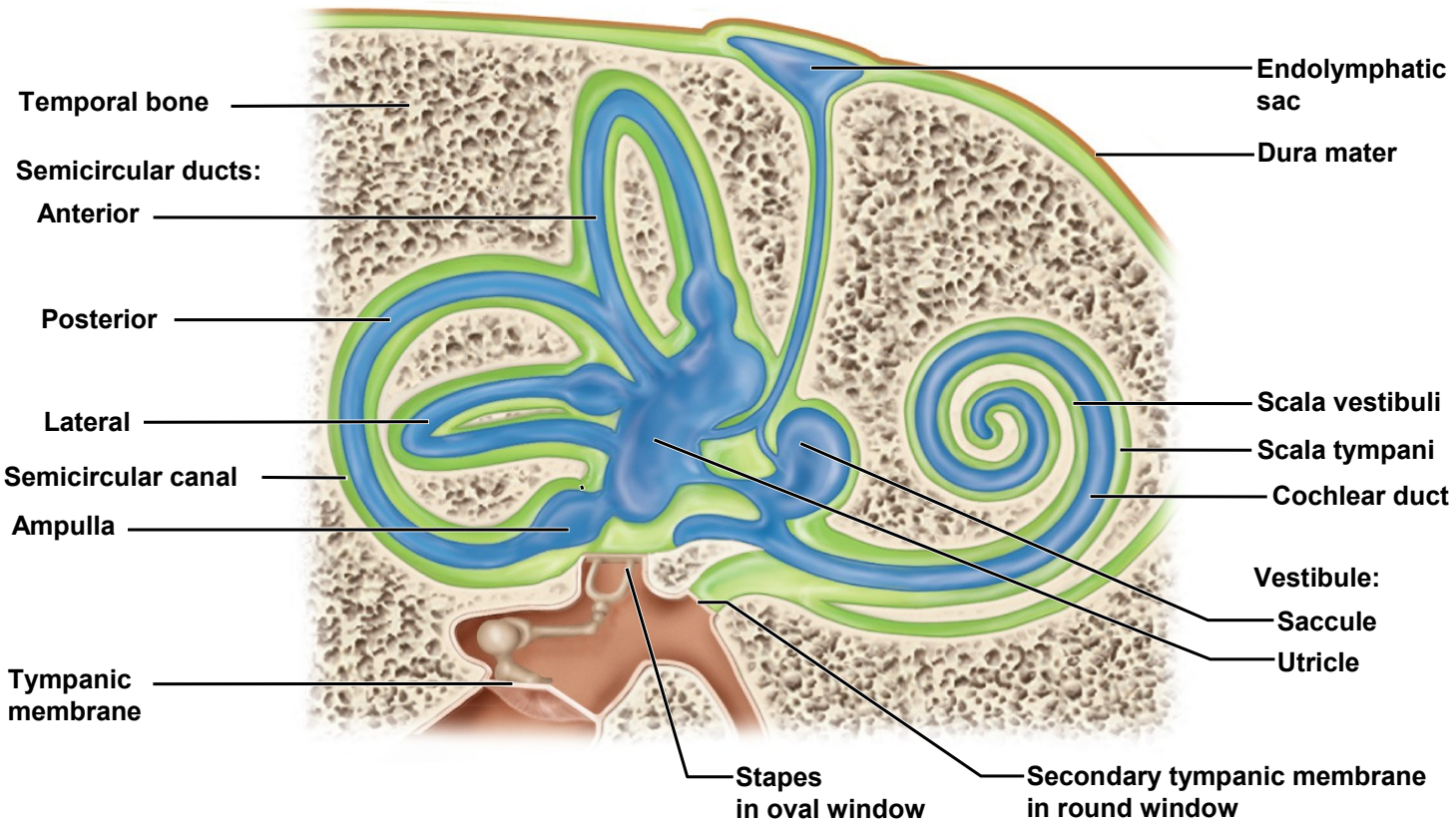
- **labyrinth =** vestibule and three semicircular ducts / equilibrium
- **cochlea** = organ of hearing
  - 2.5 coils around an screw like axis of spongy bone, the **modiolus**
  - threads of the screw form a spiral platform that supports the fleshy tube of the cochlea

Inner Ear

- **bony labyrinth** - passageways in temporal bone
- **membranous labyrinth** - fleshy tubes lining the bony labyrinth
  - filled with **endolymph** - similar to intracellular fluid
  - floating in **perilymph** - similar to cerebrospinal fluid



Structure of Inner Ear



Anatomy of Cochlea

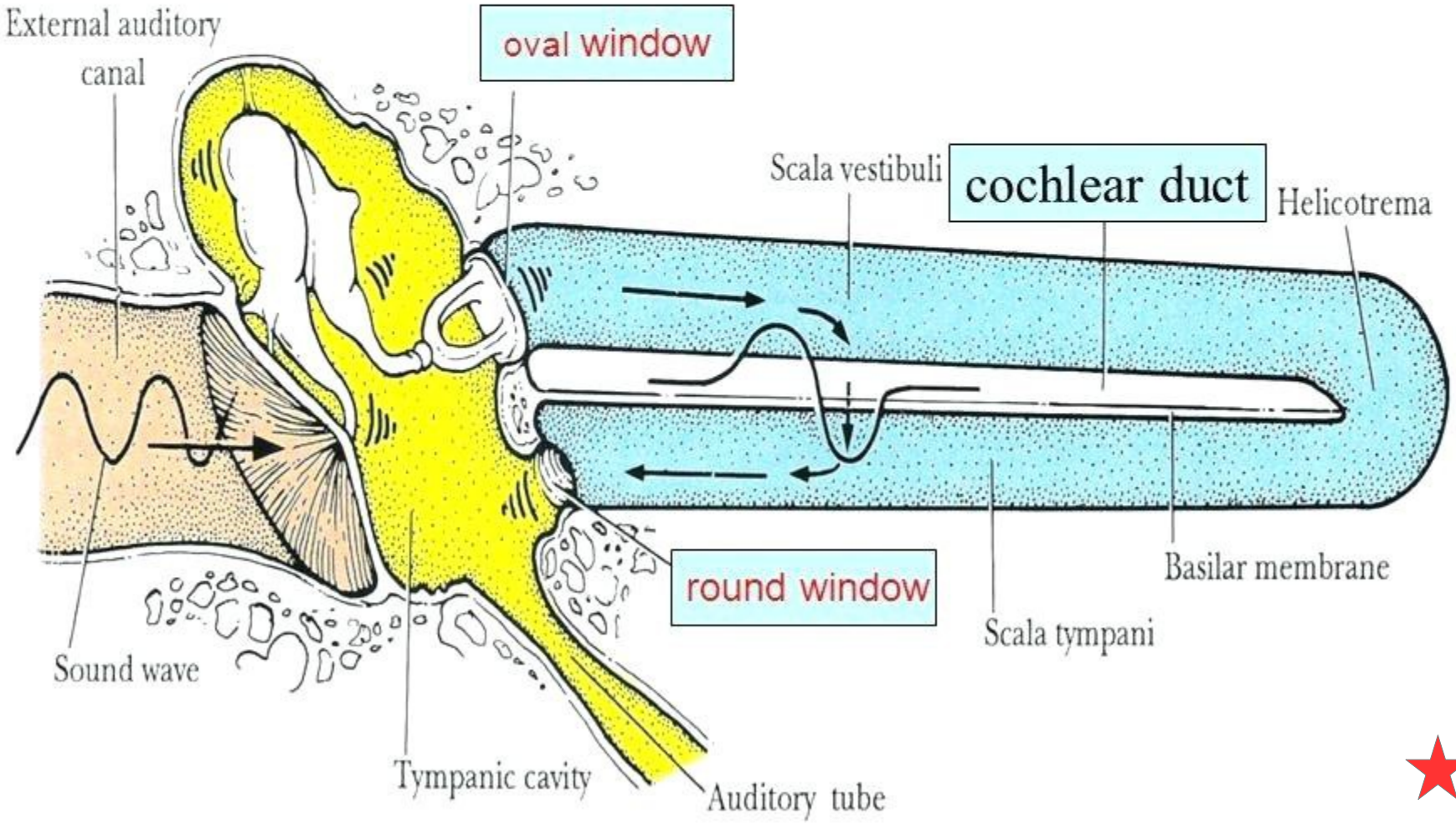
- Three fluid-filled chambers separated by membranes: scala vestibuli , scala tympani, and scala media

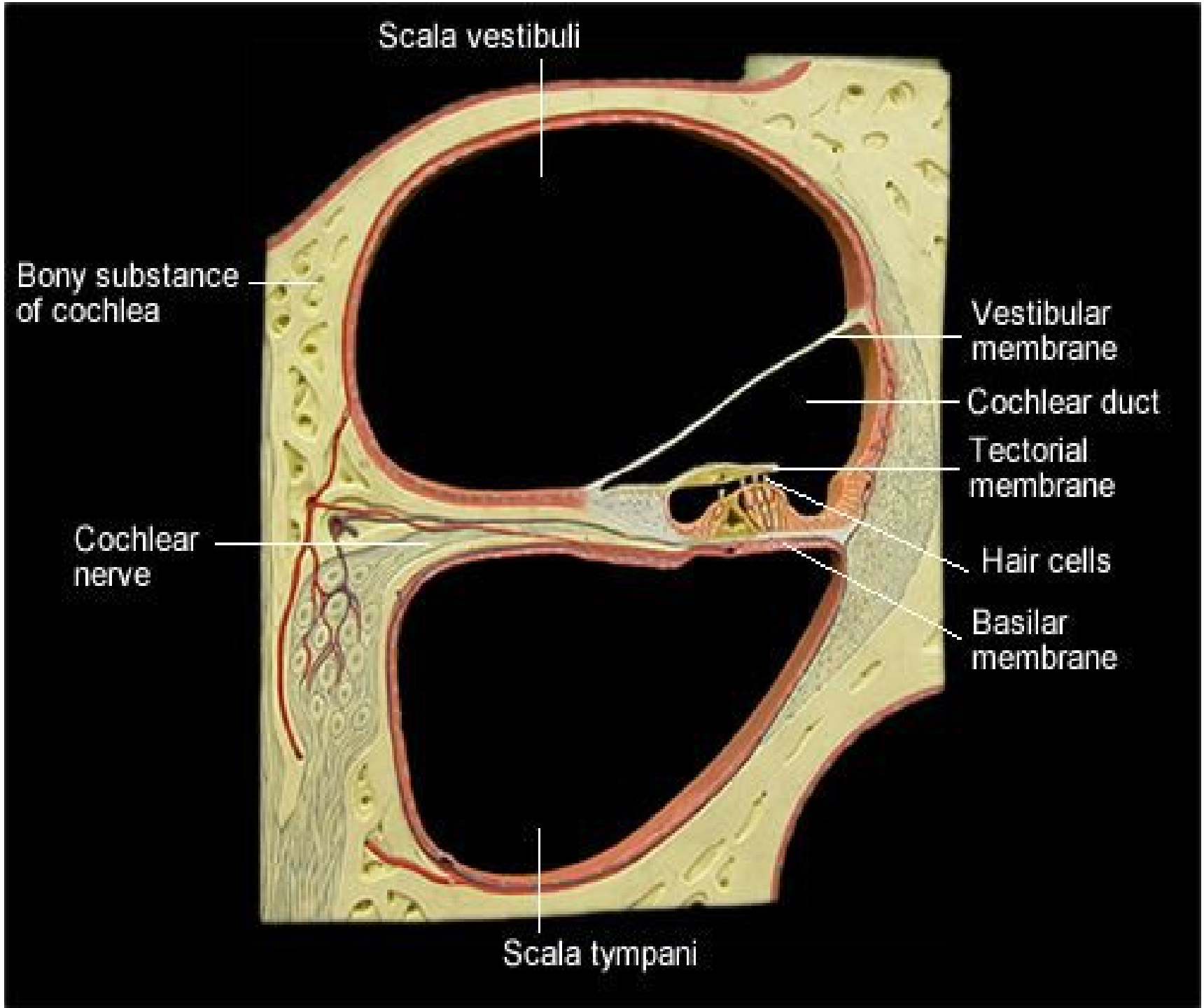
  - **scala media** (also called cochlear duct) – triangular middle chamber
    - filled with **endolymph**
    - separated from:
      - scala vestibuli by **vestibular membrane**
      - scala tympani by thicker **basilar membrane**
      - contains spiral organ - **organ of Corti** = the acoustic organ /// converts vibrations into action potentials

  - **scala vestibuli** // superior chamber
    - filled with perilymph
    - begins at oval window and spirals to apex

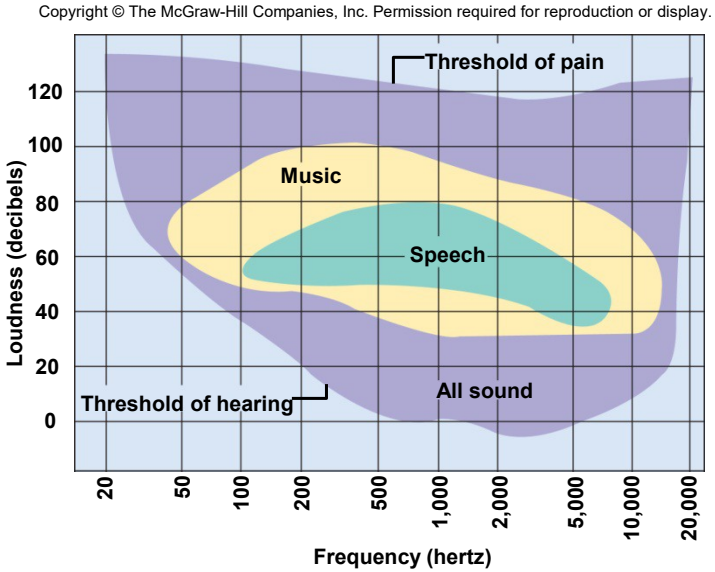
  - **scala tympani** // inferior chamber
    - filled with perilymph
    - begins at apex and ends at round window
    - round window = secondary tympanic membrane // membrane covering round window

Scala vestibuli ends with the oval window, scala tympani with the round window, located in between middle and inner ear



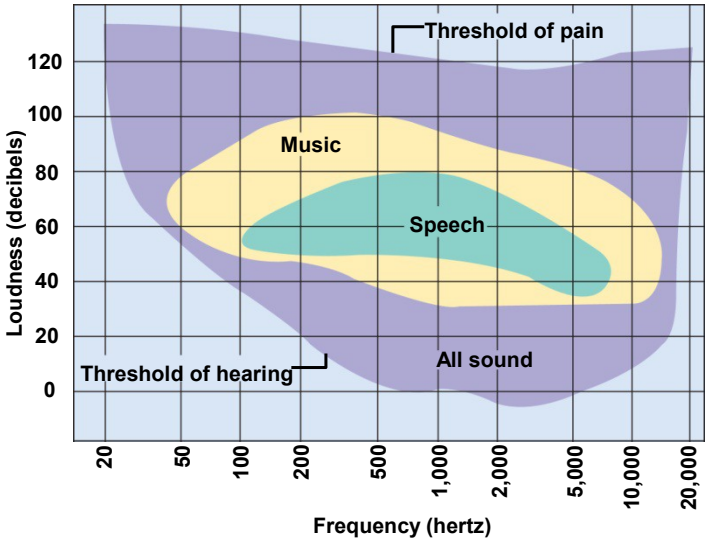

Scala vestibuli
Bony substance of cochlea
Vestibular membrane
Cochlear duct
Tectorial membrane
Cochlear nerve
Hair cells
Basilar membrane
Scala tympani

What is the difference between pitch and loudness?



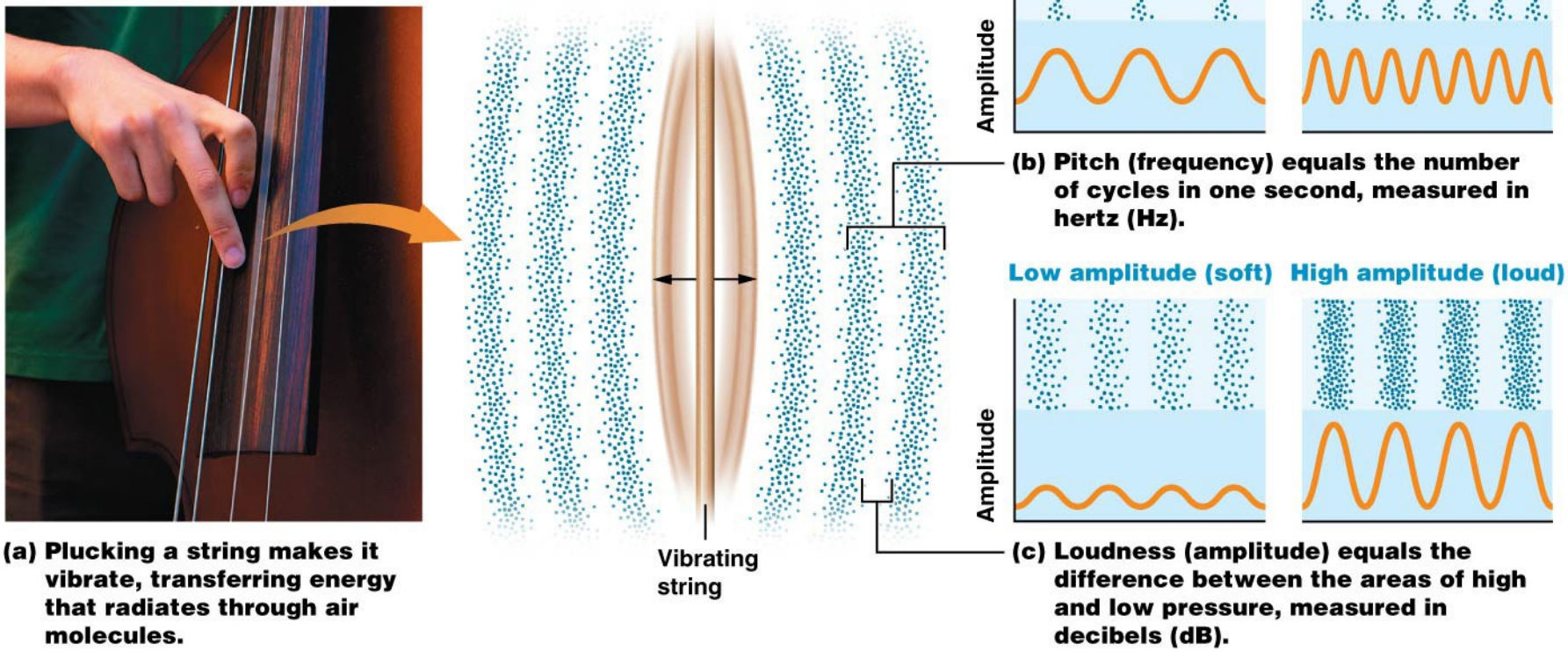
- **Pitch** – our sense of whether the sound has a 'high or low frequency"
  - determined by the **frequency** /// cycles/sec – cps or **hertz**, **Hz**
  - human hearing range is 20 Hz - 20,000 Hz (cycles/sec)
    - **infrasonic** frequencies below 20 Hz
    - **ultrasonic** frequencies above 20,000 Hz
  - speech is 1,500-5,000 where hearing is most sensitive
  - hearing loss with age is 250 to 2,050 Hz

What is the difference between pitch and loudness?



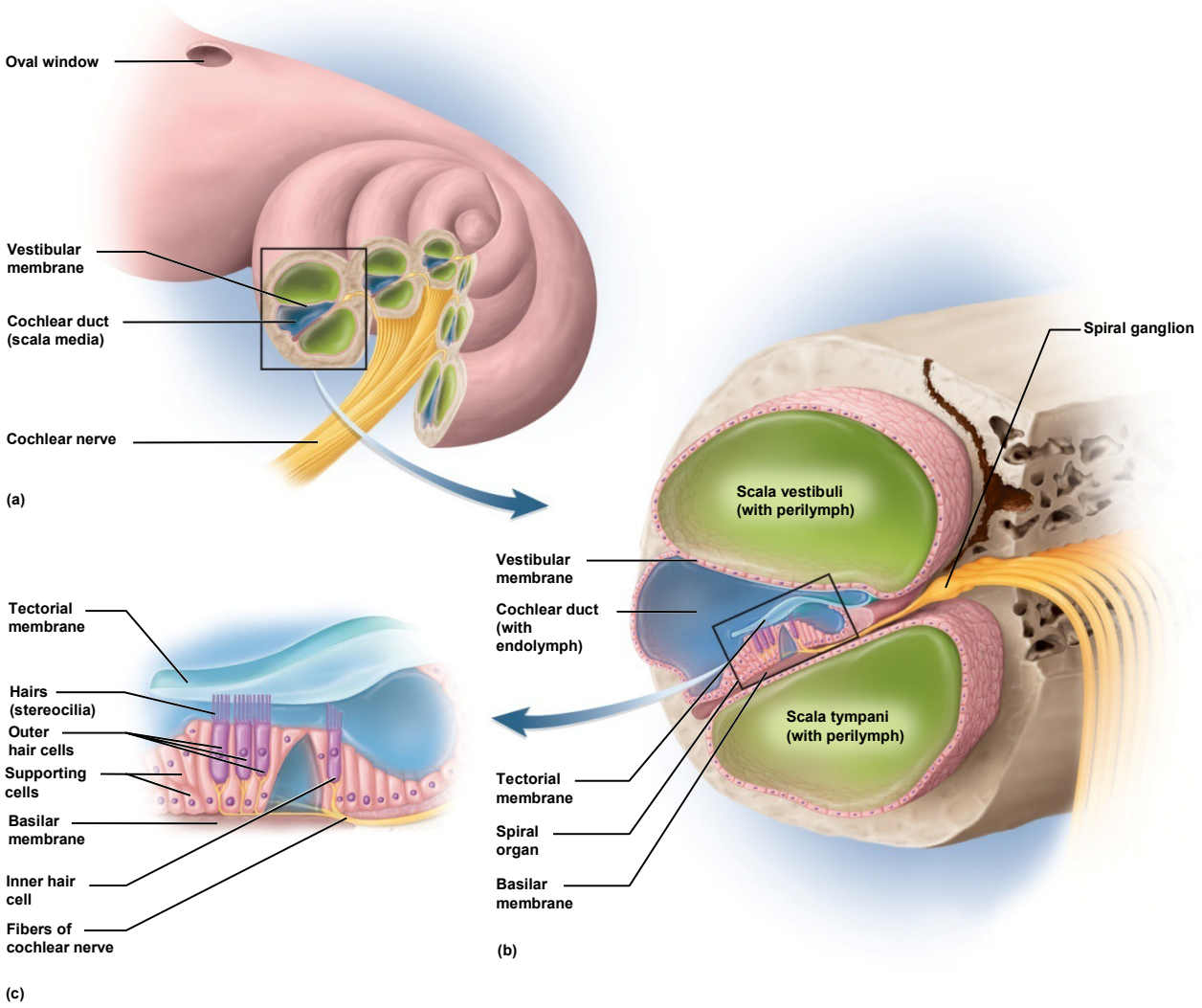
- **Loudness** = the perception of sound energy // intensity
  - the amplitude of the vibration
  - expressed in decibels (dB)
  - prolonged exposure to sounds > 90dB can cause damage

Sound waves.

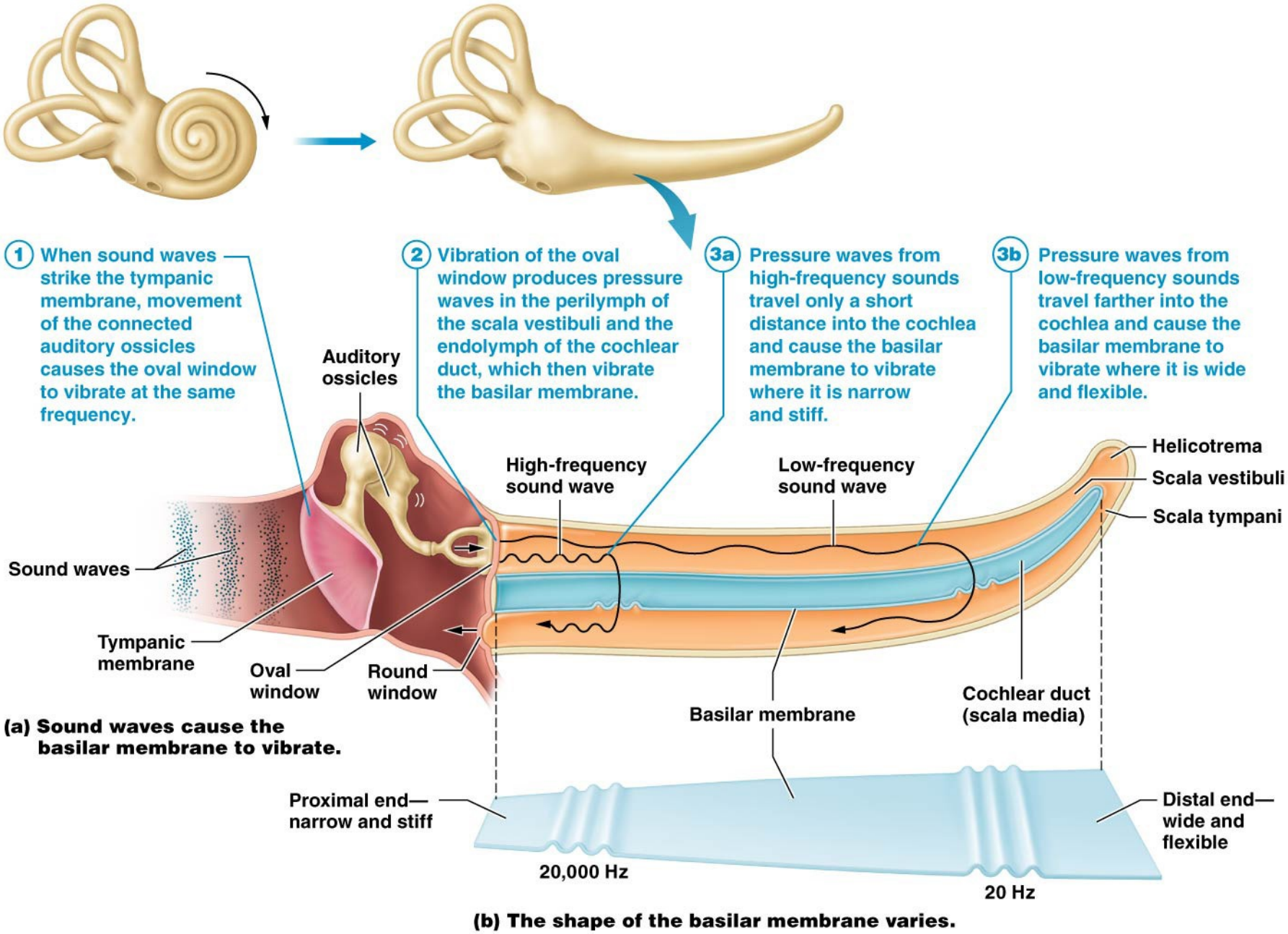


Pitch = frequency /// Loudness = amplitude

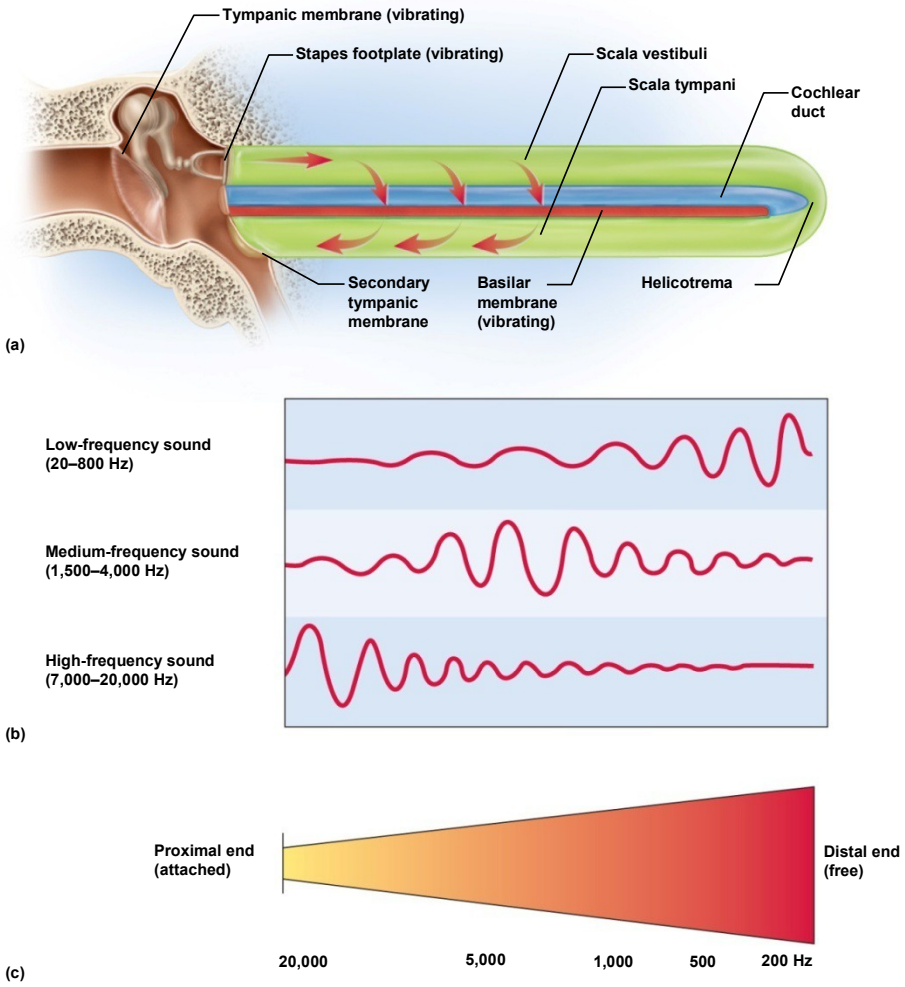
Cochlea, Cochlear Duct and Spiral Organ



Vibration of the basilar membrane.



Basilar Membrane Frequency Response



notice high and low frequency ends

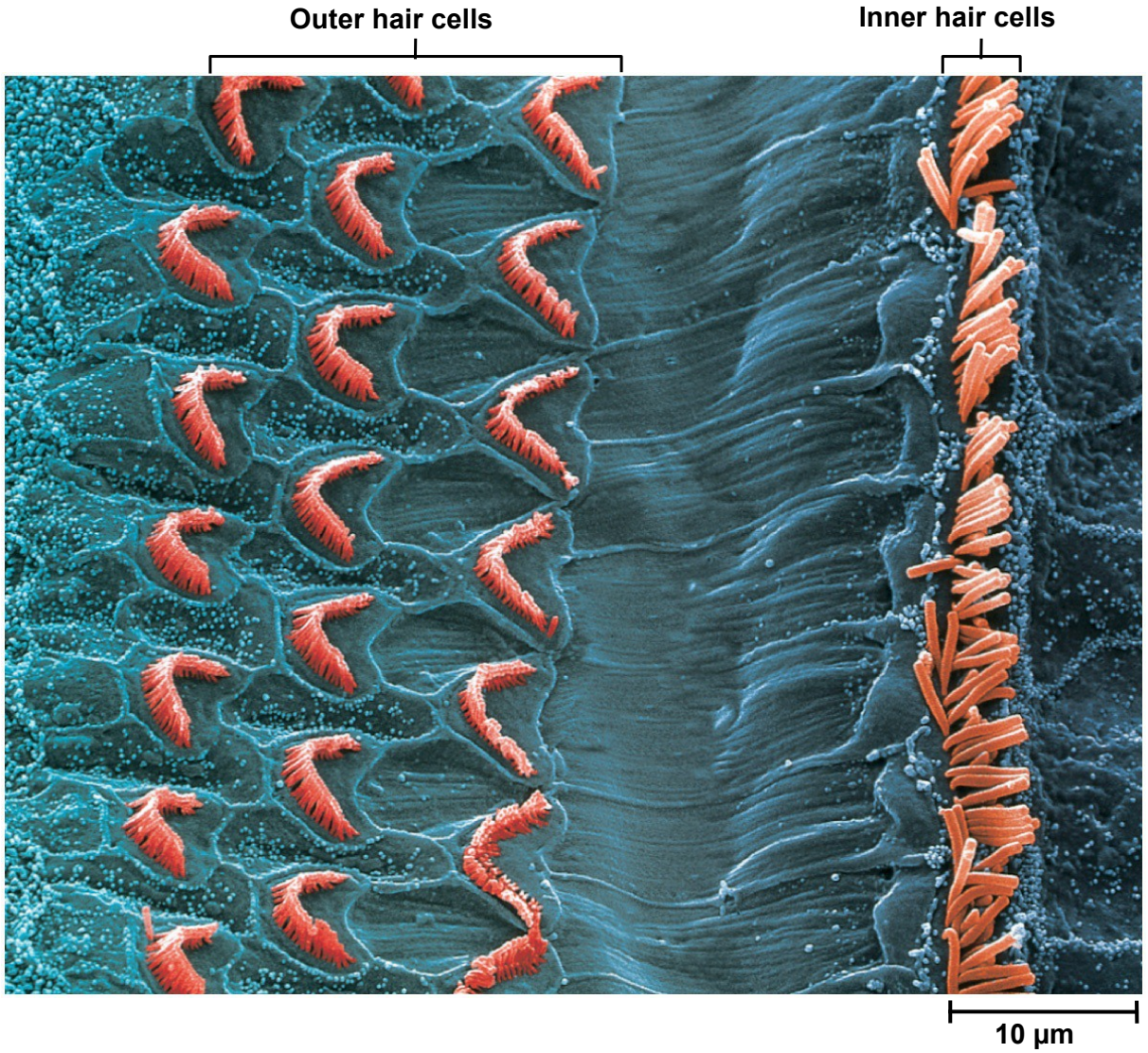
Spiral Organ (Organ of Corti)

- **spiral organ** has epithelium composed of **hair cells** and **supporting cells**

- hair cells have long, stiff microvilli called **stereocilia** on apical surface /// gelatinous **tectorial membrane** rests on top of stereocilia

- spiral organ has four rows of hair cells spiraling along its length
  - **inner hair cells** – single row of about 3500 cells // provides for hearing
  - **outer hair cells** – three rows of about 20,000 cells // adjusts response of cochlea to different frequencies // increases precision

SEM of Cochlear Hair Cells



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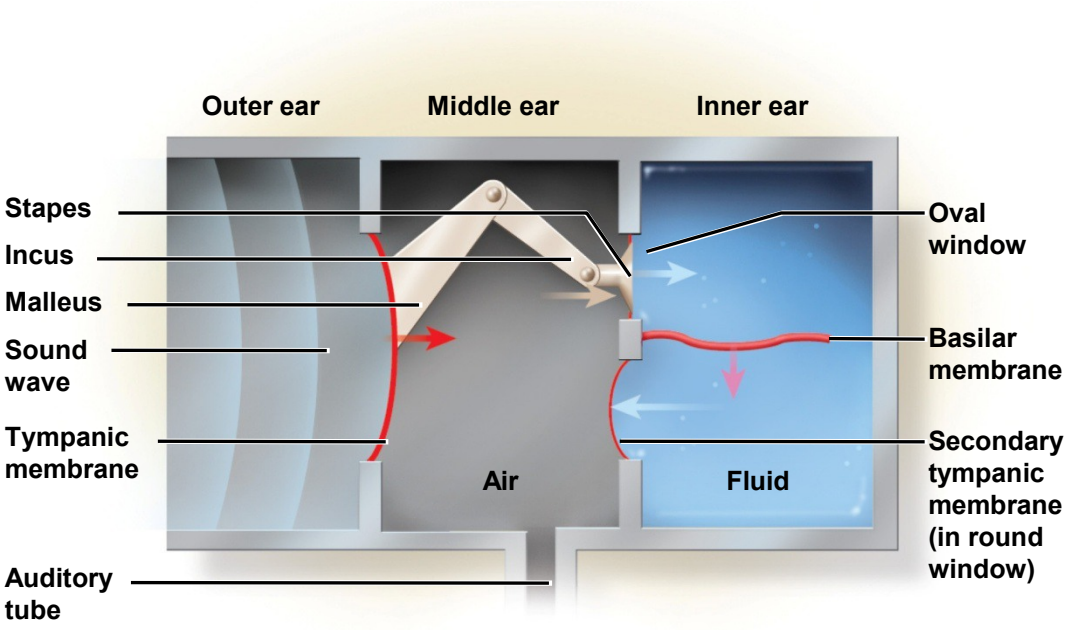
Physiology of Hearing - Middle Ear

- tympanic membrane
  - has 18 times area of oval window
  - ossicles concentrate the energy of the vibrating tympanic membrane on an area 1/18 the size
  - ossicles create a greater force per unit area at the oval window and overcomes the inertia of the perilymph
  - ossicles and their muscles have a protective function // lessen the transfer of energy to the inner ear

Stimulation of Cochlear Hair Cells

- vibration of ossicles causes vibration of basilar membrane under hair cells
  - as often as 20,000 times per second
  - hair cells move with basilar membrane



Physiology of Hearing - Middle Ear

- **tympanic reflex**
  - during loud noise, the **tensor tympani** pulls the tympanic membrane inward and tenses it
  - **stapedius muscle** reduces the motion of the stapes
  - muffles the transfer of vibration from the tympanic membrane to the oval window
  - middle ear muscles also help to coordinate speech with hearing // *dampens the sound of your own speech*

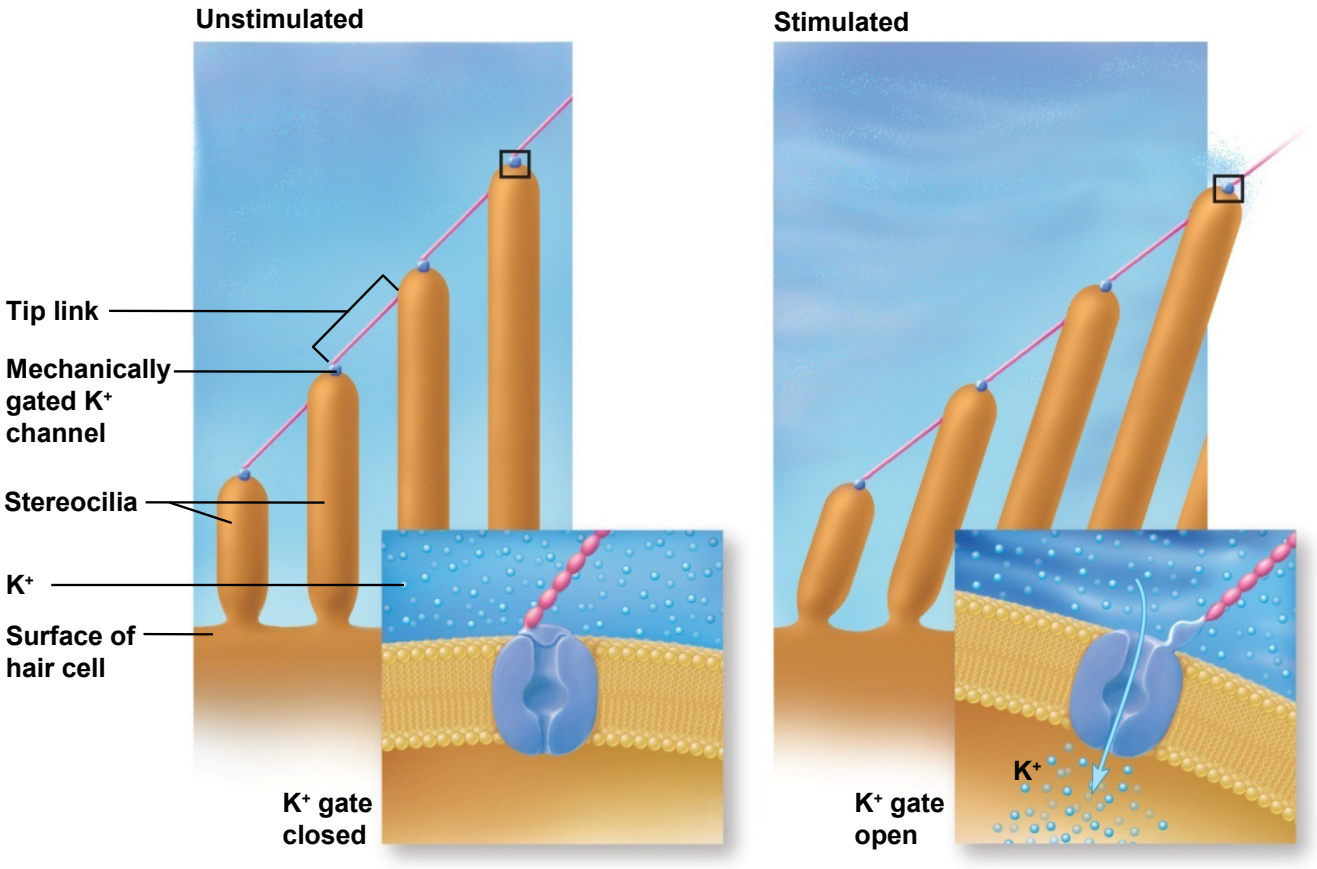
Excitation of Cochlear Hair Cells

- stereocilia of outer hair cells
  - bathed in high K^+ fluid, the endolymph
    - creating electrochemical gradient
    - outside of cell is +80 mV and inside about – 40 mV
  - tip embedded in tectorial membrane

Excitation of Cochlear Hair Cells

- stereocilium on inner hair cells
  - single transmembrane protein at tip that functions as a mechanically gated ion channel
    - stretchy protein filament **(tip link)** connects ion channel of one stereocilium to the sidewall of the next taller stereocilium
    - tallest one is bent when basilar membrane rises up towards tectorial membrane
    - pulls on tip links and opens ion channels
    - K^+ flows in – depolarization causes release of neurotransmitter
    - stimulates sensory dendrites and generates action potential in the cochlear nerve

Potassium Gates



Mechanical regulated ion gate!

Sensory Coding

- for sounds to carry meaning, we must distinguish between loudness and pitch
- variations in **loudness** (amplitude) cause variations in the intensity of cochlear vibrations
  - soft sound produces relatively slight up-and-down motion of the basilar membrane
  - louder sounds make the basilar membrane vibrate more vigorously
    - triggers higher frequency of action potentials
    - brain interprets this as louder sound
- **pitch** depends on which part of basilar membrane vibrates
  - **at basal end**, membrane attached, narrow and stiff // brain interprets signals as high-pitched
  - **at distal end**, 5 times wider and more flexible // brain interprets signals as low-pitched

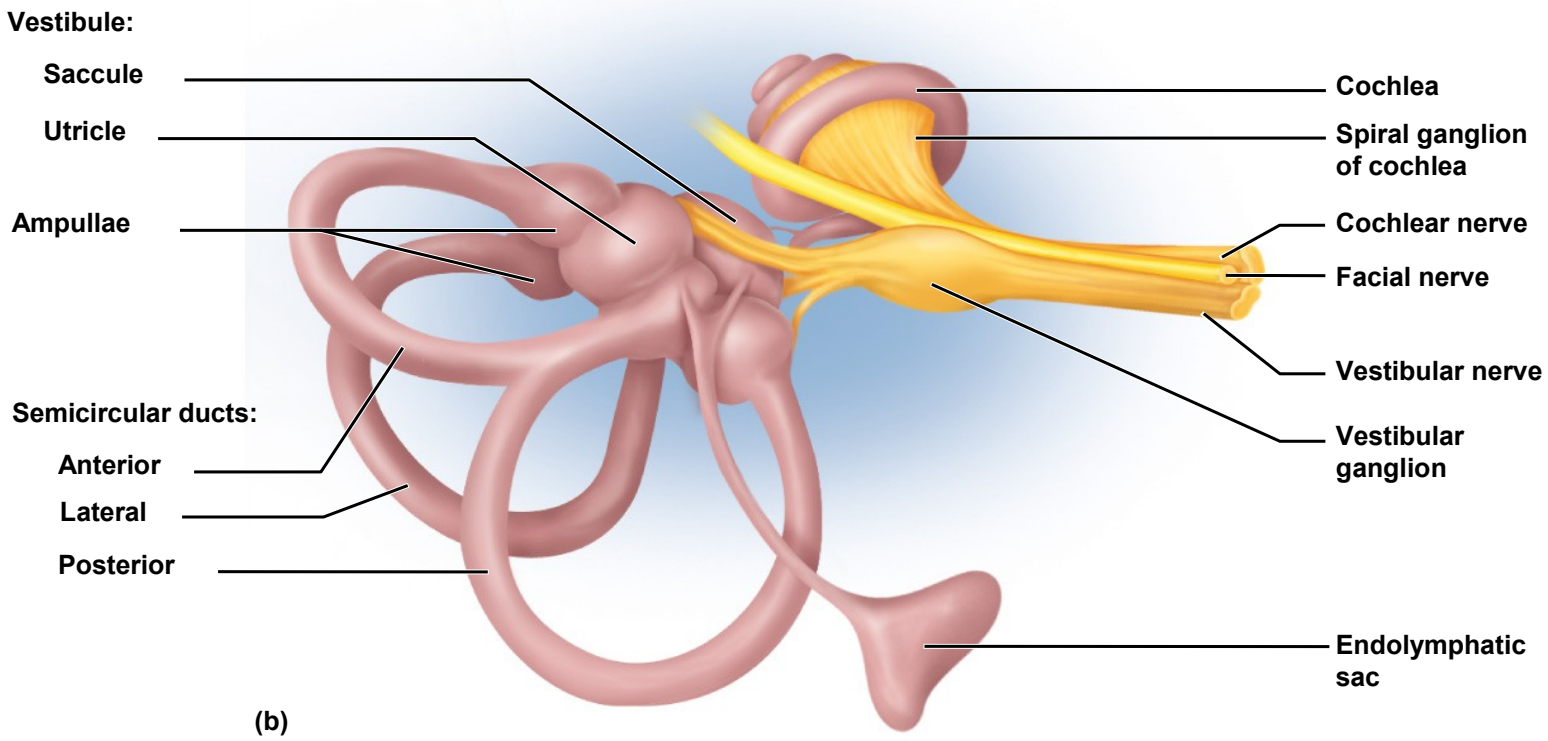
Cochlear Tuning

- increases ability of cochlea to receive some sound frequencies
- **outer hair cells** shorten (10 to 15%) reducing basilar membrane's mobility
  - fewer signals from that area allows brain to distinguish between more and less active areas of cochlea
- pons has inhibitory fibers that synapse near the base of **inner hair cells**
  - inhibiting some areas and increases contrast between regions of cochlea

Deafness

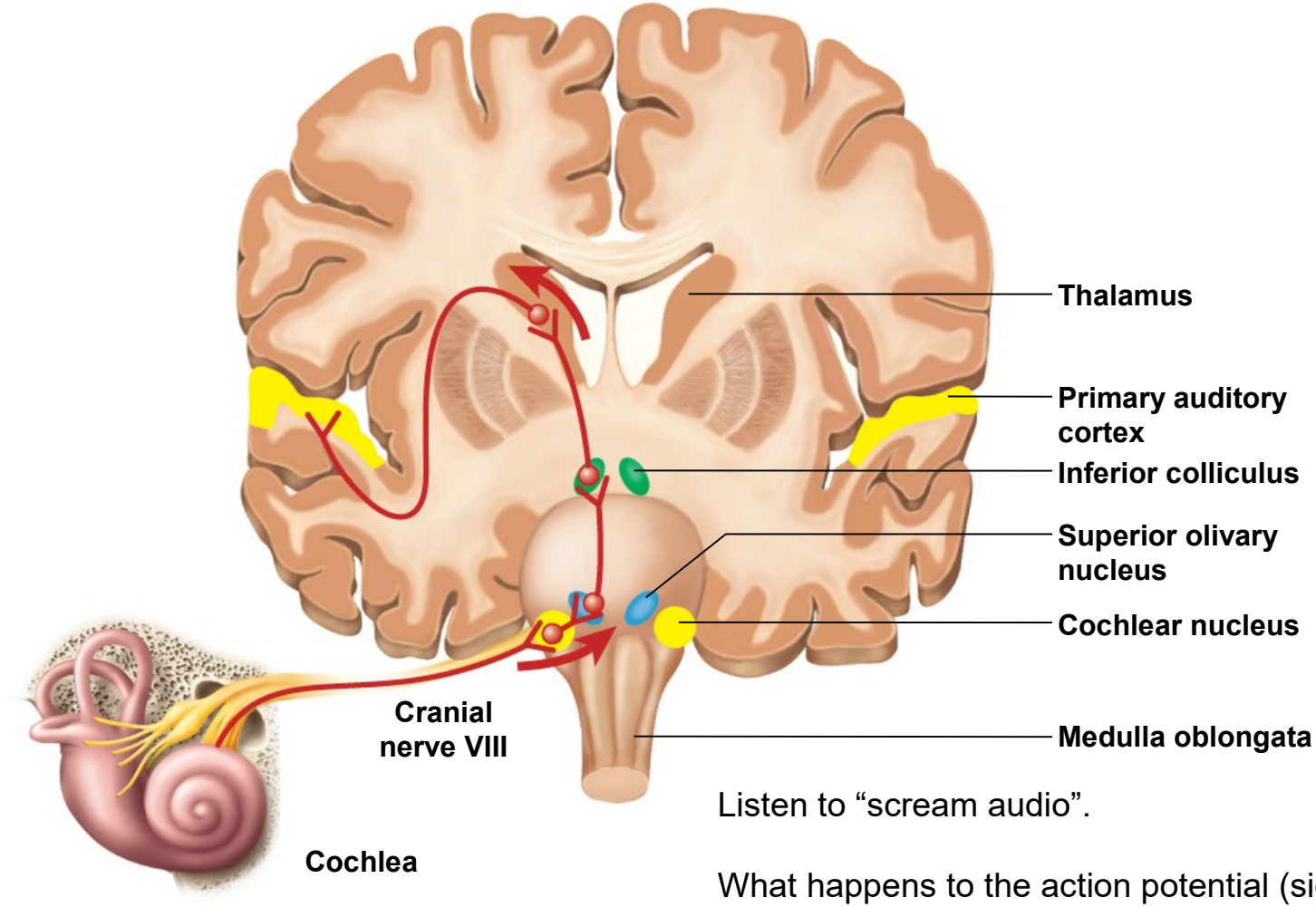
- Hearing Loss
  - conductive deafness // conditions interfere with transmission of vibrations to inner ear
    - damaged tympanic membrane, otitis media, blockage of auditory canal, and otosclerosis
    - otosclerosis - fusion of auditory ossicles that prevents their free vibration // e.g. arthritis
  - sensorineural (nerve) deafness // death of hair cells or any nervous system elements concerned with hearing
    - factory workers, musicians and construction workers

Innervation of Internal Ear



- **vestibular ganglia** - visible lump in vestibular nerve
- **spiral ganglia** - buried in modiolus of cochlea

Auditory Processing Centers



Listen to “scream audio”.

What happens to the action potential (signal) as it passes through thalamus? Why are you more likely to remember this type of memory?

What occurs as the signal passes through the inferior colliculus? What is this reflex called?

Auditory Projection Pathway

- sensory fibers begin at the bases of the hair cells
  - soma form the spiral ganglion around the modiolus
  - axons lead away from the cochlea as the cochlear nerve
  - joins with the vestibular nerve to form the vestibulocochlear nerve, Cranial Nerve VIII

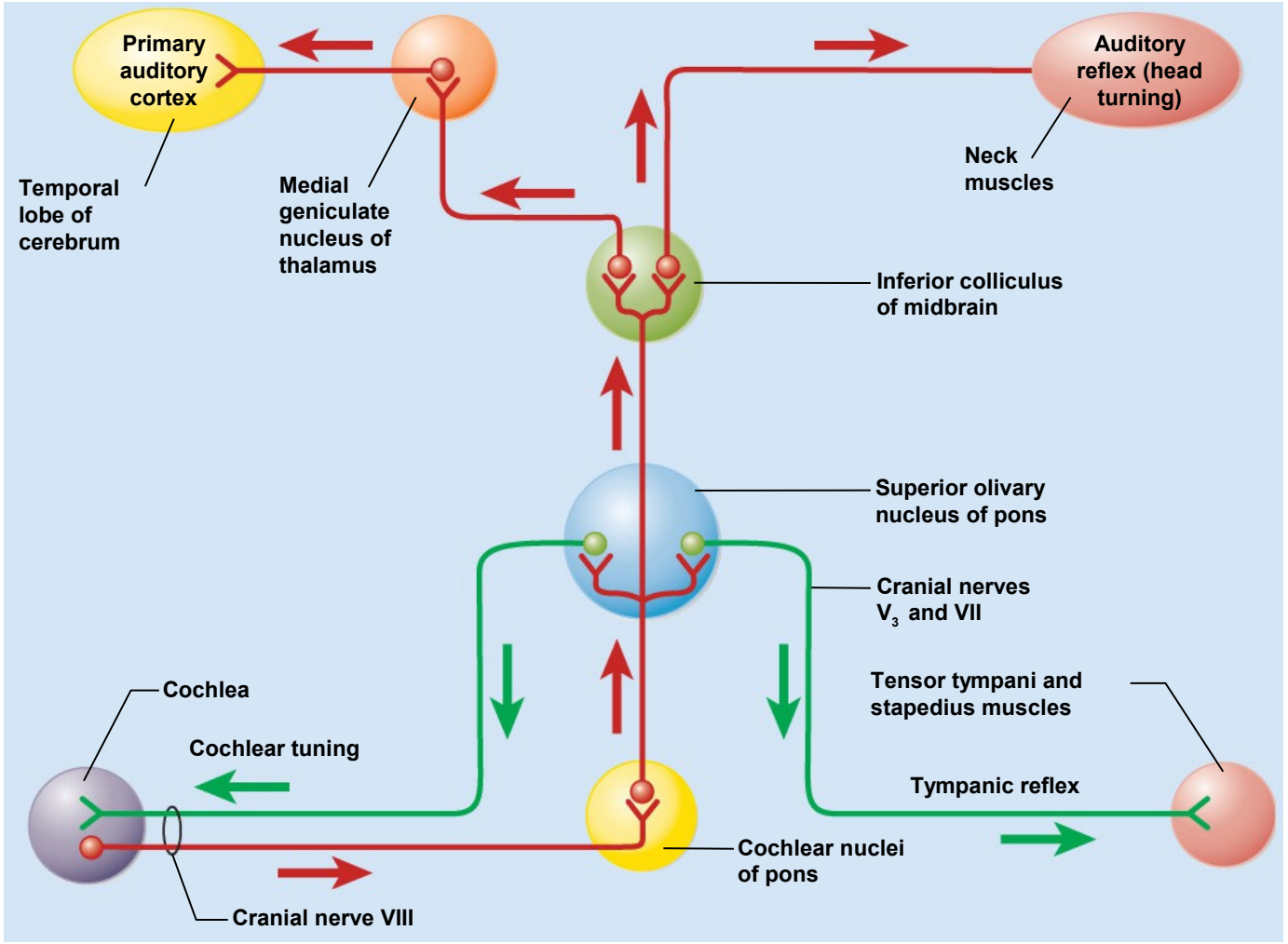
- each ear sends nerve fibers to both sides of the pons
  - end in cochlear nuclei
  - synapse with second-order neurons that ascend to the nearby superior olivary nucleus
  - superior olivary nucleus issues efferent fibers back to the cochlea /// involved with cochlear tuning

- binaural hearing – comparing signals from the right and left ears to identify the direction from which a sound is coming /// function of the superior olivary nucleus

Auditory Projection Pathway

- fibers ascend to the **inferior colliculi** of the midbrain
  - helps to locate the origin of the sound, processes fluctuation in pitch, and mediate the startle response and rapid head turning in response to loud noise
- **third-order neurons** begin in the inferior colliculi and lead to the thalamus
- **fourth-order neurons** complete the pathway from thalamus to primary auditory complex
  - involves four neurons instead of three unlike most sensory pathways
- **primary auditory cortex** lies in the superior margin of the temporal lobe // site of conscious perception of sound
- because of extensive decussation of the auditory pathway, damage to right or left auditory cortex does not cause unilateral loss of hearing

Auditory Pathway



(a)

Equilibrium

The orientation of our body in in a three-dimensional space // necessary for coordination and balance

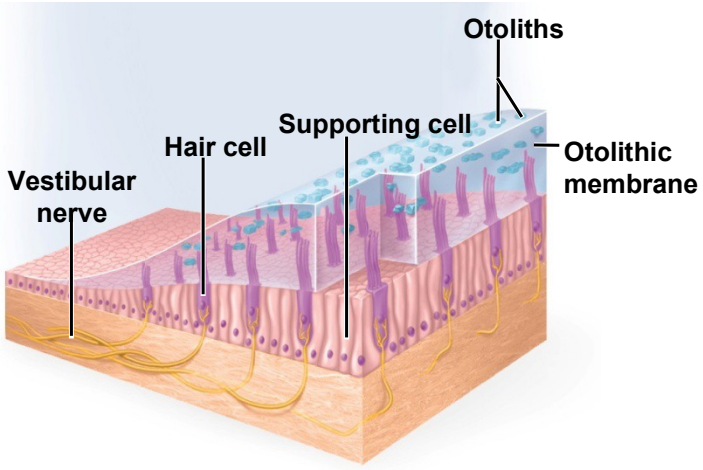
- **Vestibular apparatus** – 3 receptors for equilibrium
  - **semicircular ducts** // detect only angular acceleration
  - **two chambers –** detects static equilibrium and linear acceleration
    - Macula Saccule (anterior)
    - Macula Utricle (posterior)

Sacula and Utricle Equilibrium

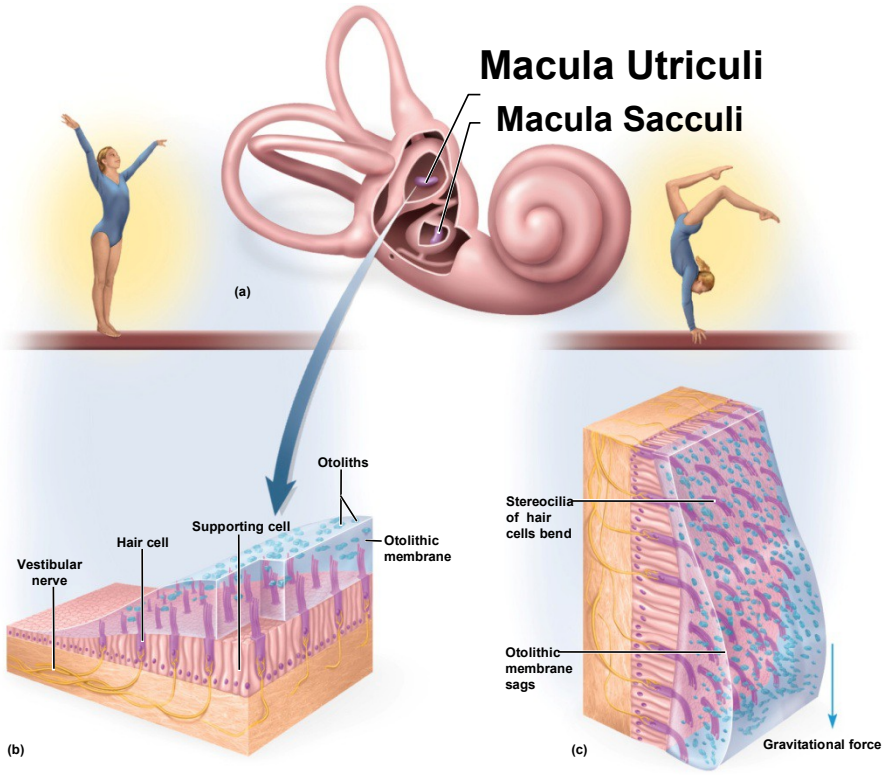
- Static equilibrium – the perception of the head when the body is stationary
- Dynamic equilibrium - perception of motion (acceleration)
    - linear acceleration - change in velocity in a straight line (elevator or car // vertical vs horizontal)
    - angular acceleration - change in velocity of rotation (car turns around corner while going same speed)

Saccule and Utricle Structure

- Each hair cell has 40 to 70 **stereocilia** and one true cilium - **kinocilium** embedded in a gelatinous **otolithic membrane**
  - **otoliths -** calcium carbonate-protein granules that add to the weight and inertia and enhance the sense of gravity and motion



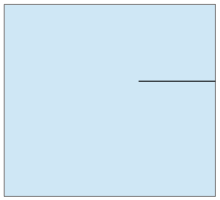
The Saccule and Utricle



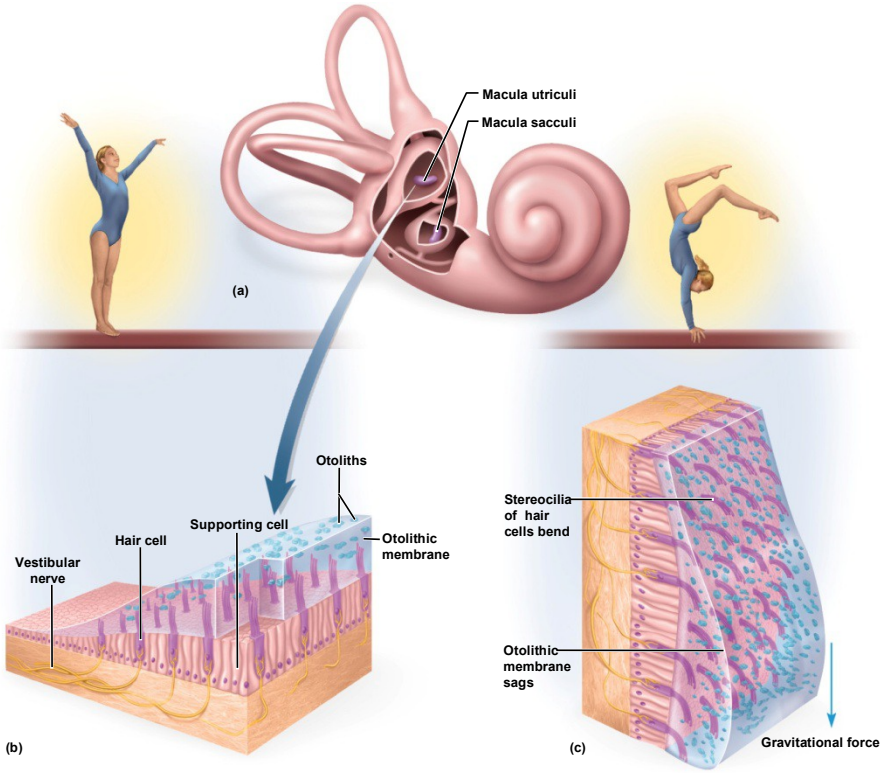
Macula Utricle

Macula Sacculi

- **Macula** = 2 by 3 mm patch of hair cells and supporting cells <u>in the saccule and utricle of the vestibule</u>
  - **macula sacculi** – on wall of saccule
  - **macula utriculi** – on floor of utricle

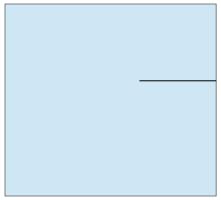


Two Type of Equilibrium Measured By Macula



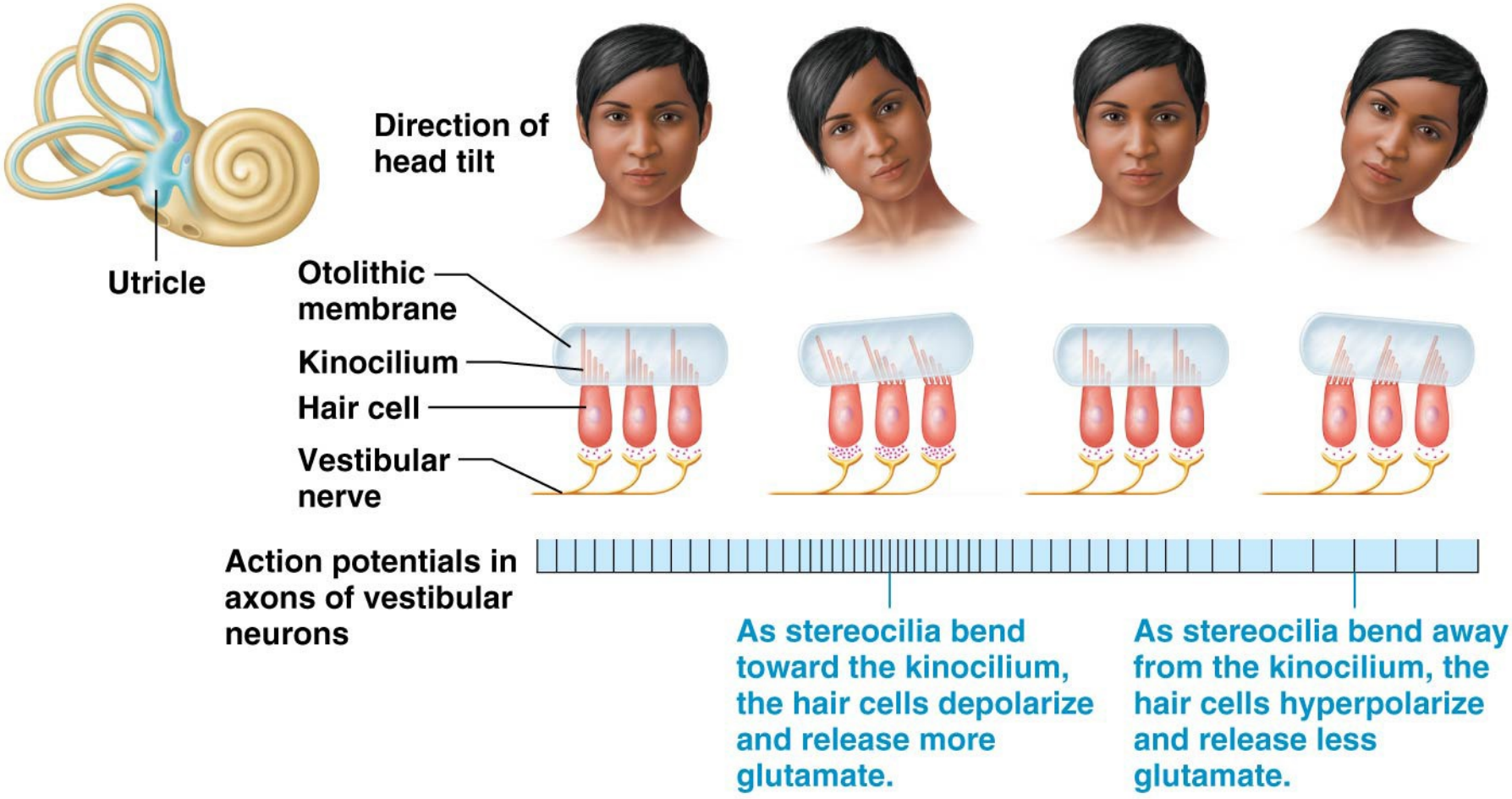
Macula Utricle

Macula Sacculi

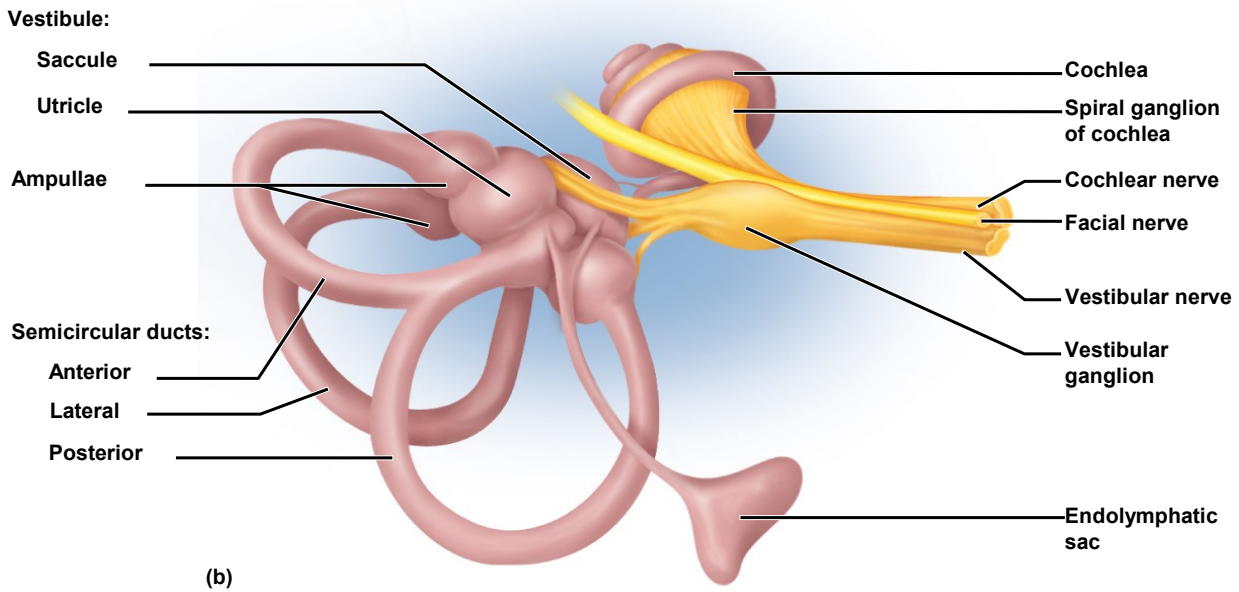


- Static equilibrium
  - when head is tilted, heavy otolithic membrane sags, bending the stereocilia, and stimulating the hair cells
- Dynamic equilibrium
  - in car, horizontal linear acceleration detected by macula utricle as otoliths lag behind, bending the stereocilia, and stimulating the hair cells
  - in elevator, the macula sacculi responds to vertical linear acceleration and deceleration

Head tilting and activity of the maculae.

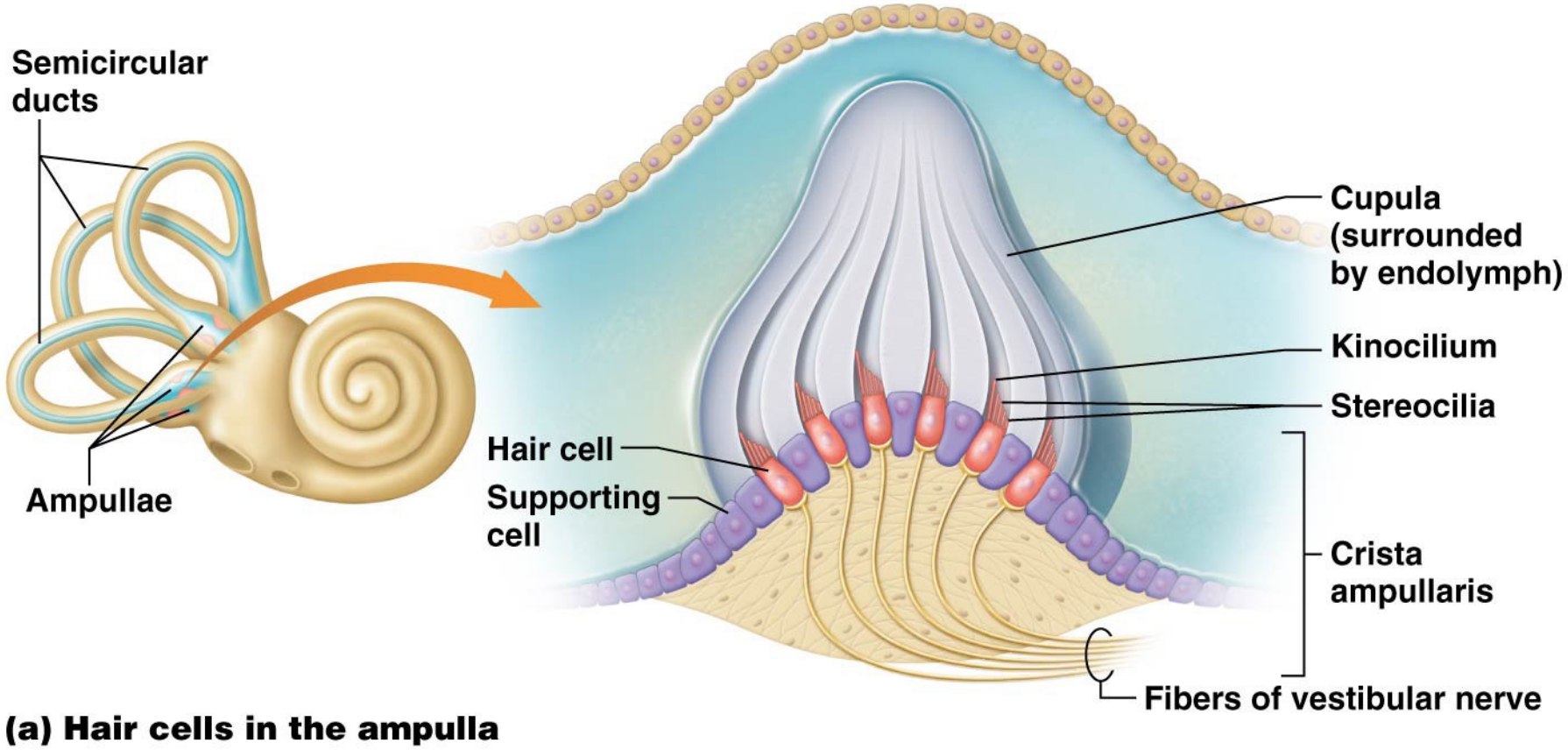


Rotational Dynamic Equilibrium and the Semicircular Ducts



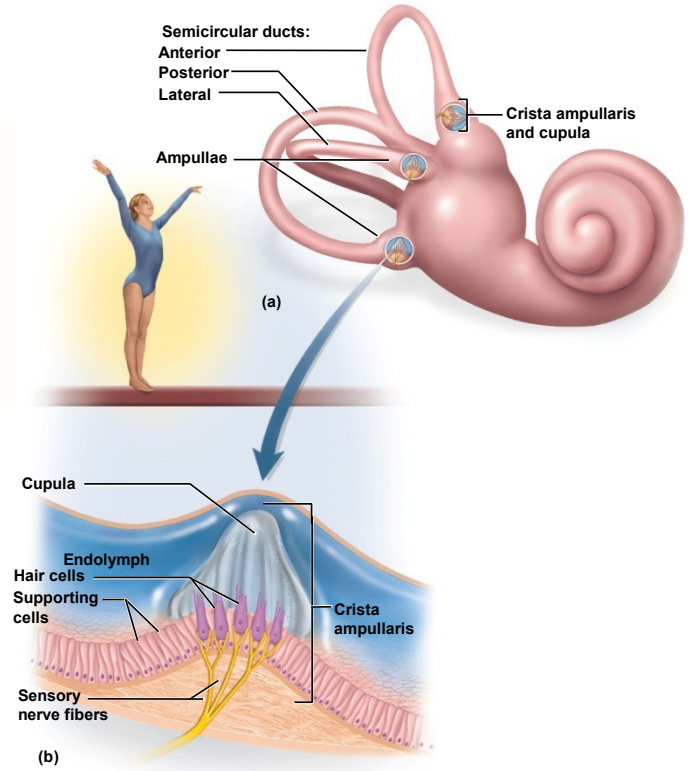
- **rotational movements** - detected by three semicircular ducts
- bony **semicircular canals** of temporal bone hold membranous **semicircular ducts**
- each duct filled with **endolymph** and opens up as a dilated sac (**ampulla**) next to the utricle
- each ampulla contains **crista ampullaris**, mound of hair cells and supporting cells

Angular movement and the semicircular canals.



(a) Hair cells in the ampulla

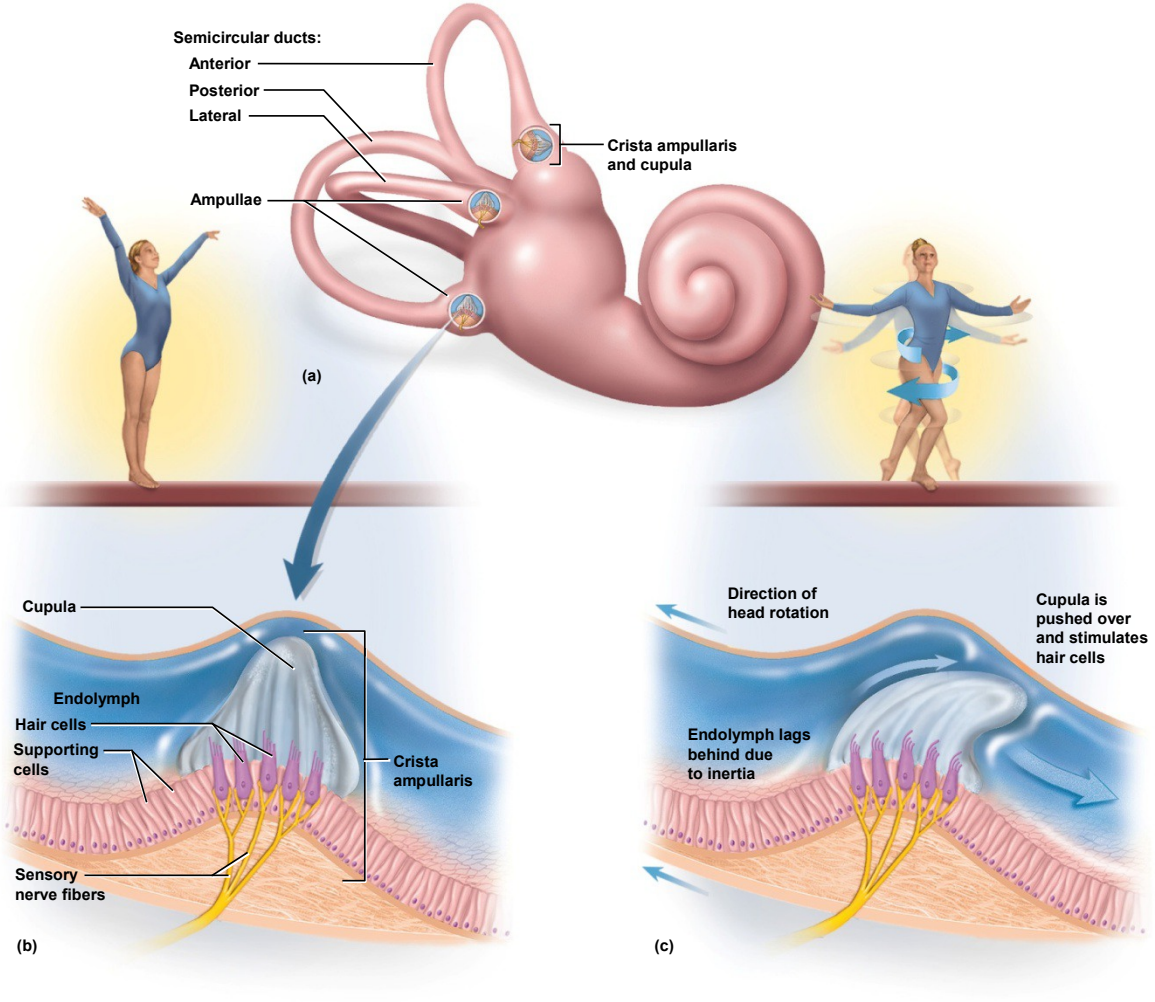
Crista Ampullaris of the Semicircular Canals



- consists of hair cells with stereocilia and a kinocilium buried in a mound of gelatinous membrane called the cupula (one in each duct)

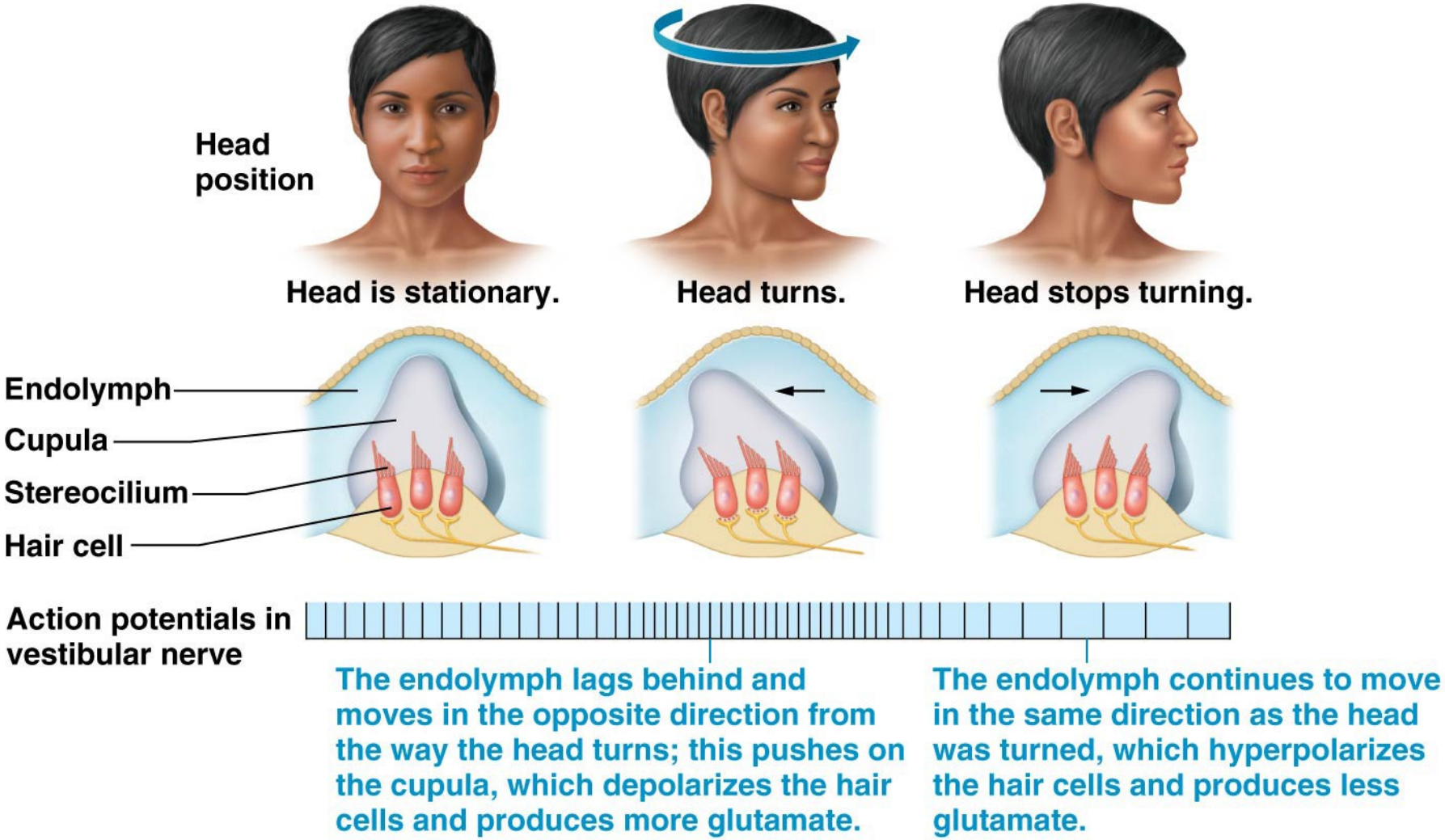
- orientation causes ducts to be stimulated by rotation in different planes

Crista Ampullaris - Head Rotation



- as head turns, endolymph lags behind, pushes cupula, stimulates hair cells

Angular movement and the semicircular canals.



(b) Transduction for angular rotation

Equilibrium Projection Pathways

- **hair cells** of macula sacculi, macula utriculi and semicircular ducts synapse on **vestibular nerve (part of CN VIII)**

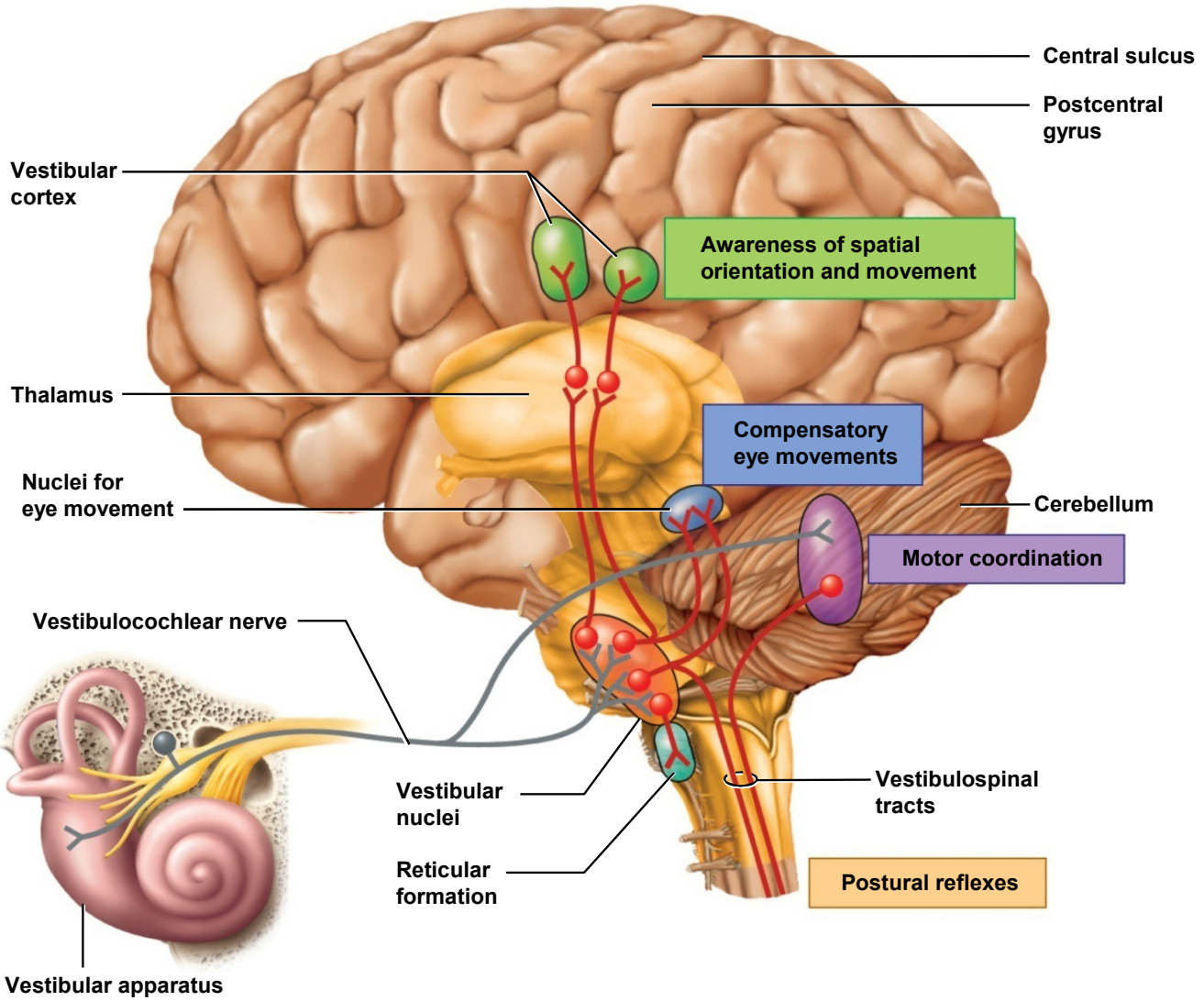
- fibers end in a complex of four vestibular nuclei on each side of the pons and medulla /// left and right nuclei receive input from both ears

- process signals about the position and movement of the body and relay information to 5 target areas:

Equilibrium Projection Pathways

- information sent to five targets:
  - cerebellum – integrates vestibular information into its control of head and eye movements, muscle tone, and posture
  - nuclei of oculomotor, trochlear, and abducens nerves (CN III, IV, and VI) to produce vestibulo-ocular reflex – e.g. helps you keeps your vision fixed on distant object while you are walking
  - reticular formation – thought to adjust blood circulation and breathing to postural changes
  - spinal cord – descend through vestibulospinal tracts of spinal cord /// innervate extensor (antigravity) muscles
  - thalamus - thalamic relay to cerebral cortex for awareness of position and motor control of head and body

Vestibular Projection Pathways



How the special senses work together.

	Smell	Taste	Vision	Hearing	Vestibular sensation
(1) Receptors detect and transduce stimuli.	Olfactory neurons detect and transduce Na^+ in salty air.	Gustatory cells detect and transduce Na^+ in salt spray.	Photoreceptors detect and transduce light reflected from waves.	Hair cells in cochlea detect and transduce sound waves produced by the ocean and your friend's laugh.	Hair cells in vestibule detect and transduce position and motion of your head.
(2) Cranial nerves transmit neural signals to the CNS.	Olfactory nerve (I) to olfactory tract	Facial nerve (VII) Glossopharyngeal nerve (IX) Vagus nerve (X)	Optic nerve (II)	Vestibulocochlear nerve (VIII)	Vestibulocochlear nerve (VIII)
		Brainstem		Brainstem	
(3) Neural signals are relayed through the thalamus (except those for olfaction).		Thalamus			
(4) Awareness occurs in the primary sensory cortices.	**Inferomedial temporal lobe** • *You notice the air smells salty.*	**Inferior parietal lobe** • *You taste the salty spray in the air.*	**Medial occipital lobe** • *You see large waves and the movement of your friend falling off his surfboard.*	**Temporal lobe** • *You hear the roar of the waves and your friend's laugh.*	**Parietal lobe** • *You are aware that you are sitting up on your towel.*
(5) The frontal lobe and limbic system integrate the special senses.	**Frontal lobe** • *You notice the air smells salty.* • *You realize the wave is big.* • *You realize your friend is falling off his surfboard.*			**Limbic system** • *You remember that this is the beach where your family vacations each year.* • *You recognize your friend.* • *You are relieved that your friend is safe.*	