Vision

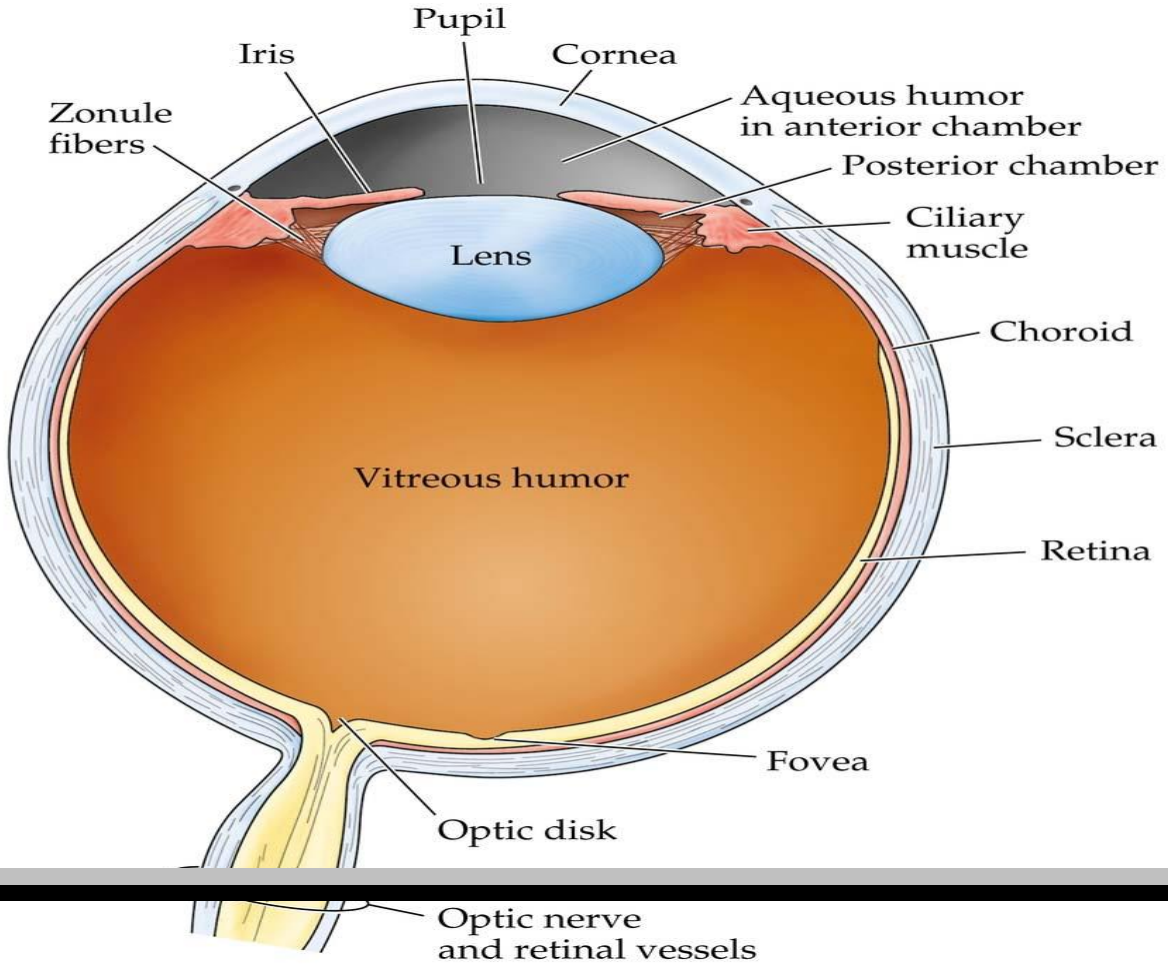
Vision involves processes in which light energy is transduced into neural activity and the neural activity is processed by the brain. Human visual systems permit light reflected off distant objects to be:

1. Localized relative to the individual within his or her environment
2. Identified based on size, shape, color, and past experience
3. Perceived to be moving (or not)
4. Detected in a wide variety of lighting conditions

Light entering the eye is focused on the retina which converts light energy into neuronal activity. Axons of the retinal neurons are bundled to form the optic nerves and, lastly, visual information is distributed to several brain structures that perform different functions

Anatomy of the Eye

a. Pupil: Opening that allows light to reach the retina



b. Iris: Circular muscle that controls the diameter of the pupil

c. Aqueous humor: Fluid behind the cornea

d. Sclera: Outermost layer that forms the eyeball

e. Extraocular muscles: Attached to the eye and skull and allow movement

f. Conjunctiva: Membrane inside the eyelid attached to the sclera

g. Optic nerve: Axons of the retina leaving the eye

h. Cornea: Transparent surface covering the iris and pupil

i. Optic disk (blind spot): No vision is possible due to that blood vessels originate here. These vessels shadow the retina. Optic nerve fibers also exit here and no photoreceptors are present.

j. Macula: Area of the retina responsible for central vision

k. Fovea: Center of the retina (where most of the cones are)

l. Lens: Transparent surface that contributes to the formation of images

m. Ciliary muscles: Change the shape of the lens and allow focusing

n. Vitreous humor: More viscous than the aqueous humor. It lies between the lens and the retina and provides the spherical shape of the eye.

o. Retina: Is the inner most layer of cells at the back of the eye. It transduces light energy into neural activity

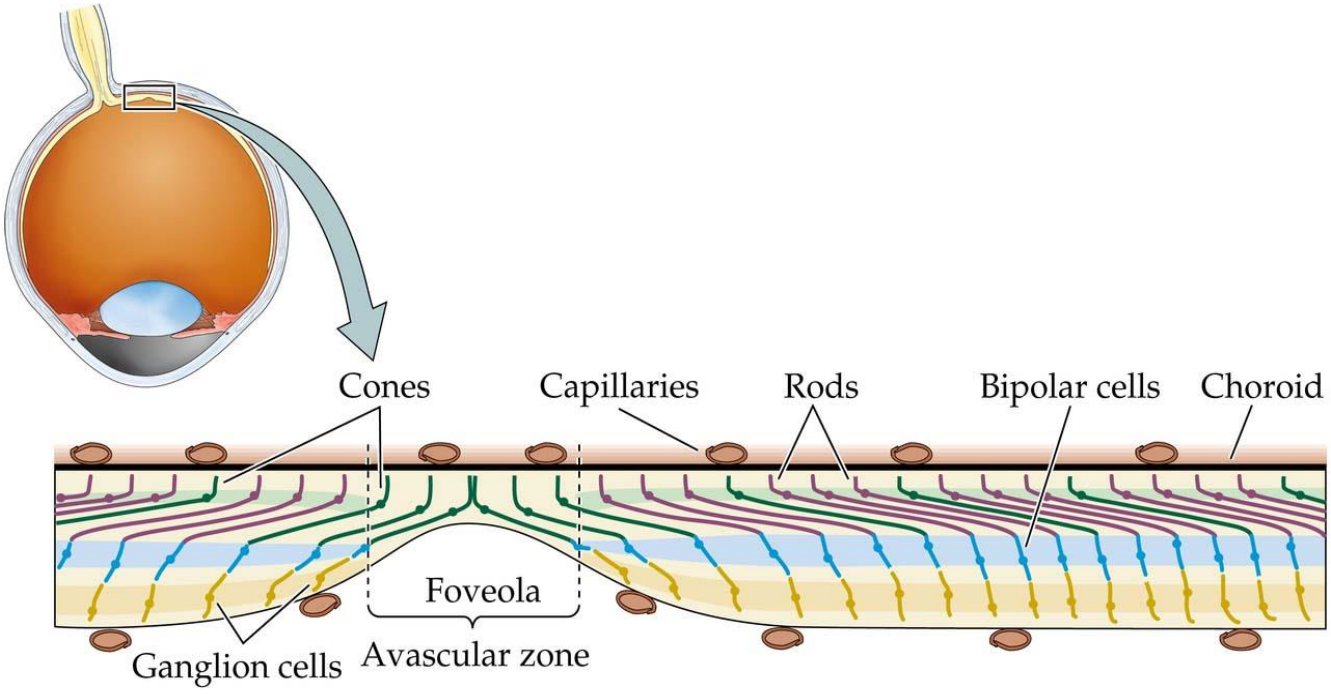
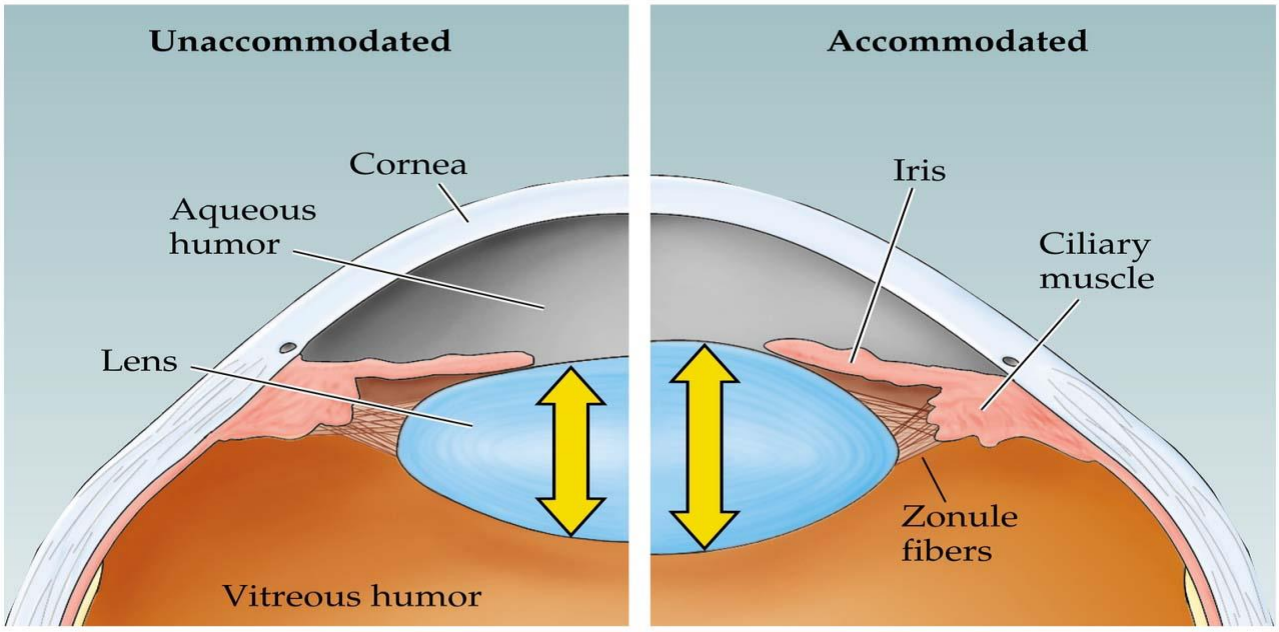


Image Formation

Image formed on the back of the retina is reversed and inverted. The visual field is the total space that can be viewed by the retina which is 150 degrees, 90 on temporal side and 60 on the nasal side. Pupil contributes to optical qualities of the eye. It adjusts for different light levels and contributes to simultaneous focusing on near and distant objects. The lens participates in accommodation for near and far objects.

From distant objects, light rays run in parallel and they slow down as they cross the cornea and aqueous humor. Light rays bend perpendicular to the tangent of the corneal curvature to run as the radii of the cornea. Focal distance is the distance between the refractive surface and where the light rays converge. So, it depends on the curvature of the cornea. The distance between the cornea and the retina is normally 2.4 cm ±.

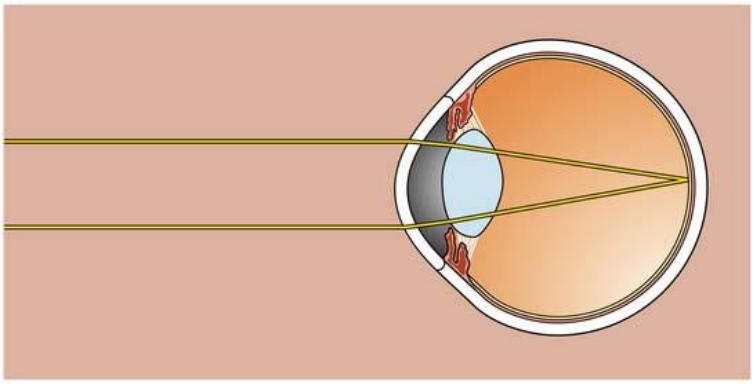
From objects within 9 meters, light rays do not travel in parallel because some of them diverge. The lens adds refractive power provided by changing its shape. Contraction of ciliary muscles causes the tension on the suspensory ligaments to release. Lens becomes rounded and greater curvature provides greater refraction.



Emmetropia (normal vision)

Parallel light rays are focused on the retina without accommodation

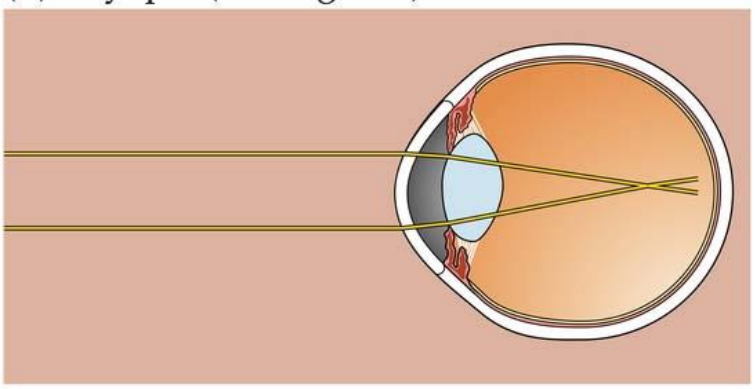
(A) Emmetropia (normal)



Myopia (nearsightedness)

Eye ball is too long. Light rays converge in front of the retina. Lens can accommodate for near objects but not distant. Condition can be corrected with a concave lens

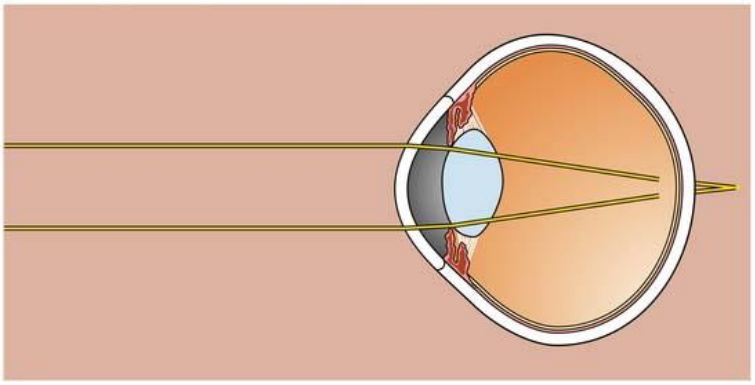
(B) Myopia (nearsighted)



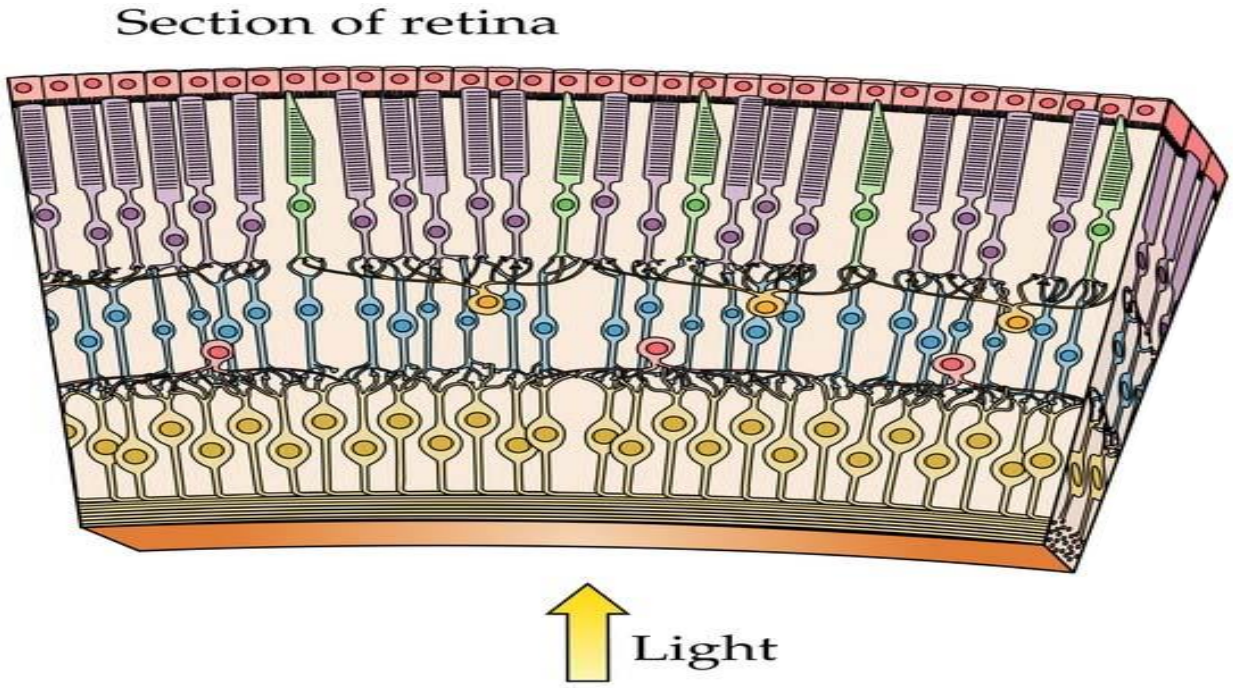
Hyperopia (farsightedness)

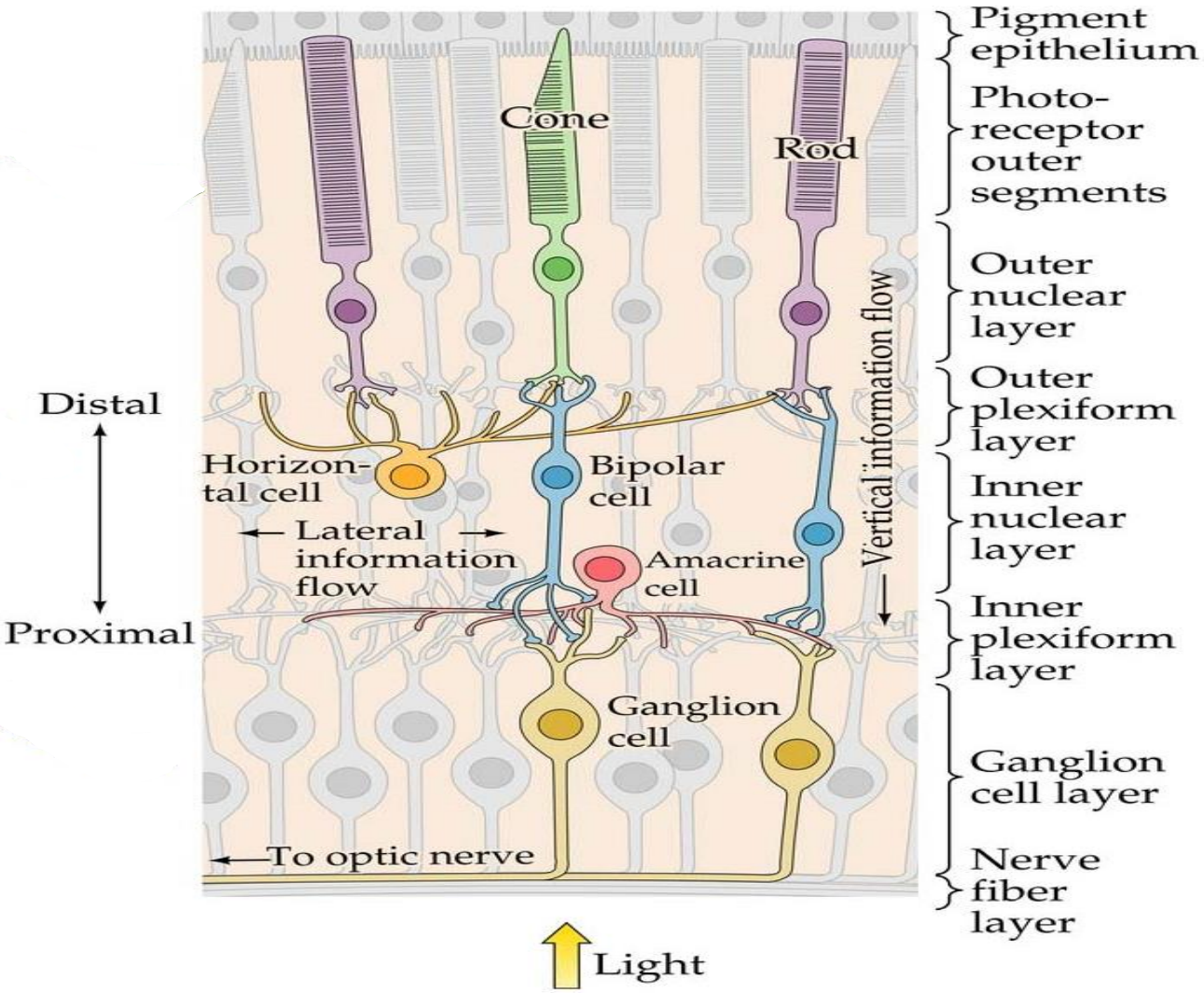
Eye ball is too short. Image is focused at a point behind the retina. Lens can accommodate for distant objects but not for near. Condition can be corrected with a convex lens (to increase refractive power)

(C) Hyperopia (farsighted)



Microscopic Anatomy of the Retina





Cell types in retina:

a. Photoreceptors: Are the only light sensitive cells in the retina.

b. Bipolar cells: Connect photoreceptors to ganglion cells

c. Ganglion cells: Fire action potential and send axons to the brain. They are the only output cells

d. Horizontal cells: Receive inputs from photoreceptors and project laterally to bipolar cells

e. Amacrine cells: Receive inputs from bipolar cells and project laterally to ganglion cells

They arrange primarily in three layers (but there are subdivisions). Light travels through these layers to reach the photoreceptors. At the back of the eye is a pigmented epithelium that absorbs any light not absorbed by the photoreceptors. The 3 layers are:

a. Ganglion cell layer: Cell bodies of the ganglion cells

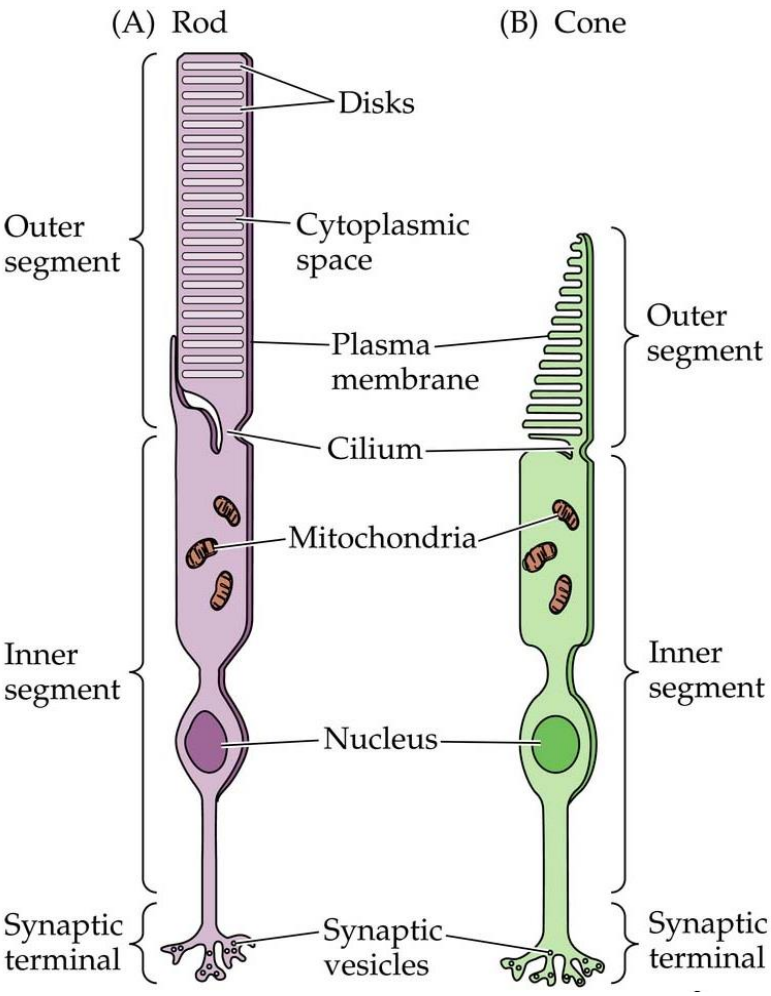
b. Inner nuclear layer: Cell bodies of the bipolar cells

c. Outer nuclear layer: Cell bodies of the photoreceptors

Photoreceptors are of two kinds based on appearance and function, *rods* and *cones*.

Rods are long, cylindrical with many disks. Photopigment is in the disk. Rods have a much higher pigment concentration. They are 1000 times more sensitive to light than cones. They function, mainly, in *scotopic* conditions (nighttime lighting). All rods have the same pigment which is *rhodopsin*

Cones are shorter with tapering outer segment and relatively few disks. They function in *photopic* conditions (daytime lighting). There are three different types of cones based on type of photopigment. The photopigments are differentially sensitive to wavelength of light.



Rods and cones are distributed regionally. The center of the eye (i.e., the fovea) contains only cones. Peripheral retina consists primarily of rods with few cones. Central retina has approximately the same number of photoreceptor and ganglion. Peripheral retina has many photoreceptors (rods) converge on a single output ganglion cell. So, peripheral retina is more sensitive to light.

Photoreceptors transduce (change) light energy into changes in membrane potential. The light activates *G-proteins* which stimulate various *effector enzymes*. Enzymes alter the intracellular concentration of cytoplasmic *second messengers*. Change in 2nd messenger concentration closes a Na+ channel.

In complete darkness, there is a steady influx of Na^+ which depolarizes the photoreceptor membrane. Movement of + charge across the membrane is called the *dark current*. Na^+ channels responsible for this current are gated by cGMP (cyclic guanosine monophosphate). cGMP is produced continually in photoreceptors. Na^+ channels stay open in the dark.

In the light, cGMP is converted to GMP (phosphodiesterase hydrolyzes cGMP). Membrane hyperpolarizes in response to light (Na^+ channels close). Rhodopsin photopigment is located in stacked disks in the outer segment of the rods. It is comprised of retinal and opsin. Opsin absorbs light.

Photoreceptors no longer respond at particular light intensities. Activation of rods by light bleaches the photopigment and changes the wavelengths absorbed by rhodopsin.

Cones contain three different opsins. Each maximally activated by different wavelengths of light:

a. Blue: 430 nm
b. Green: 530 nm
c. Red: 560 nm

All colors are created by mixing the proper ratio of red, green and blue. Colors are assigned by the brain based on a comparison of the readout of the three cone types. White color results from equal activation of all three.

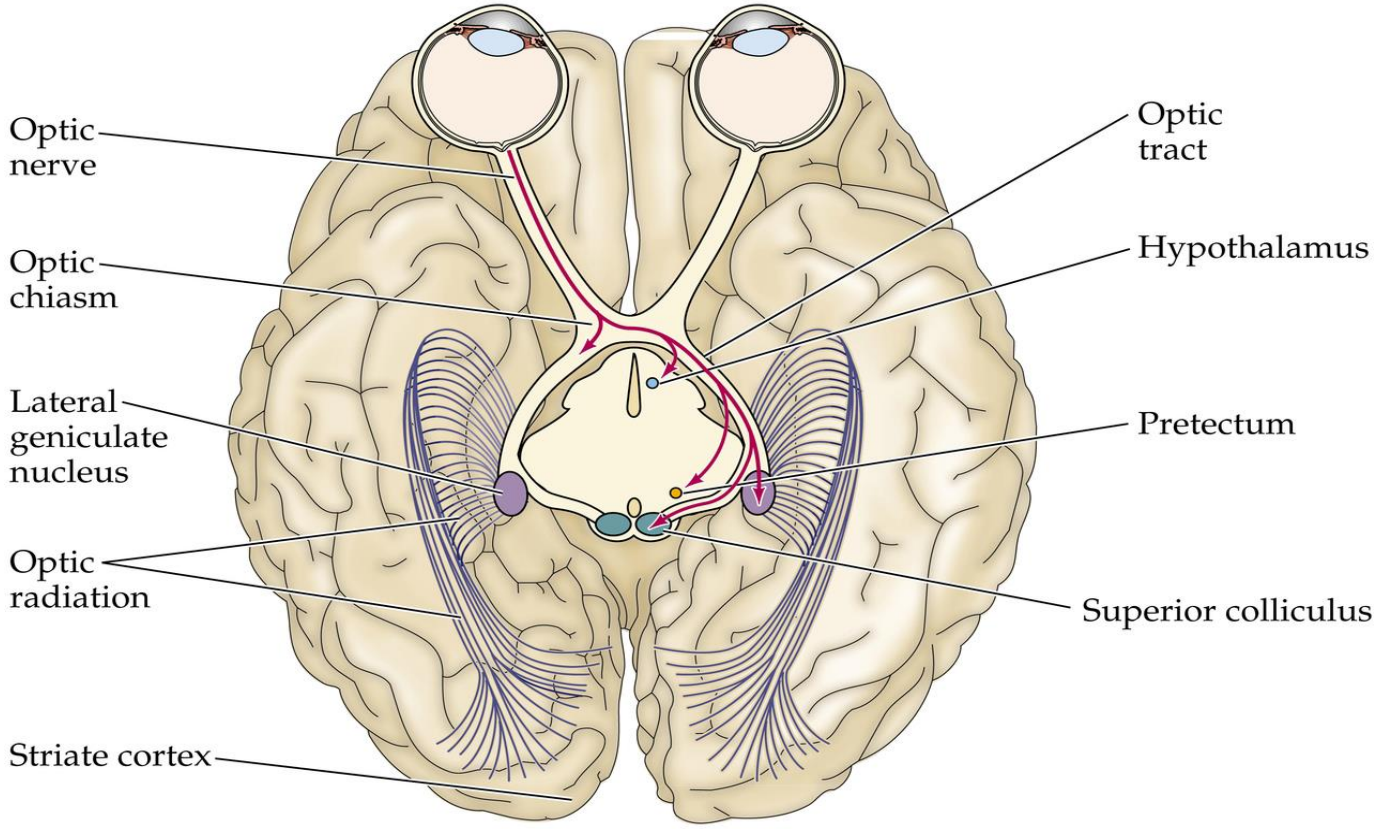
Axons of ganglion cells form the optic nerve. Light energy (or its absence) is transduced into a chemical signal. In response to dark, photoreceptors are depolarized and release NT (glutamate). Photoreceptors make synaptic contact with bipolar cells either directly or indirectly via horizontal cells. Bipolar cells, in response to the glutamate released by photoreceptors, are either depolarized or hyperpolarized. Based on their response to glutamate, bipolar cells can be classified as:

a. *OFF* cells ("off" refers to light being off) depolarize when there is no light. In darkness, the glutamate released by the photoreceptor causes an EPSP in the bipolar cell

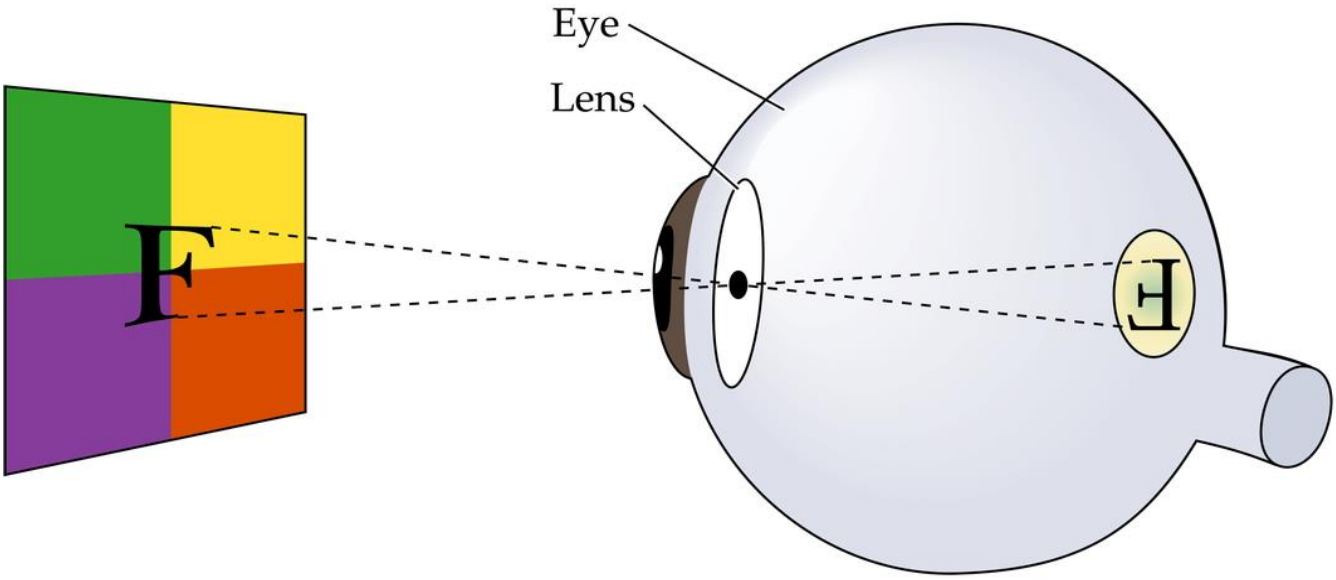
b. *ON* cells ("on" refers to light being on) hyperpolarize when there is no light (they depolarize when there is light). In darkness, the glutamate released by the photoreceptor causes an IPSP in the bipolar cell.

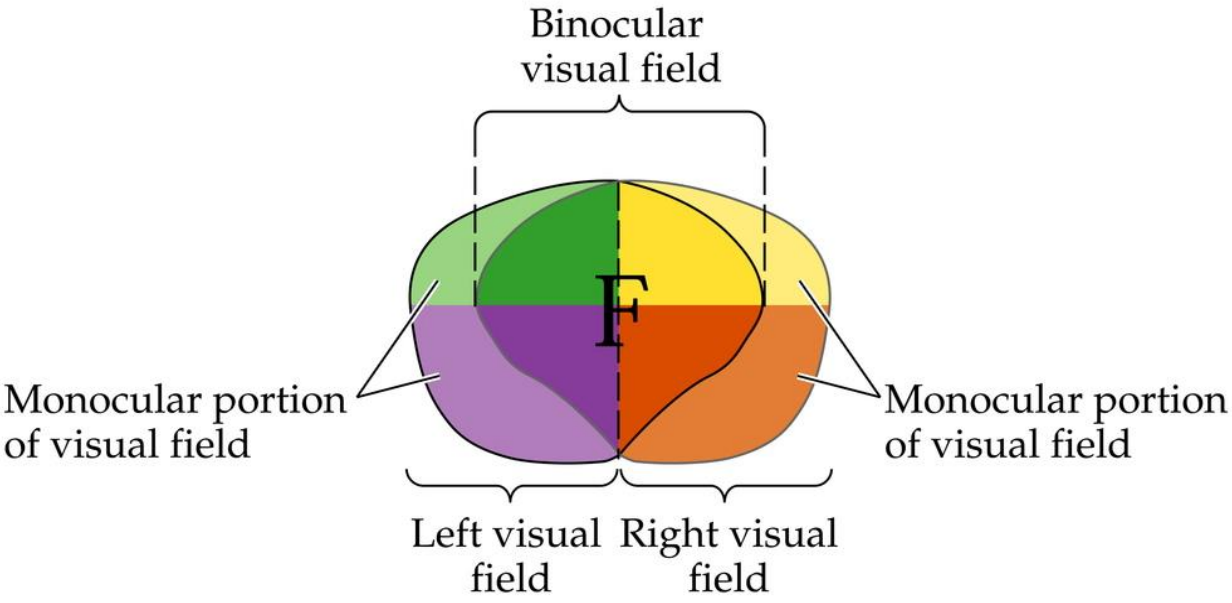
Neural Circuitry

From retina to optic nerve to optic chiasm (partial decussation) to optic tract to LGN (lateral geniculate nucleus of the thalamus) to primary visual cortex to other cortical areas.



Information from the visual fields crosses to the left side of the brain. Right and left eyes perceive parts of both visual worlds. Image is inverted and reversed





Audition

Audible variations in air pressure (compressions) result in molecules to be displaced forward leaving a corresponding area of lower pressure. Sound waves vary in two ways:

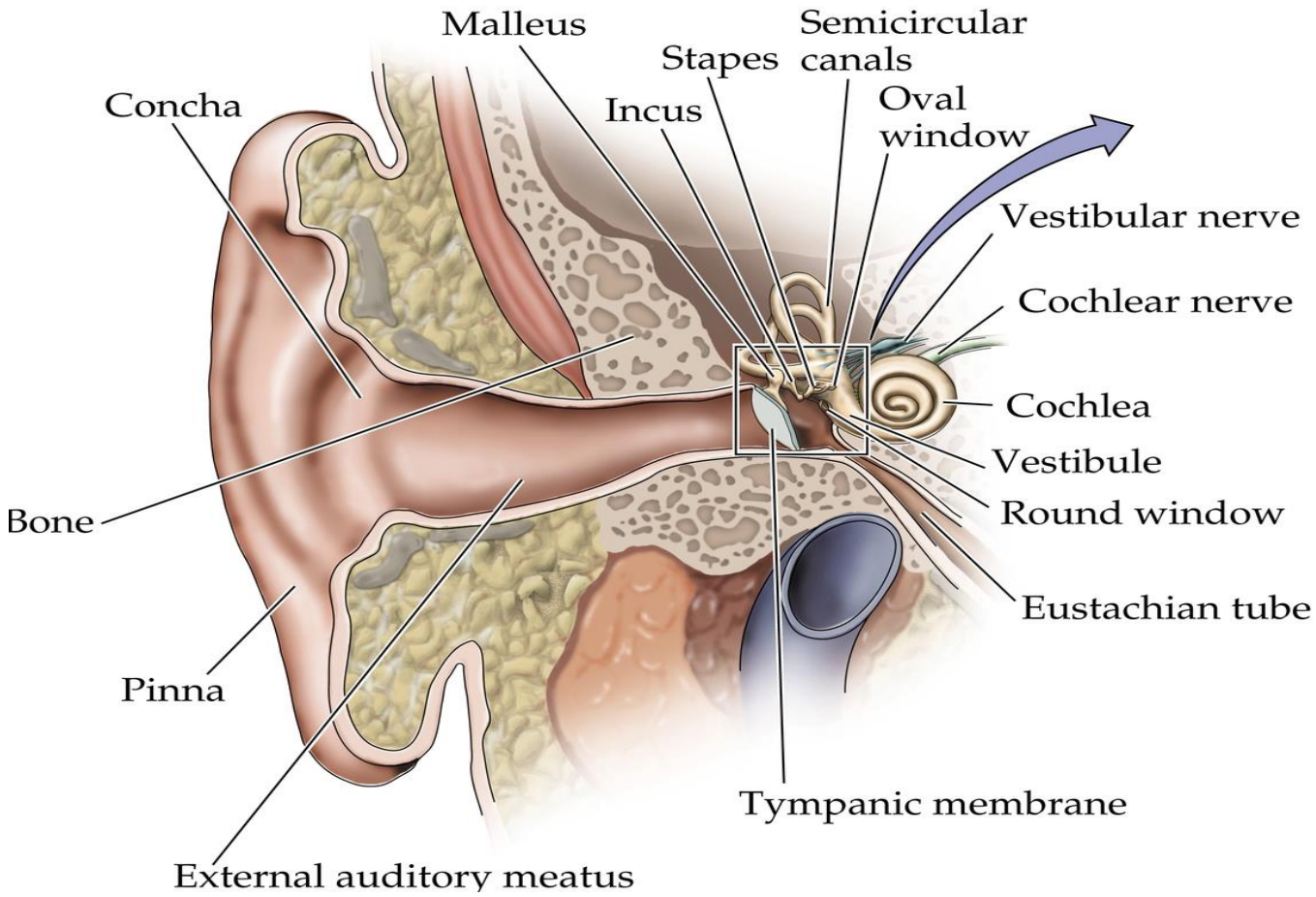
a. Amplitude or intensity: peak to trough; perceived as differences in loudness

b. Frequency or pitch: number of compressions per second, its unit is hertz (1 cycle/second)

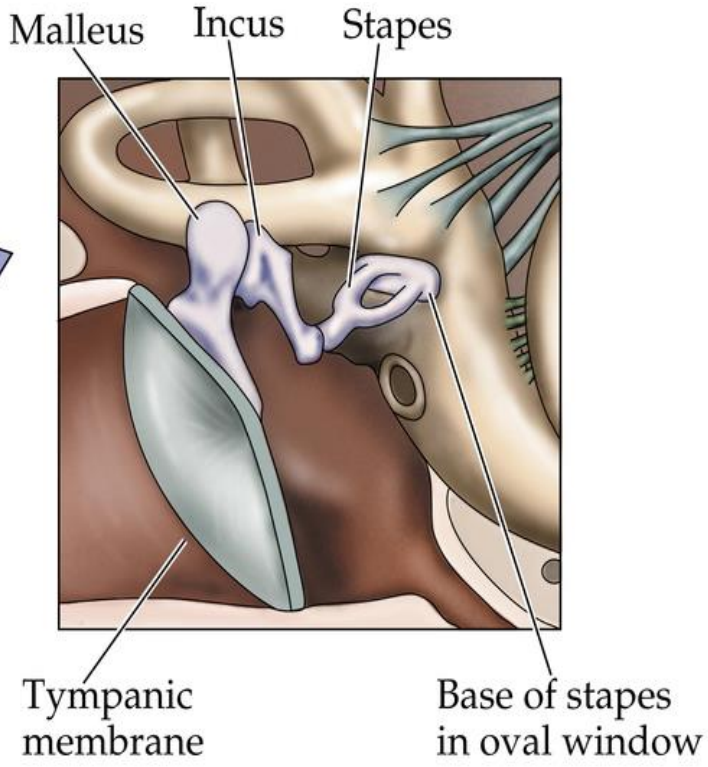
Structure of the Auditory System

There are three divisions of the ear: *Outer*, *middle* and *inner ears*. Outer ear involves *pinna* and *auditory canal*. Middle ear involves *tympanic membrane* and *ossicles*. Inner ear involves *cochlea, vestibule and semicircular canals*.

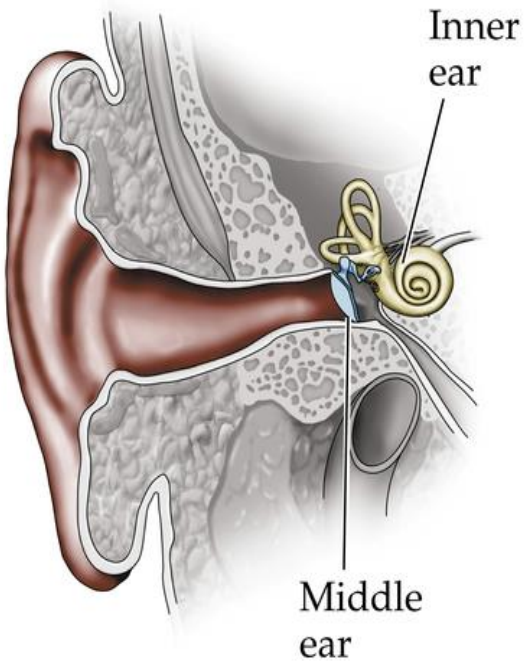
Pinna is a funnel shaped outer ear made of skin and cartilage. Auditory canal is a channel leading from the pinna to the tympanic membrane.



Tympanic membrane moves in response to variations in air pressure. Ossicles are series of bones in a small air filled chamber which transfer the movement of the tympanic membrane into the *oval window*. These ossicles are *malleus (hammer), incus (anvil) and stapes (stirrup). Eustachian tube* connects the air-filled middle ear to the pharynx. It contains a valve. With yawning or swallowing, the valve in the tube is opened and the pressure is relieved.



Cochlea is filled with an incompressible fluid. More force is required to displace fluid than air. Bones in the middle ear amplify the pressure (Pivot points act as fulcrums). Malleus is displaced in response to the movement of the tympanic membrane (bottom moves towards the inner ear and the top moves towards the outer ear). This pulls the top of the incus towards the outer ear and pushes the bottom towards the inner ear. Stapes is consequently pushed forward against the oval window which is compressed inward. Oval window is smaller and the same pressure across a smaller area results in a greater force.

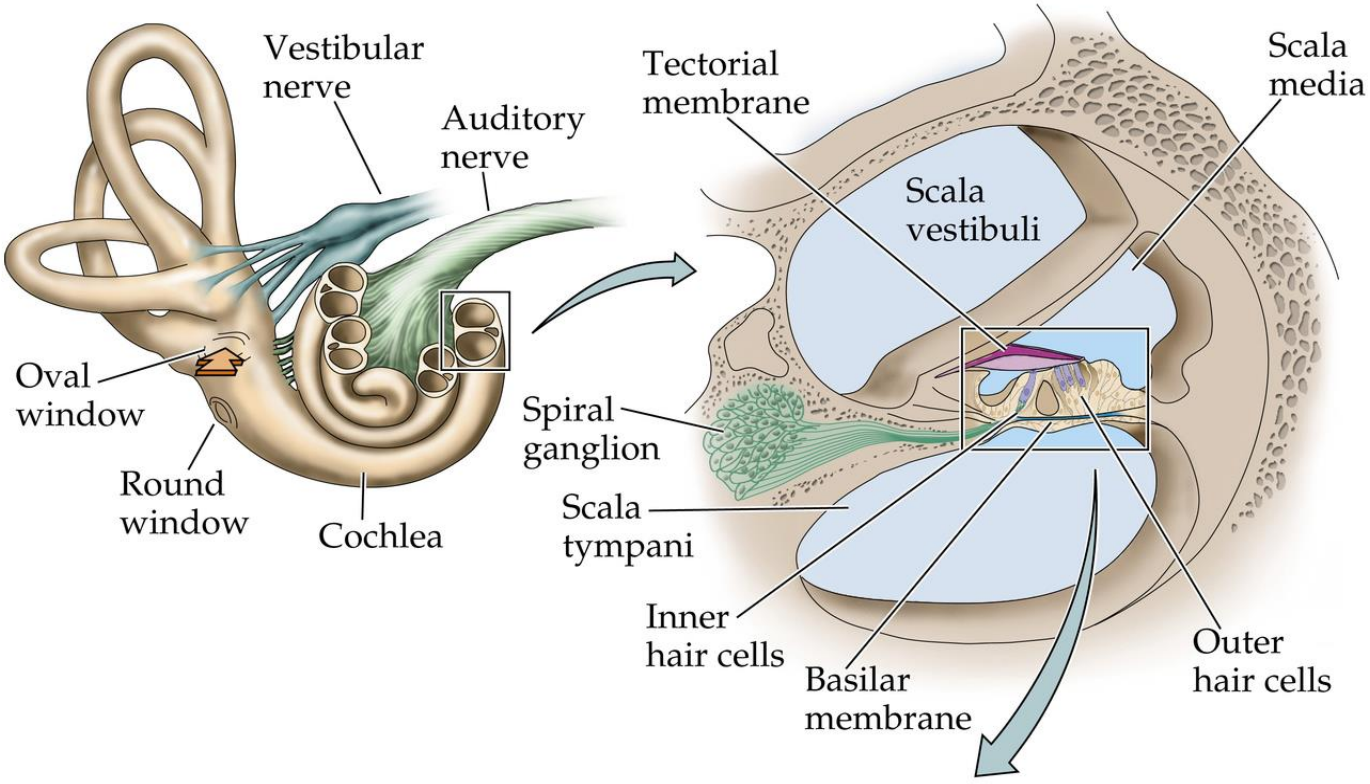


Inner ear converts the physical movement of the oval window into neural signal. This takes place in the cochlea. Vestibular apparatus is not part of the auditory system, instead, it is involved in balance

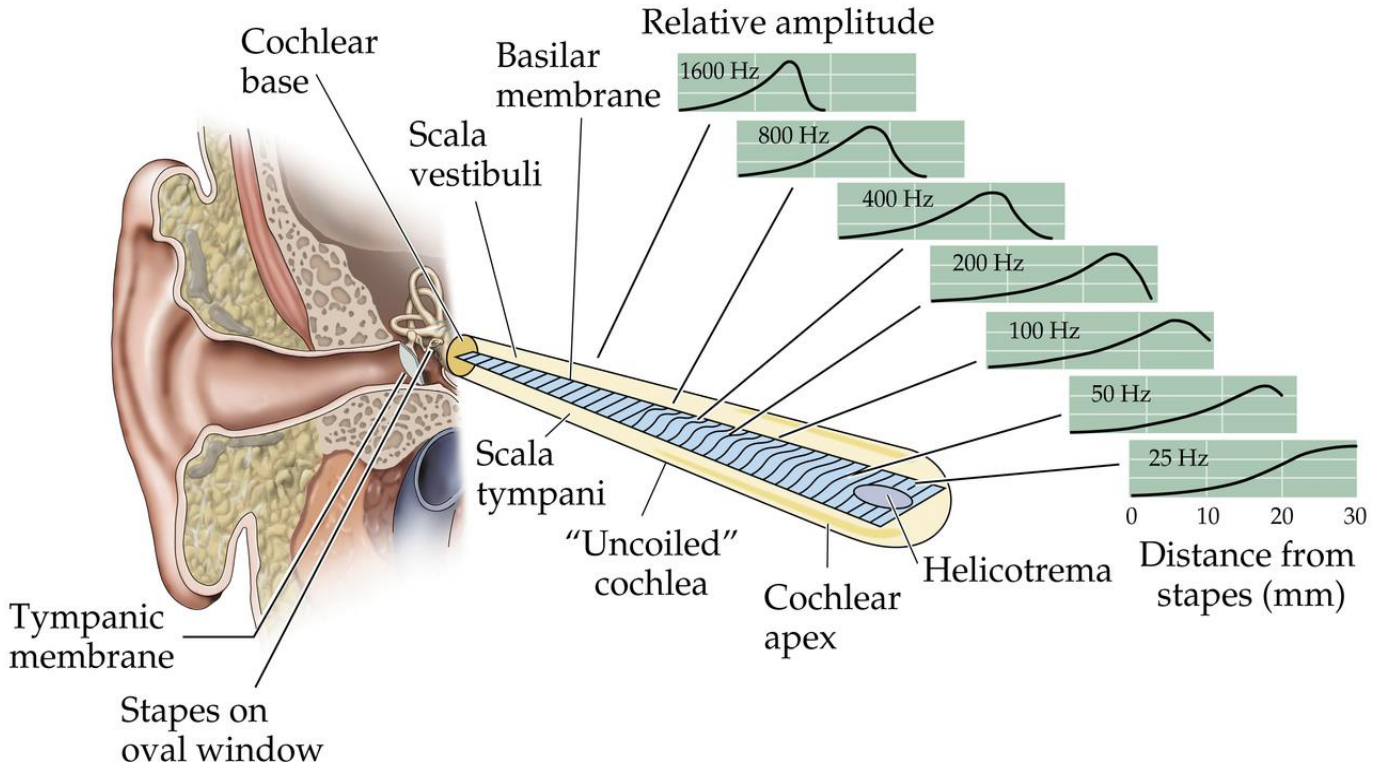
Processes involved in audition

1. Sound waves move the tympanic membrane.
2. Tympanic membrane moves the ossicles.
3. Ossicles move the membrane at the oval window.
4. Motion at the oval window moves the fluid in the cochlea.
5. Movement of the fluid in the cochlea causes a response in sensory neurons.
6. Signal is transferred and processed by a series of nuclei in the brain stem.
7. Information is sent to a relay in the thalamus **MGN** (medial geniculate nucleus).
8. MGN projects to the primary auditory cortex in the temporal lobe.

Cochlea transduces the mechanical displacement of the oval window into a neural signal. Its cross section reveals three chambers: *Scala vestibule, scala tympani* and *scala media*. *Basilar membrane* separates scala media and scala tympani. Fluid is continuous between scala vestibuli and scala tympani by physical connection known as the *helicotrema*. *Organ of corti* is located in the scala media and contains *auditory receptor cells*

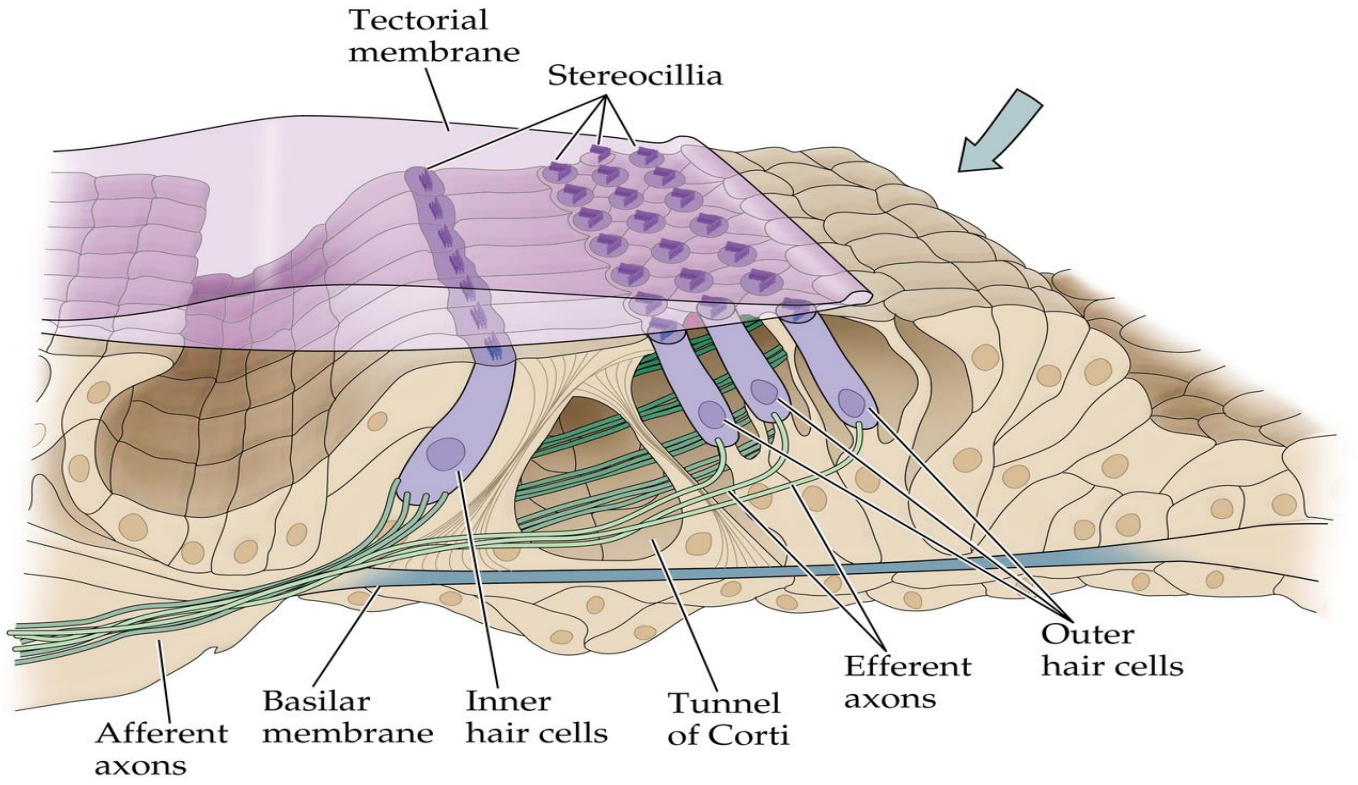


Mechanical force pushes on the oval window. The fluid within the cochlea is incompressible. So, it pushes forward conserving the wave properties of the sound (i.e. the movement of the fluid has frequency and amplitude) and causing the round window to bulge out. Basilar membrane is flexible and bends in response to sound. Structural properties of the basilar membrane determine the way it responds to sound. It is wider at apex than base (5:1). Its stiffness decreases from base to apex. High frequency sounds have higher energy and can displace the stiffer part of the basilar membrane (near the base). Lower frequency sounds have lower energy and displace the apex end. Basilar membrane establishes a place code in which different locations are maximally deformed in response to different frequency sounds

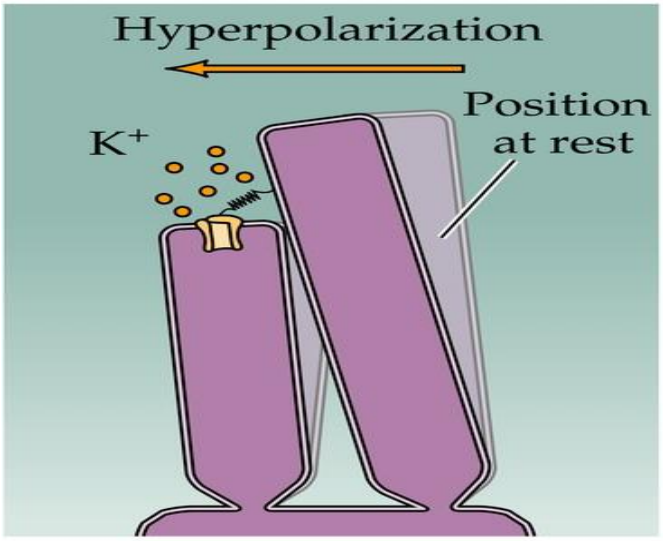


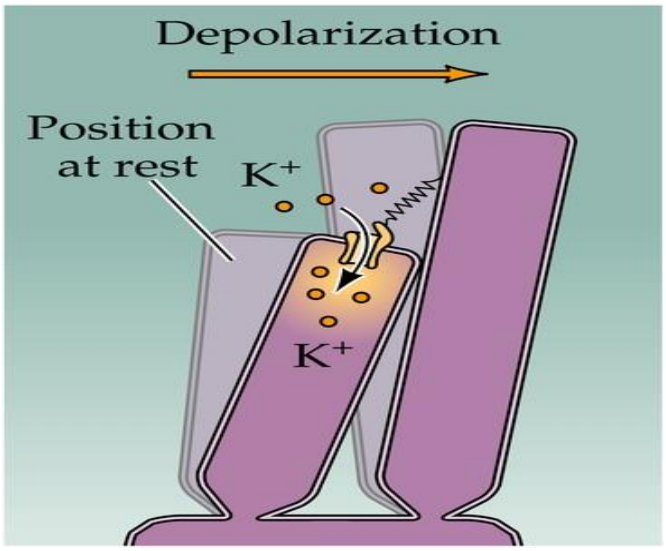
Organ of Corti

It is composed of: Outer hair cells, inner hair cells, tectorial membrane, reticular membrane, basilar membrane, stereocilia and spiral ganglion. The hair cells with stereocilia are the auditory receptors.



Bending of these cilia is the critical event in the transduction of sound into neural signal. Hairs extend above the reticular membrane and come in contact with the tectorial membrane. When the basilar membrane moves in response to the motion of the stapes, the whole complex moves as a unit either towards or away from the tectorial membrane. Lateral motion of the reticular membrane bends the stereocilia. Depending on the direction that the hairs bend, the inside of the hair cells will either depolarize or hyperpolarize. Changes in cell potential result from the opening of K^+ channels on the tips of the stereocilia. K^+ channels are mechanically gated with flaps that are connected to the neighboring cilia by a special protein molecule. Depending on the direction that the hairs bend, the channel will either be opened or closed. Opening the channel allows K^+ to enter and depolarize the hair cell. Closing the channel stops the flow of K^+. In response to be depolarization resulting from influx of K^+, Ca^{++} channel is activated. Influx of Ca^{++} causes the release of synaptic vesicles from the end of the hair cell.

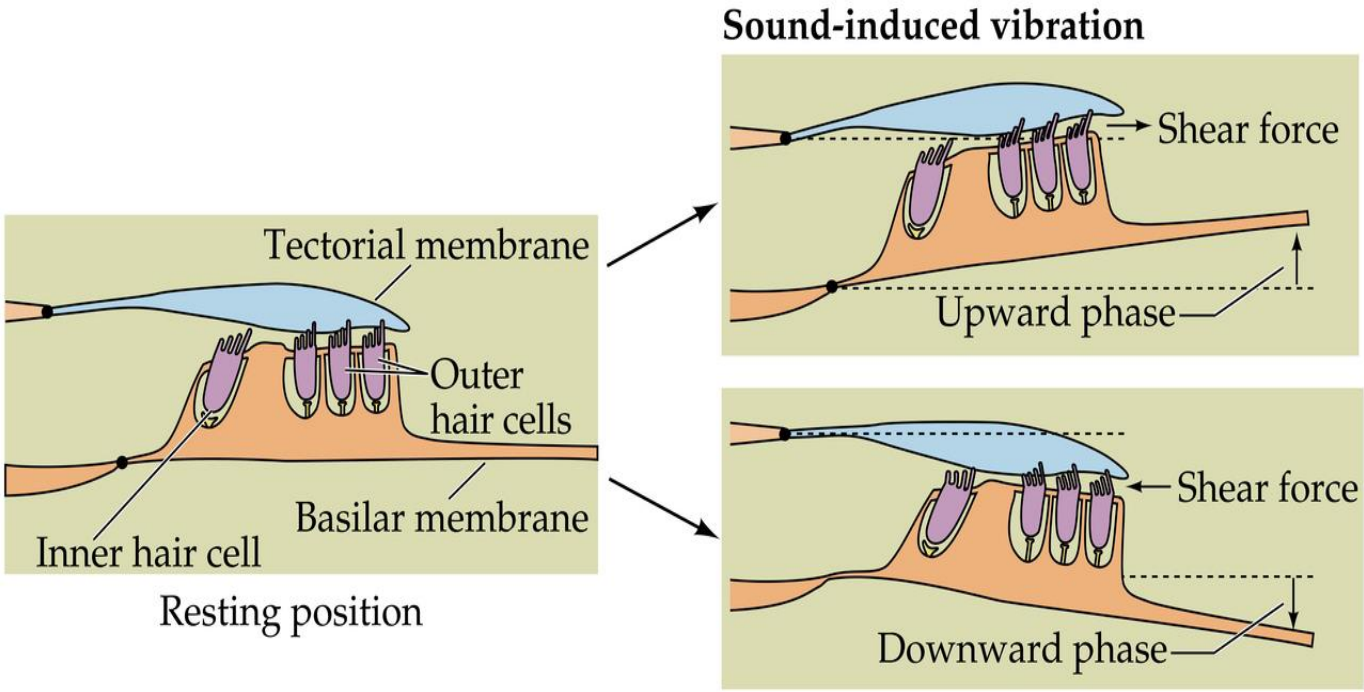




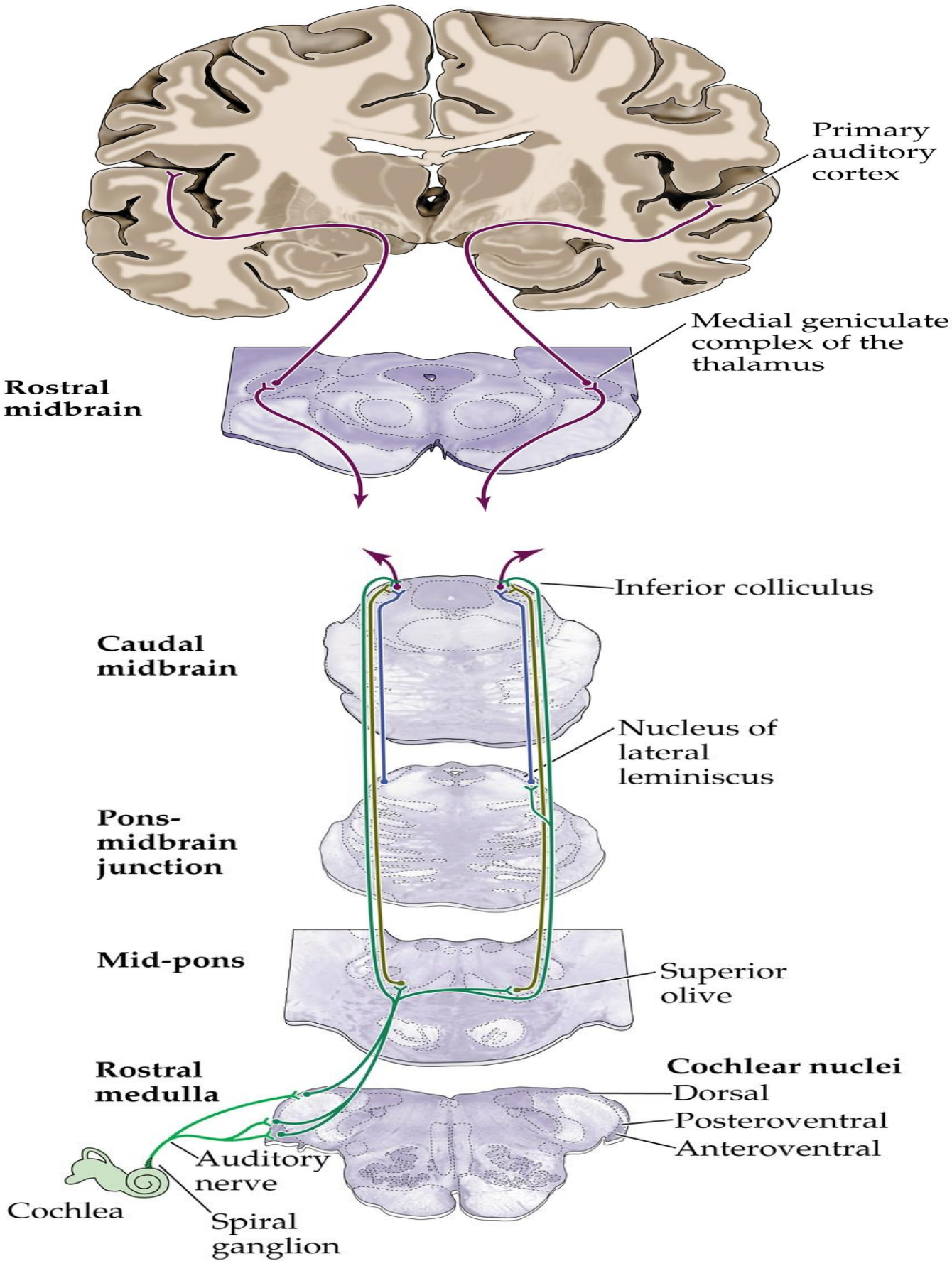
Action potential occurs at the level of the output ganglion. Multiple outer hair cells make synaptic contact with a single ganglion cell while many ganglion cells can contact the same inner hair cell. Ganglion cell makes synaptic contact with a single inner hair cell.

75% of all hair cells are outer hair cells. Outer alter the stiffness of the tectorial membrane and Only 5% of the fibers in the auditory nerve are from outer hair cells.

Perception of *intensity of sound depends on firing rate of individual hair cells and activation of multiple hair cells*. while perception of *frequency is a consequence of the mechanics of the basilar membrane* (different portions of the basilar membrane are maximally deformed by sound of different frequencies).



Summarized audition circuitry



Chemical Senses

Taste and olfaction are the most familiar chemical senses. There are many types of chemically sensitive cells called chemoreceptors which are distributed throughout the body and report subconsciously and consciously about our internal state. These types are:

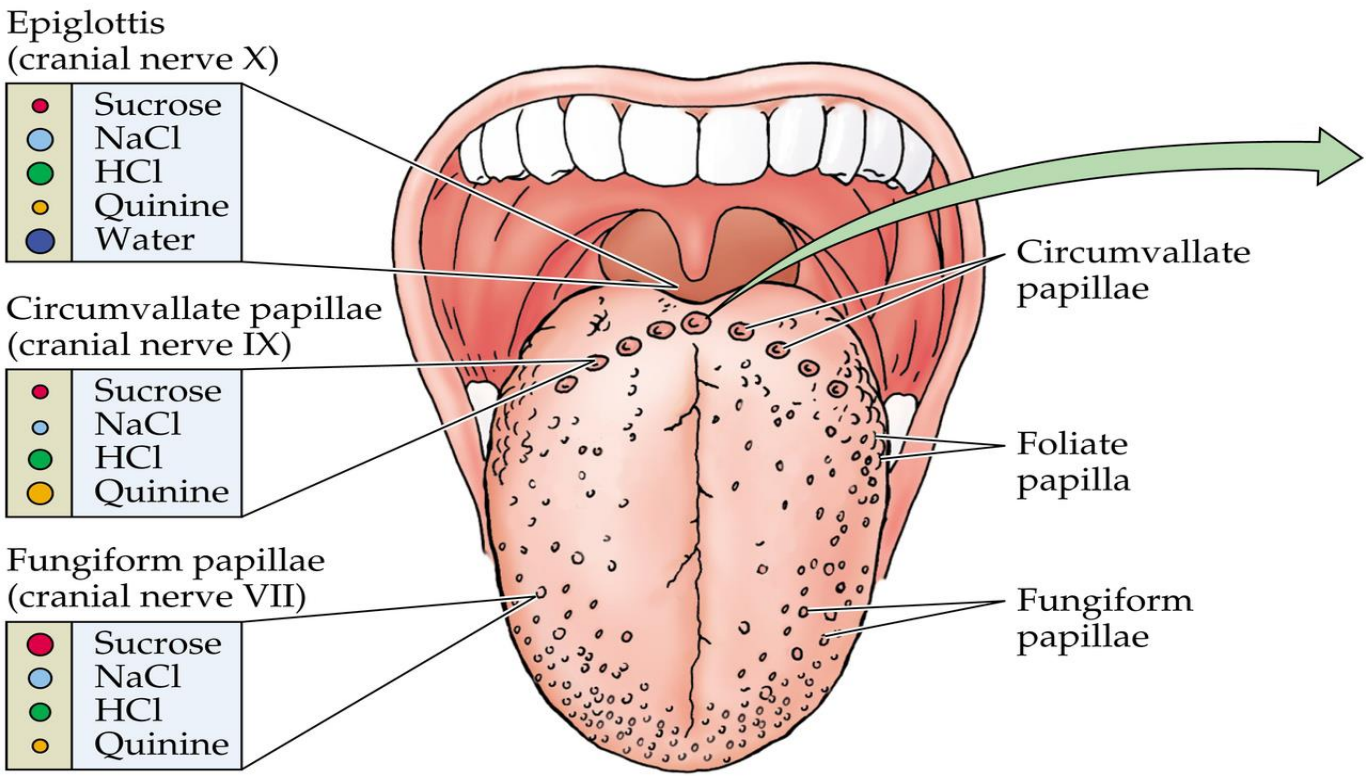
1. Chemoreceptors in skin and mucus membranes warn us about irritating chemicals.
2. Nerve endings in the digestive organs detect many types of ingested substances that cause discomfort, activate vomiting reflexes, etc.
3. Chemical receptors in the arteries in the neck measure CO_2 and O_2 levels in the blood.
4. Sensory endings in the muscles respond to acidity (burning sensation)

Taste (Gustation) and smell (Olfaction) have similar tasks
1. Detection of environmental chemicals
2. Both are required to perceive flavor
3. Both have strong and direct connections to our most basic needs (thirst, hunger, emotion, sex, and certain forms of memory)
4. Systems are separate and different and only merge at higher levels of cortical function. They:
    a. Have different chemoreceptors
    b. Use different transduction pathways
    c. Have separate connections to the brain
    d. Have different effects on behavior

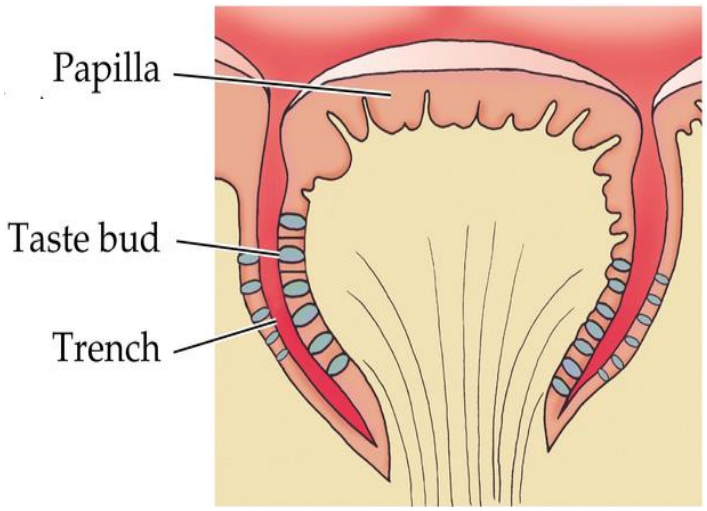
Gustation

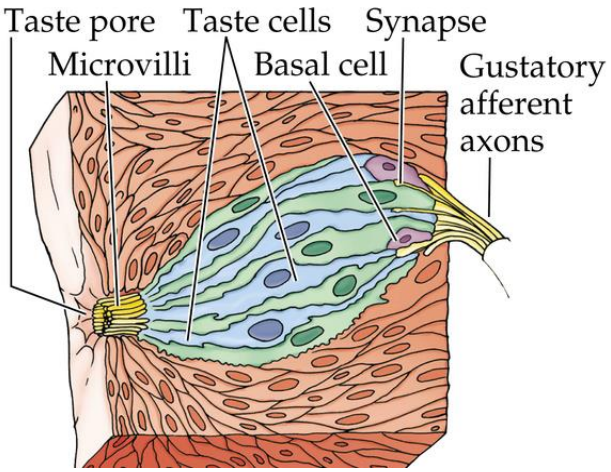
Basic categories of tastes are: *1. Salty, 2. Sour, 3. Sweet and 4. Bitter*. Each food activates a different combination of basic tastes. Most foods have a distinctive flavor as a result of their taste and smell occurring simultaneously. Other sensory modalities may contribute to a unique food-tasting experience like texture, temperature, pain sensitivity (some hot and spicy flavors are actually a pain response). Organs of taste are tongue, pharynx and palate (epiglottis have some sensitivity). Nasal passages are located so that odors can enter through the nose or pharynx and contribute to the perception of flavor

Tongue



Tongue is the primary organ of taste. Most of which is receptive to all basic tastes but some regions are most sensitive to a given taste. Receptors for bitter tastes are located across its back, sour on side closest to the back, salty on side more rostral than sour and sweet across front. There are several types of small projections called papillae. Each papilla has one to several hundred taste buds. Each taste bud has 50-150 taste cells. Taste cells are only 1% of the tongue epithelium. Taste receptor cells are not neurons. They form synapses with the endings of gustatory afferent axons near the bottom of the taste bud.

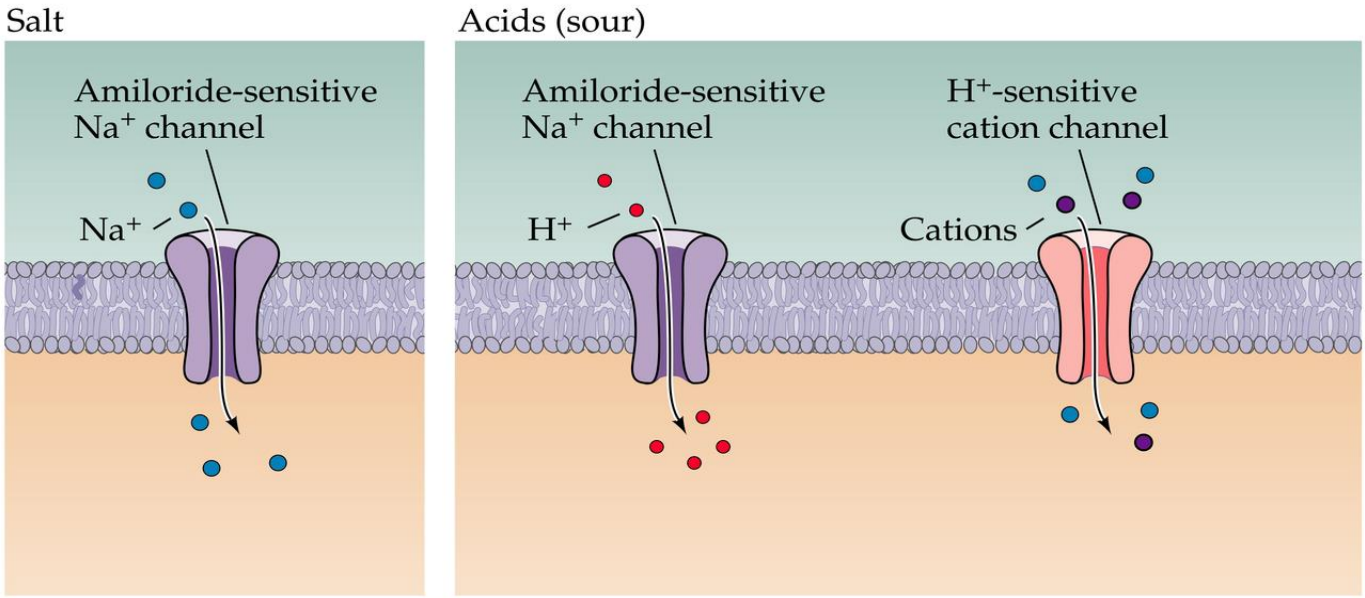




Gustatory Transduction

When taste receptor is activated by the appropriate chemical, its membrane potential changes. Depolarizing receptor potential cause Ca^{++} to enter the cytoplasm and trigger the release of NT. Taste stimuli may:

a. Pass directly through an ion channel (salt and sour)
b. Bind to and block ion channels (sour and bitter)
c. Bind to and open ion channels (some sweet amino acids)
d. Bind to membrane receptors that activate 2nd messenger systems that in turn open or close ion channels (sweet and bitter)



Salt

1. Na^+ flows down a concentration gradient into the taste receptor cell (most salts are Na^+ salts: NaCl)
2. Na^+ increase within the cell depolarizes the membrane and opens a voltage dependent Ca^{++} channel
3. Ca^{++} increase causes the release of NT

Sour

1. Foods that are sour have high acidity (low pH)
2. H^+ ions pass through the same channel that Na^+ does
3. H^+ also blocks a K^+ channel
4. Net movement of + into the cell depolarizes the taste cell
   a. Opens a Ca^{++} channel
   b. Causes NT release

Sweetness

1. Molecules that are sweet bind to specific receptor sites and activate a cascade of 2nd messengers in certain taste cells
2. Molecules bind receptor
3. G-protein activates an effector enzyme adenylate cyclase (cAMP produced)
4. cAMP causes a K^+ channel to be blocked
5. Cell depolarizes
6. Ca^{++} channel opens and Ca^{++} in
7. NT released

Bitter

Chemicals in the environment that are deleterious often have a bitter flavor. Senses have evolved primarily to protect and preserve. Ability to detect bitter has two separate mechanisms which may be attributed to this evolutionary pressure.

System I

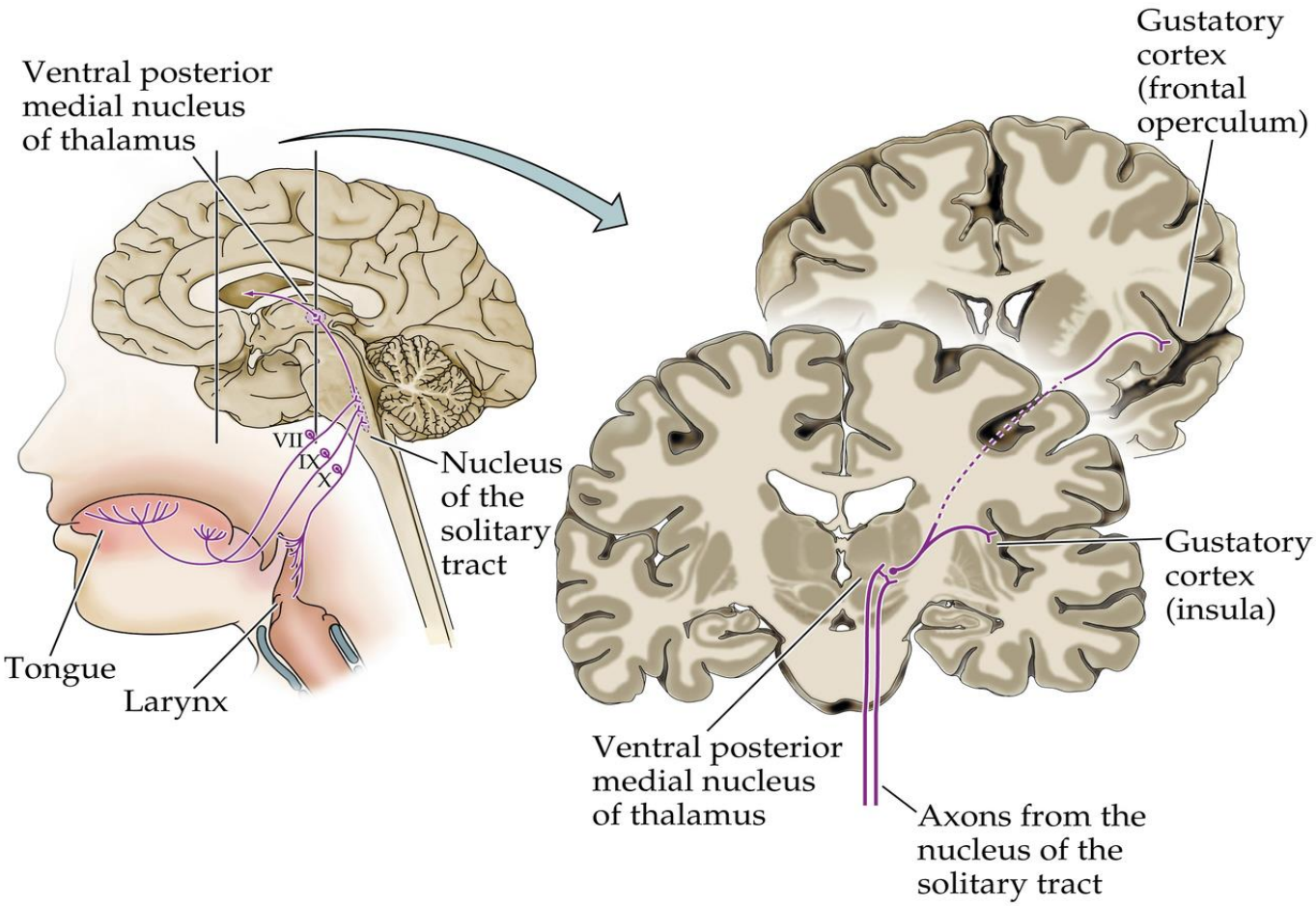
a. Bitter tastants can directly block a K^+ channel (same transduction mechanisms as acids)
b. Cell depolarizes
c. Ca^{++} channel is opened and Ca^{++} in
d. NT released

System II

a. Bitter tastant binds bitter receptor
b. G-protein activates an effector enzyme-phospholipase C
c. Ca^{++} is released from intracellular storage
d. Ca^{++} increase causes NT release

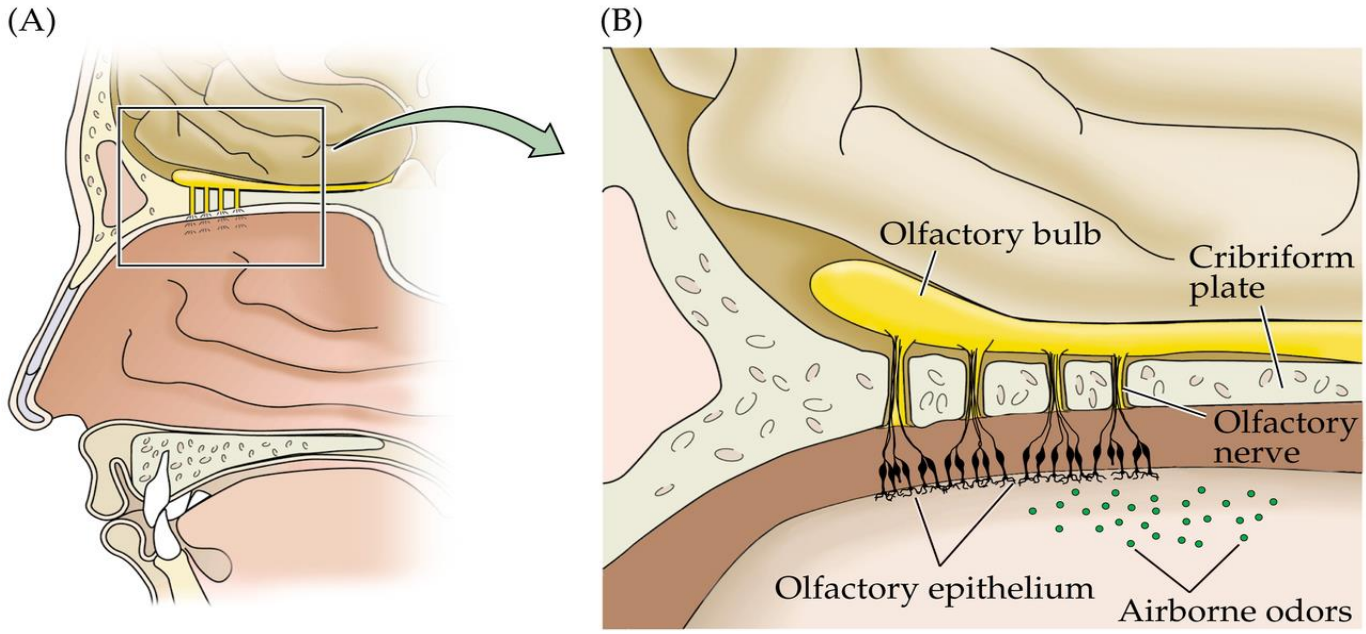
Taste Neural Pathway

1. NT release from taste cells causes an AP in the gustatory afferent axon
2. Three different cranial nerves (VII, IX and X) innervate the taste buds and carry taste information from the tongue, palate, epiglottis and esophagus. Efferent target of this information is gustatory nucleus in the medulla.
3. Information is relayed to the thalamus
4. Information then goes to the primary gustatory cortex (parietal lobe)



Olfaction

Olfaction is a sense of smell. As many as 100,000 unique odors can be discriminated and 80% of which are noxious. Odors perceived to be noxious are often deleterious (rotting meat, etc.). Olfactory epithelium is the organ of smell *not the nose*. Olfactory epithelium is a thin sheet of cells high up in the nasal cavity. Size of the olfactory epithelium is proportionate to olfactory acuity. Man has 10 cm^2 while dog has 170 cm^2. Dogs also have 100 times receptors per cm^2 more than man.



Olfactory receptors are neurons, which fire action potentials. They are the only neurons in the nervous system that are replaced regularly (every 4-8 weeks) throughout life. They are continuous with the CNS. Ends of the olfactory receptors are a mucus (water-soluble) which contains cells of the immune system and is shed every ten minutes (individual with an infection like cold, flu, etc. has a runny nose where mucus is shed more frequently to protect the olfactory receptors from infection). There are 500-1000 different odor-binding proteins. Each olfactory receptor cell expresses only one type of binding protein. The receptor is G-protein-coupled:

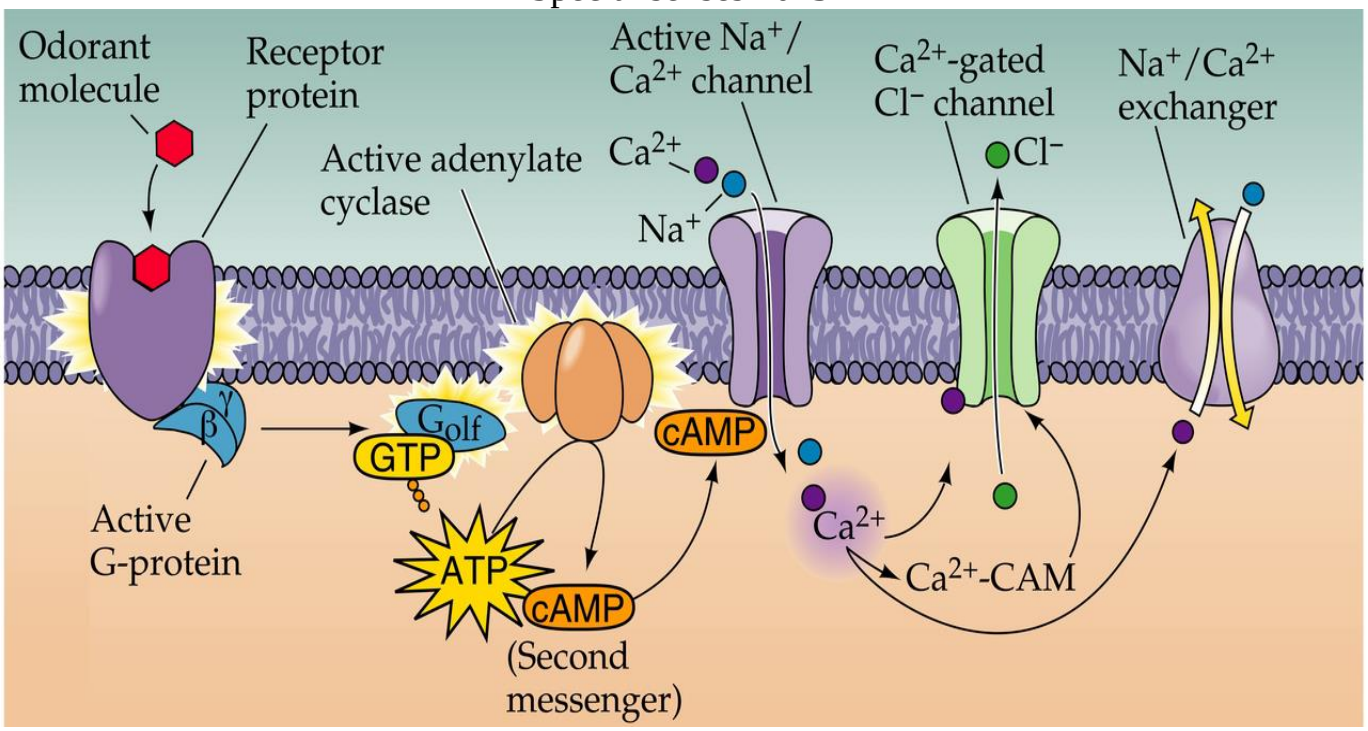
a. Receptor binding activates an effector enzyme (either adenylate cyclase or phospholipase C, depending on the nature of the odorant)

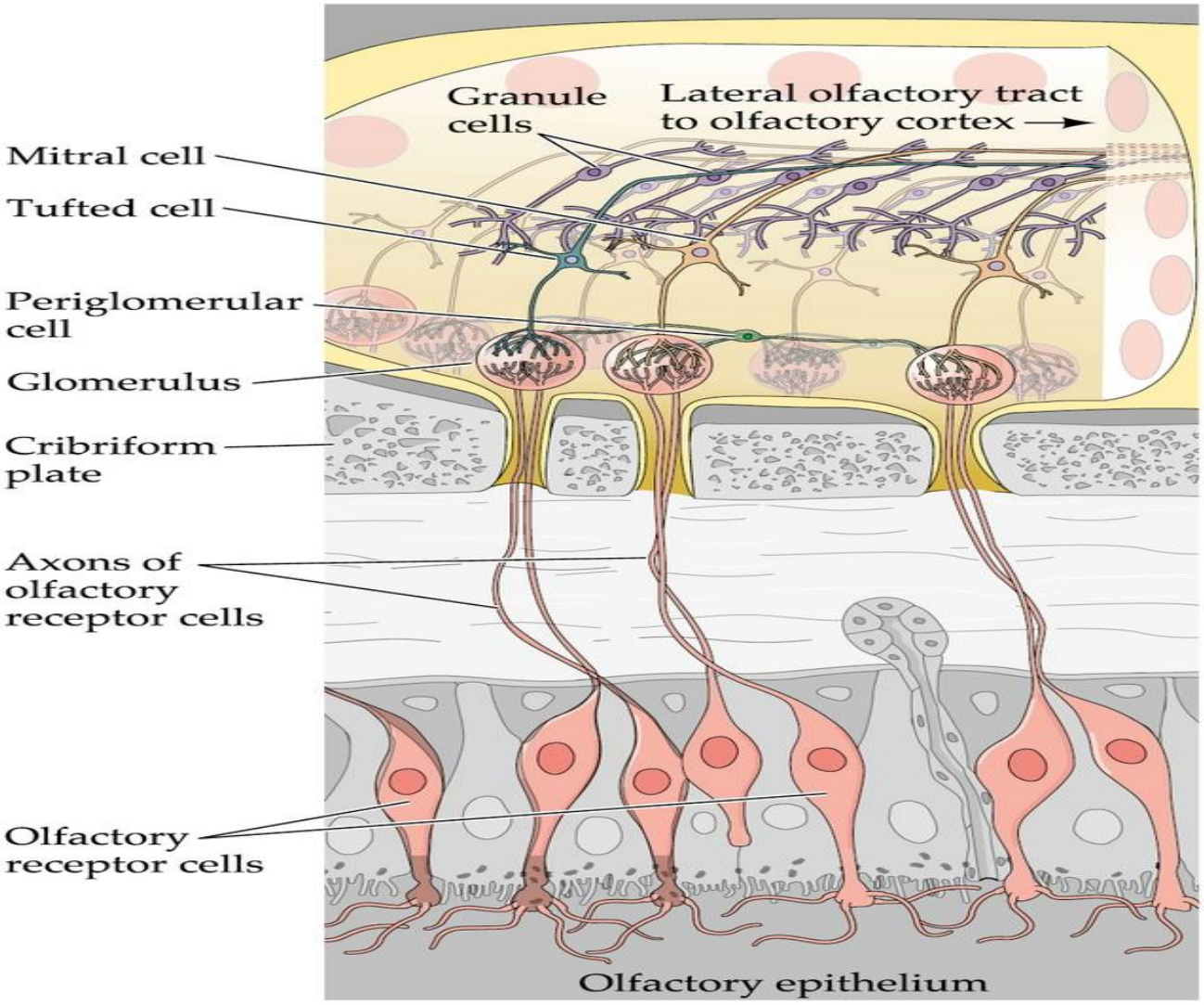
b. 2nd messenger (cAMP or IP3) opens a Ca^{++} channel

c. Ca^{++} influx does not cause NT release. It opens a Cl- channel

d. Cl- leaves the cell and the membrane is depolarized

e. Sufficient depolarization causes an AP results


Odorant molecule
Receptor protein
Active adenylate cyclase
Active Na+/ Ca2+ channel
Ca2+
Na+
Ca2+-gated Cl− channel
Cl−
Na+/Ca2+ exchanger
β
γ
Golf
GTP
cAMP
Active G-protein
ATP
cAMP
(Second messenger)
Ca2+
Ca2+-CAM


Granule cells
Lateral olfactory tract to olfactory cortex
Mitral cell
Tufted cell
Periglomerular cell
Glomerulus
Cribriform plate
Axons of olfactory receptor cells
Olfactory receptor cells
Olfactory epithelium

Olfactory Pathway

Projects directly to the cortex. Cortex then projects to the thalamus and other cortical structure. Olfactory receptor cell axons leave the olfactory epithelium, coalesce to form a large number of bundles (together this is the olfactory nerve, cranial nerve I) which run directly into the olfactory bulb. In the olfactory bulb, primary synapses between the olfactory receptor axons and mitral cells (the projection neuron of the olfactory system). Glomeruli are spherical arrangement of mitral cells. Within the bulb, there are a number of other cells that contribute to the formation of special circuits for processing olfactory information (e.g., granule and periglomerular cells).

Axons of the mitral cells form a bundle known as the lateral olfactory tract which projects primarily to the pyriform cortex. Minority projections to the accessory olfactory nuclei, the olfactory tubercle, the entorhinal cortex, and the amygdala. Pyramidal cells in the pyriform cortex in turn project to the thalamus, neocortical regions, the hippocampus and the amygdala