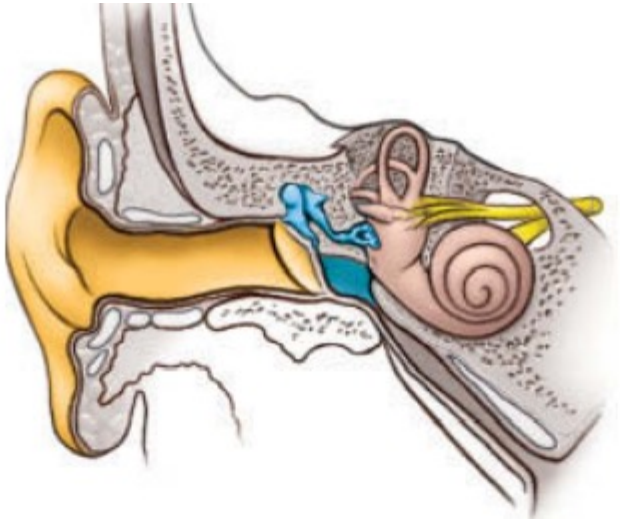
Neurophysiology

Vestibular system

Fatima Ryalat, MD, PhD



The inner ear contains two systems for sensory processing:

1. Hearing
2. Equilibrium (balance)⇒ vestibular system

Equilibrium

- The ear not only detects sound, but also changes in equilibrium or balance.

- Body movements that stimulate the receptors for equilibrium include linear acceleration or deceleration, and rotational (angular) acceleration or deceleration.

- The receptor organs for equilibrium are called the vestibular apparatus; these include the utricle and saccule of the vestibule and the semicircular ducts of the semicircular canals.

Vestibular apparatus

- It is encased in a system of bony tubes and chambers located in the petrous portion of the temporal bone, called the bony labyrinth.

- Within this system are membranous tubes and chambers called the membranous labyrinth.

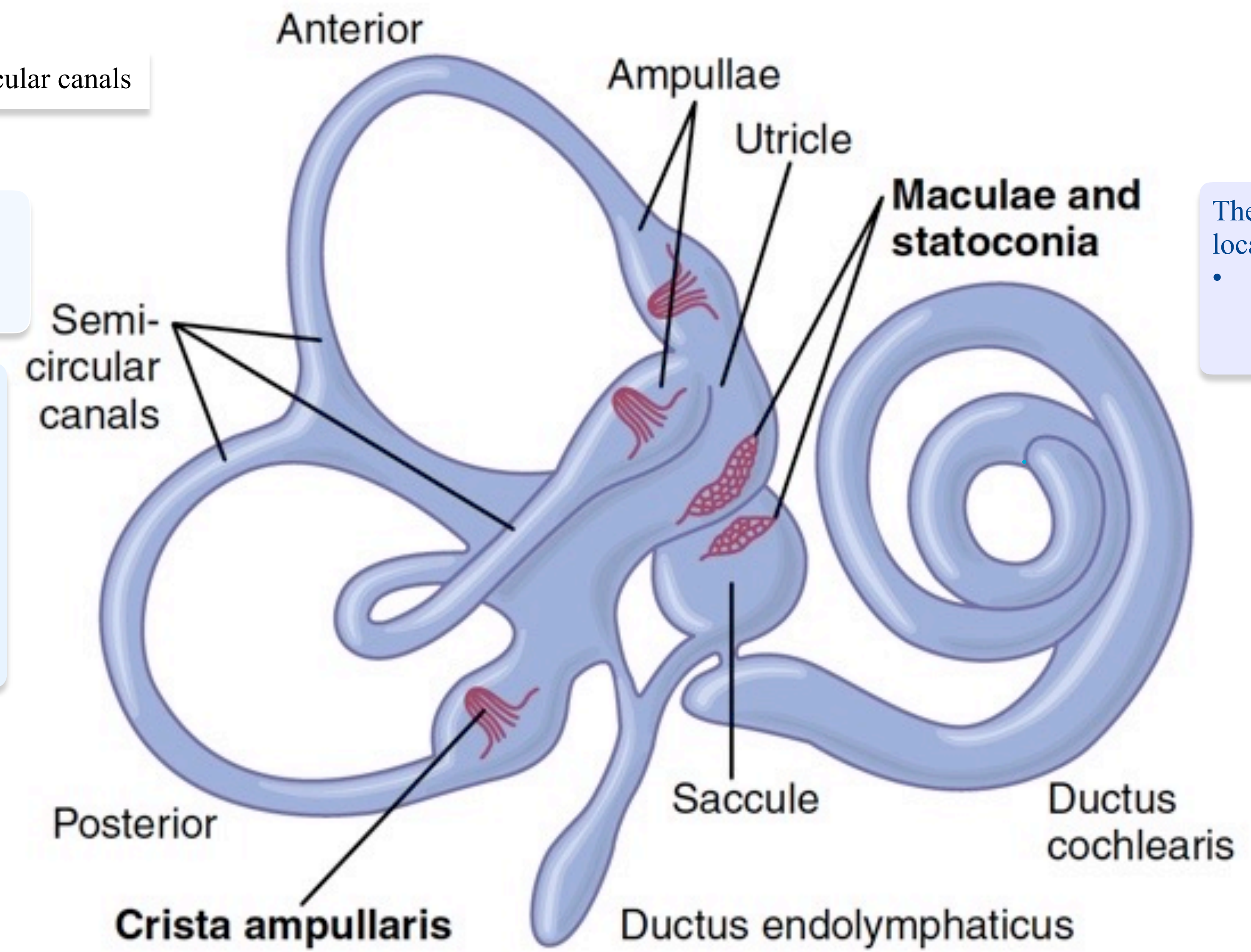
- The membranous labyrinth is the functional part of the vestibular apparatus.

In General, the vestibular system is divided into :

- Otolithic organs
- Semicircular canals

In each labyrinth, there are three semicircular canals that are oriented perpendicular to each other in three dimensions (3D).

The vestibular and cochlear systems are connected through the shared endolymphatic fluid in the cochlear duct.
If there are issues with the endolymph, such as balance problems, it can also lead to hearing problems



MEMBRANOUS LABYRINTH

The **maculae** are sensory structures located within the utricle and saccule.

- Each inner ear contains two maculae: the utricular macula and the saccular macula (otolithic organs)

Otolithic Organs: Utricle and Saccule

- Attached to the inner walls of both the utricle and the saccule is a small, thickened region called the macula.

- The two maculae contain the receptors for linear acceleration or deceleration and the position of the head.

These two structures detect the position of the **head**

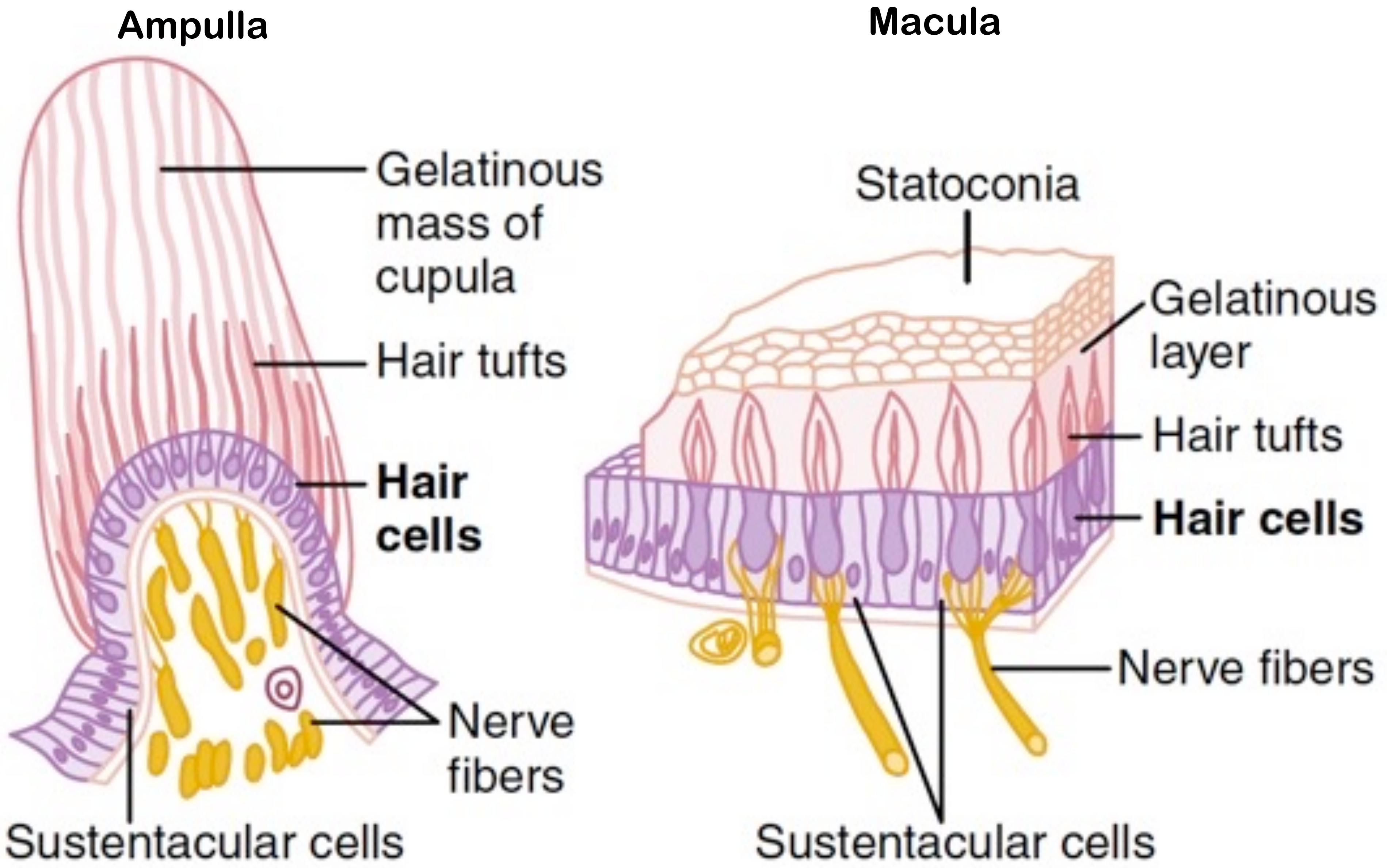
- The maculae consist of two types of cells: hair cells, which are the sensory receptors, and supporting cells.

Utricle and Saccule

- Supporting cells secrete the thick, gelatinous, glycoprotein layer, called the otolithic membrane, that rests on the hair cells.

- Each macula is covered by a gelatinous layer in which many small calcium carbonate crystals called statoconia (otolith) are embedded.

- Also in the macula are thousands of hair cells. these hair cells project cilia up into the gelatinous layer.



CRISTA AMPULLARIS AND MACULA

Statoconia (otolith) غُبار التَّوازن

- The bases and sides of the hair cells synapse with sensory endings of the vestibular nerve.

- The calcified statoconia have a specific gravity two to three times the specific gravity of the surrounding fluid and tissues.

Due to the higher specific gravity of the otoliths, they exert a greater force under the influence of gravity than the surrounding fluid and tissues. This difference in weight allows the otoliths to move within the utricle and saccule, stimulating sensory hair cells that are connected to them.

These otoliths enhance the macula's ability to detect linear acceleration by adding mass and inertia to the system.

- **Inertia** (القصور الذاتي) refers to the tendency of an object to resist changes in its state of motion (Newton's 1st law)

Otolithic Organs: Utricle and Saccule

- The maculae of the utricle and saccule are perpendicular to one another.

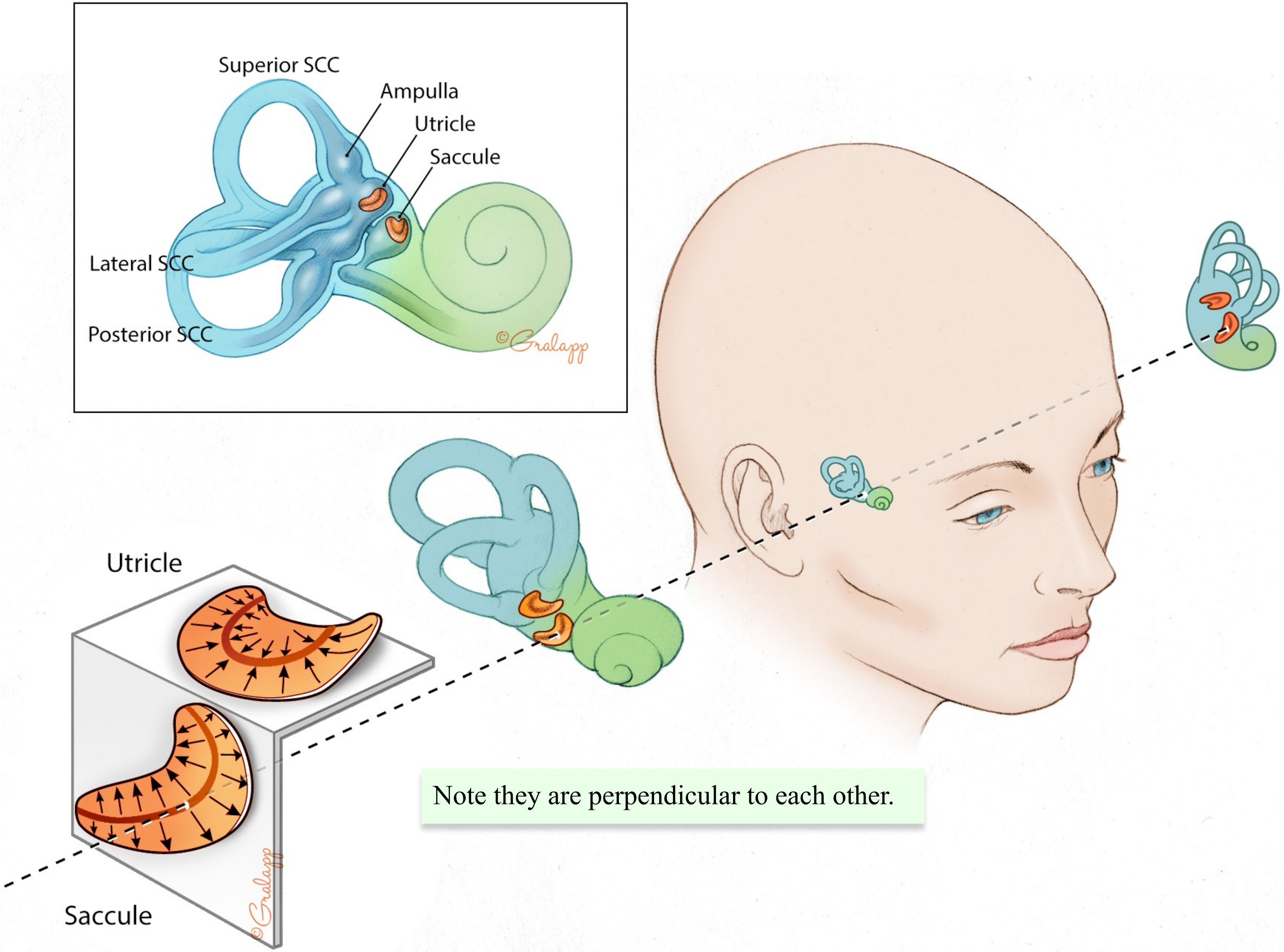
- When the head is in an upright position, the macula of the utricle is oriented horizontally, and the macula of the saccule is oriented vertically.

For upright position

For laying down position**

- Because of these orientations, the utricle and saccule have different functional roles.

The utricle primarily detects horizontal linear acceleration, while the saccule primarily detects vertical linear acceleration,
**it would be more accurate to say that the saccule detects vertical linear acceleration rather than for the laying down position ^^



Note they are perpendicular to each other.

Maculae

- The macula of the utricle plays an important role in determining the orientation of the head when the head is upright.

- Conversely, the macula of the saccule signals head orientation when the person is lying down.

Maculae

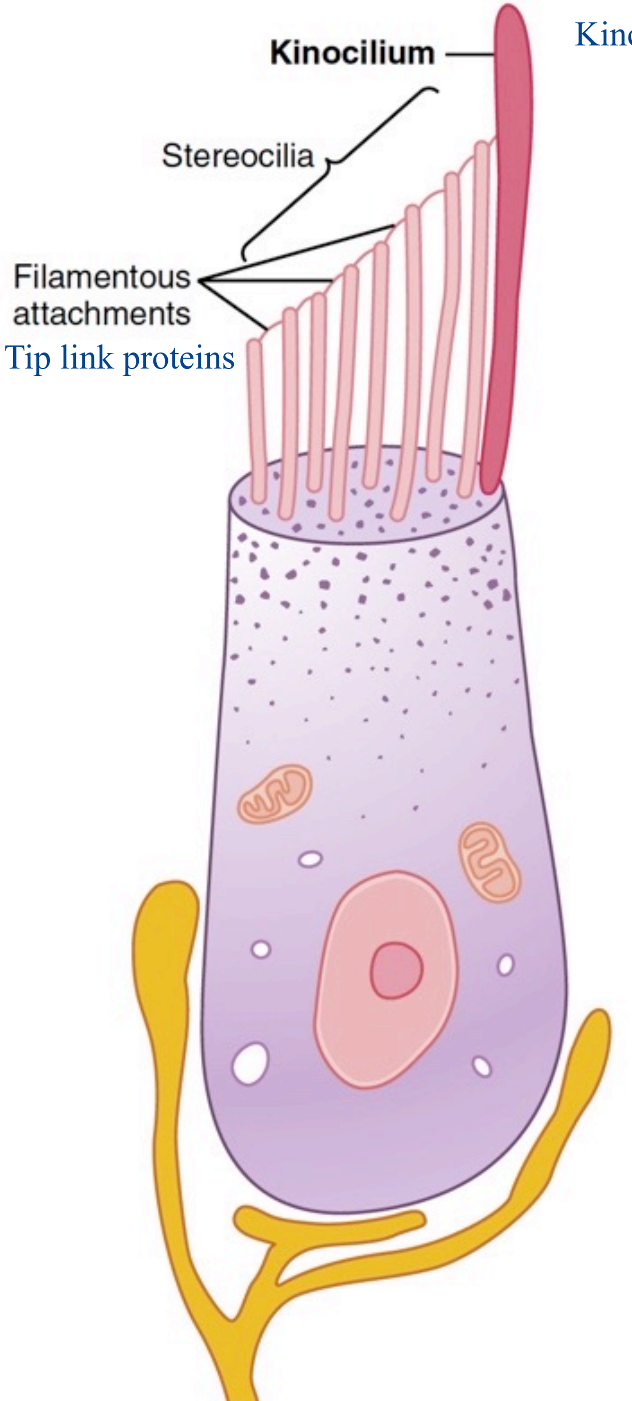
- The hair cells are all oriented in different directions in the maculae of the utricles and saccules so that with different positions of the head, different hair cells become stimulated.
- The “patterns” of stimulation of the different hair cells apprise the brain of the position of the head with respect to the pull of gravity.
- In turn, the vestibular, cerebellar, and reticular motor nerve systems of the brain excite appropriate postural muscles to maintain proper equilibrium.

Tip links, which are filamentous proteins, attach to potassium (K^+) channels.

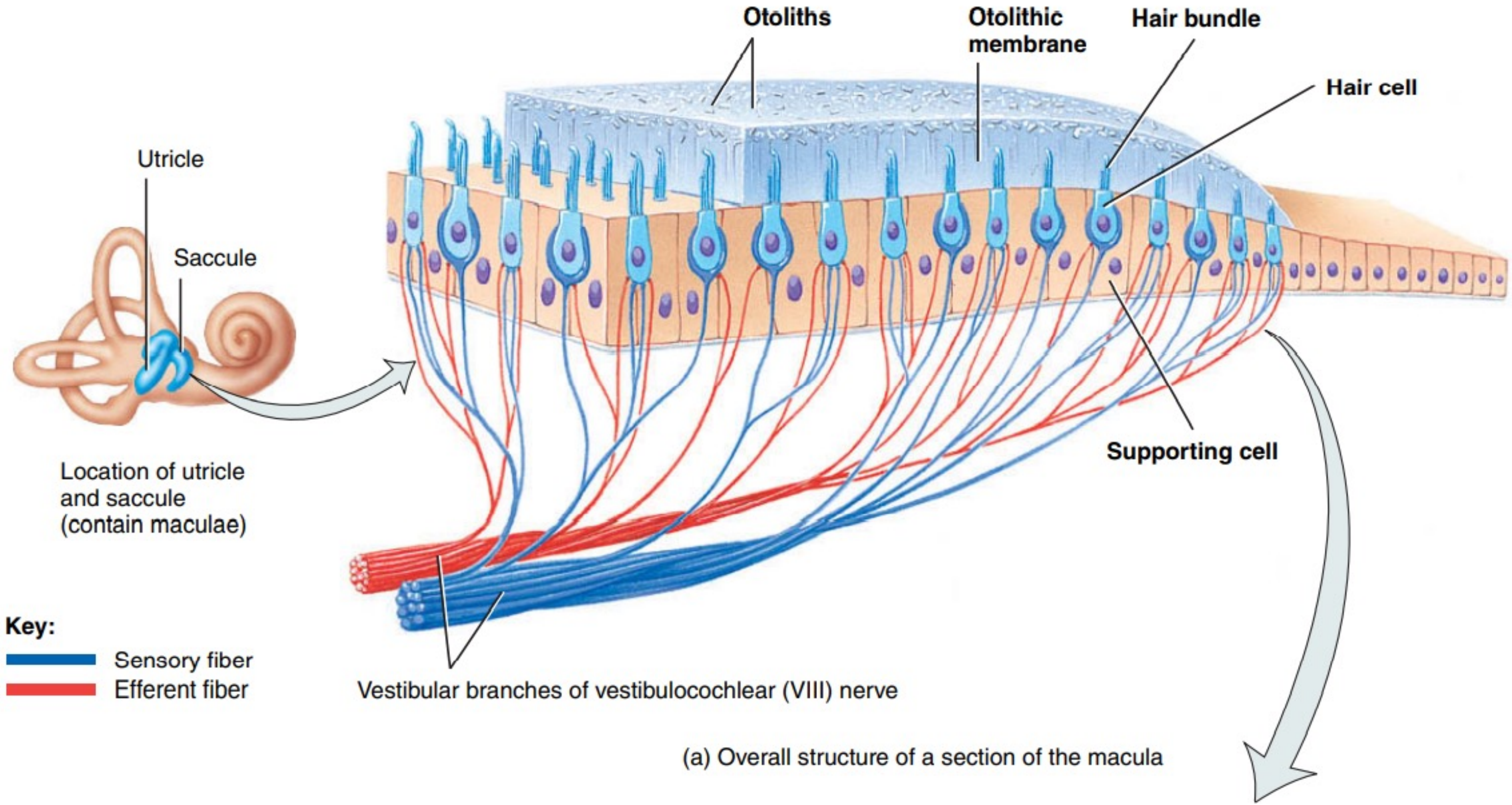
- The opening of these channels depends primarily on the movement of stereocilia. Consequently, the movement of stereocilia is responsible for initiating action potentials.
- In the resting state, the channels are partially open, resulting in a certain degree of depolarization.
- When the movement is directed towards the longest stereocilia, it leads to strong depolarization.
- Conversely, when the movement is directed away from the longest stereocilia, it results in hyperpolarization.

the exact same concept of hearing, but in this case receptor calls are located in the **ampulla,** which are enlarged regions at the beginning of the semicircular canals.

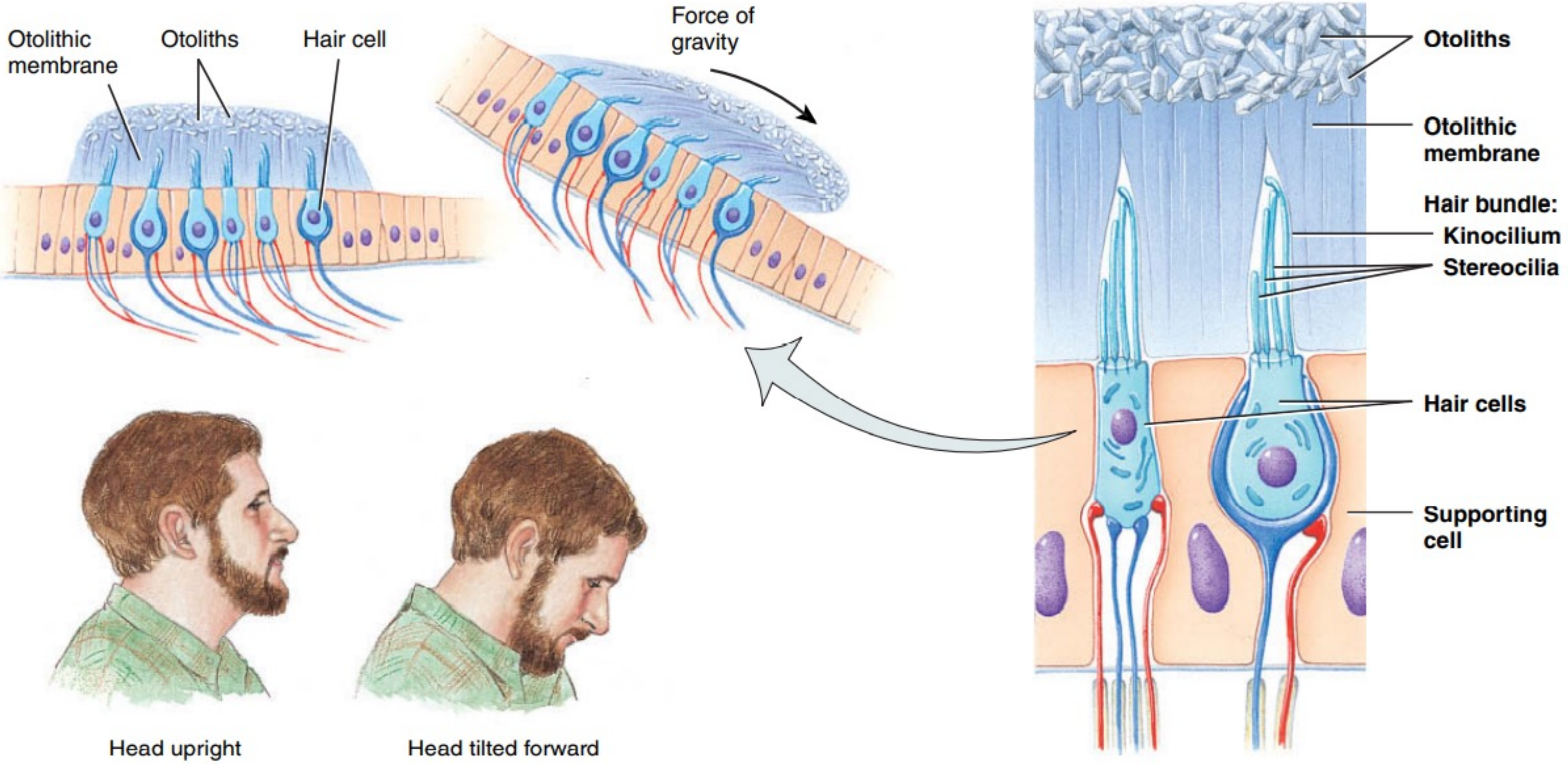
- Each ampulla is oriented according to its corresponding semicircular canal.
- This alignment allows the ampulla to detect and respond to rotational movements in the plane of its corresponding semicircular canal.



Kincocilim :is the longest stereocilia



(a) Overall structure of a section of the macula



(c) Position of macula with head upright (left) and tilted forward (right)

(b) Details of two hair cells

Vestibular system

- When you move forward, it can result in linear acceleration in the direction of your movement (utricle). similarly, when you are on an elevator and it ascends upward, this also result in vertical linear acceleration (saccule).

- The position of the head is detected by the utricles and saccule.

As seen in Figure A, when the head is in a straight position, note that the receptor cells have gelatinous material and otoliths on top of them. In the upright position, they are straight, which indicates partial depolarization. The central nervous system (CNS) perceives this as a resting state with no movement. However, if a person moves their head down, as shown in Figure B, it results in bone movement. The receptor cells attached to it will also move, and due to the force of gravity, the otoliths will move in the same direction (causing a bending of the cilia)

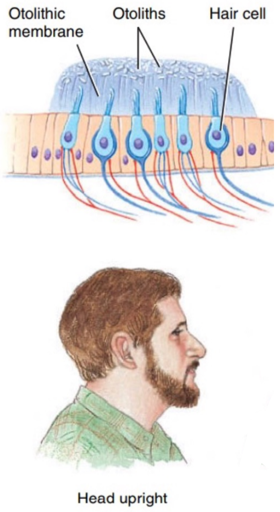


Figure A

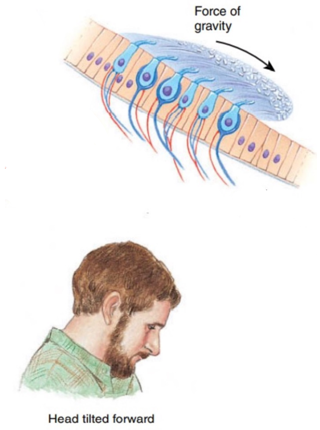


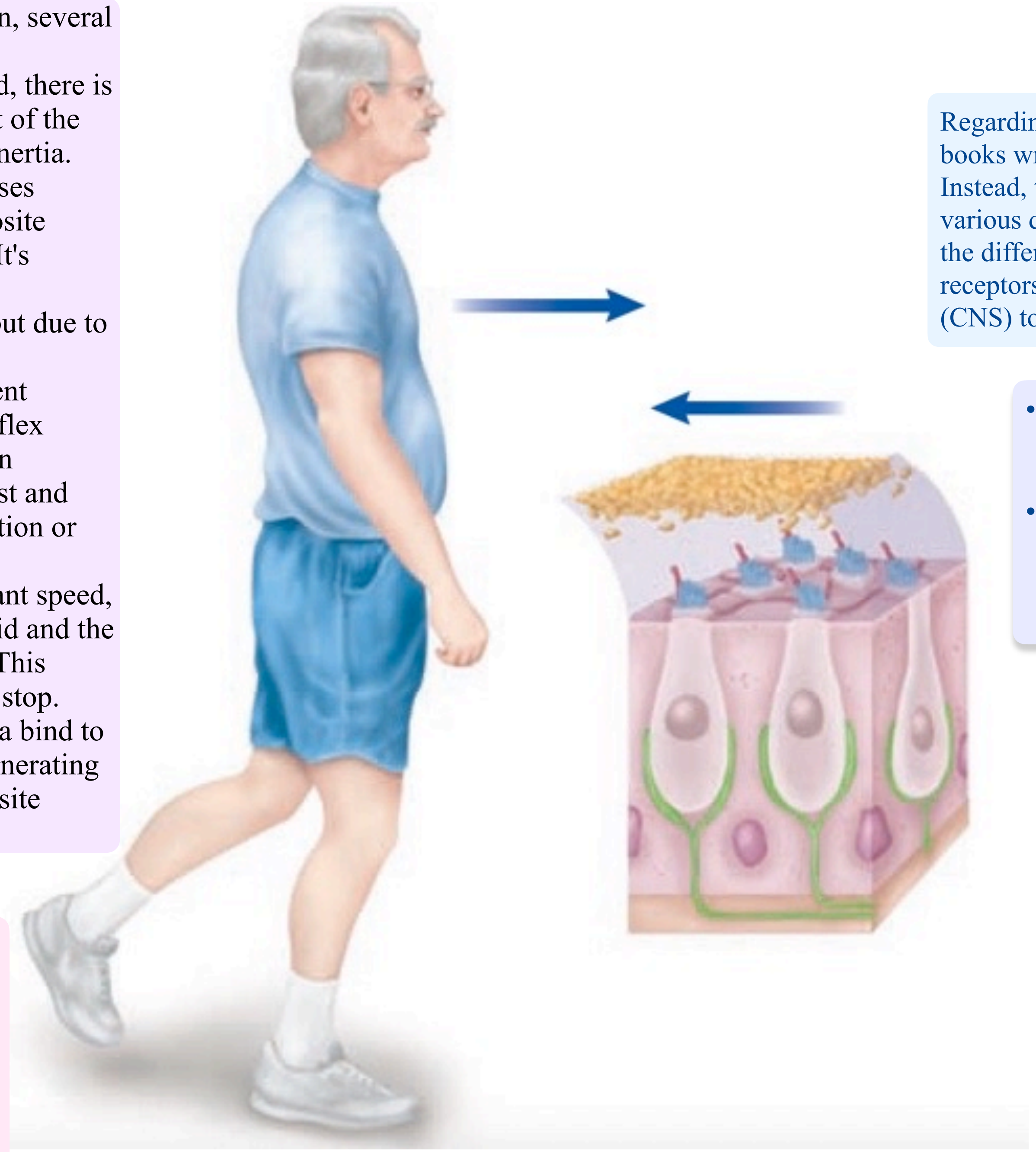
Figure B

During linear acceleration or deceleration, several factors come into play:

1. When a person starts moving forward, there is a slight delay between the movement of the head and the fluid due to the fluid's inertia.
2. As a result, the initial movement causes bending of the stereocilia in the opposite direction of the person's movement. It's important to note that the stereocilia themselves do not move backward, but due to inertia, they appear to do so.
3. This temporary sensation of movement backward leads to the initiation of reflex contraction of muscles. It serves as an important signal for the body to adjust and maintain balance during the acceleration or deceleration phase.
4. Conversely, when moving at a constant speed, the fluid catches up, and both the fluid and the saccule move in the same direction. This continues until the person decides to stop.
5. When the person stops, the stereocilia bind to the other side due to inertia, again generating a sensation of movement in the opposite direction.

On other words

During linear acceleration or deceleration, the fluid's inertia and the resulting bending of the stereocilia play a crucial role in sensing the movement and initiating appropriate reflex responses for maintaining balance.



Regarding the receptors in the utricles and saccules, some books write that they are not oriented in the same direction. Instead, they are arranged throughout the maculae in various directions. This arrangement is significant because the different degrees of stimulation and binding within the receptors are interpreted by the central nervous system (CNS) to determine the precise position.

- Utricle & Saccule they are important for head position & linear acceleration deceleration.
- On the other hand, semicircular canal are important for rotational and angular acceleration & deceleration such as spinning, in one of the three dimensions.

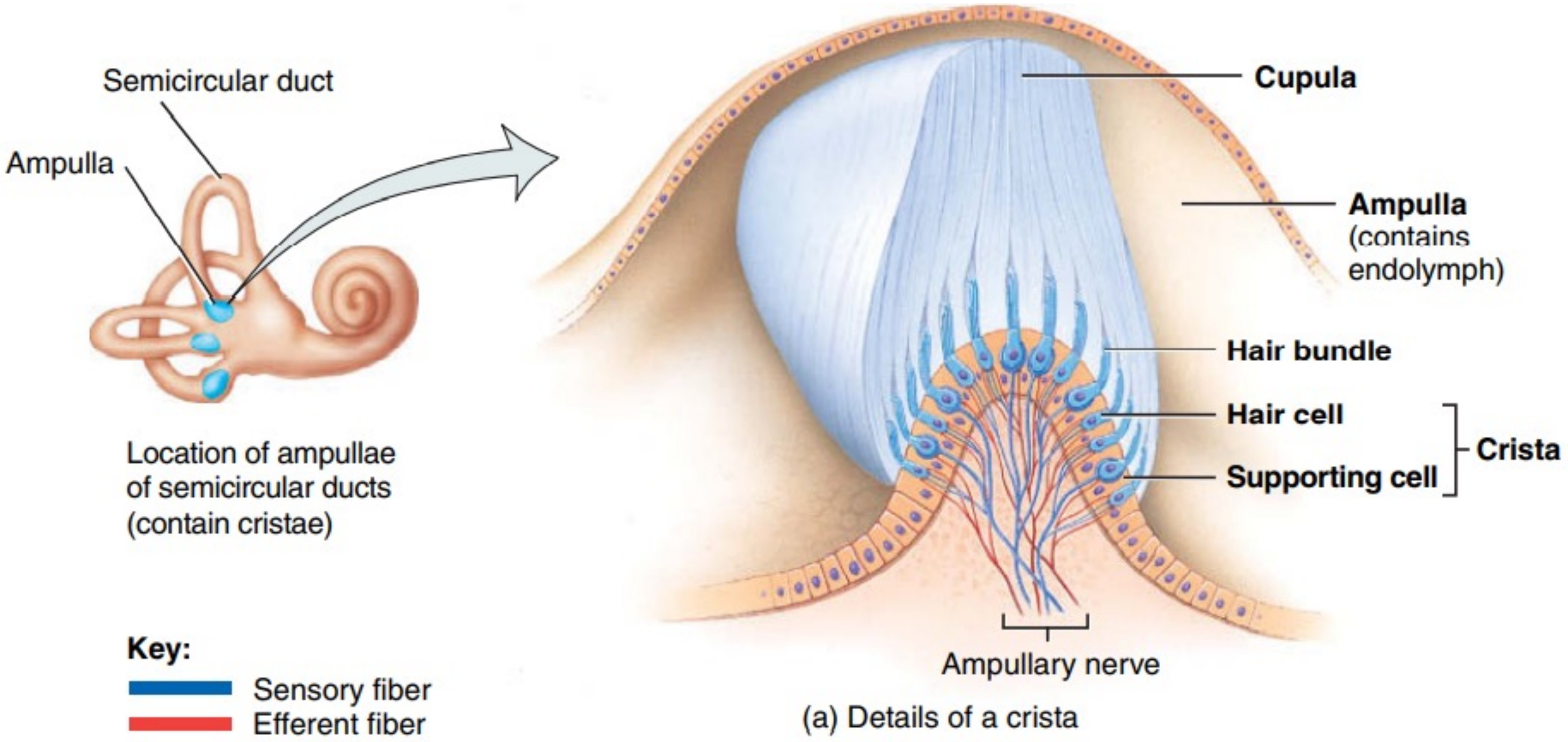
Semicircular Ducts

- The three semicircular ducts lie at right angles to one another in three planes. The two vertical ducts are the anterior and posterior semicircular ducts, and the horizontal one is the lateral semicircular duct.

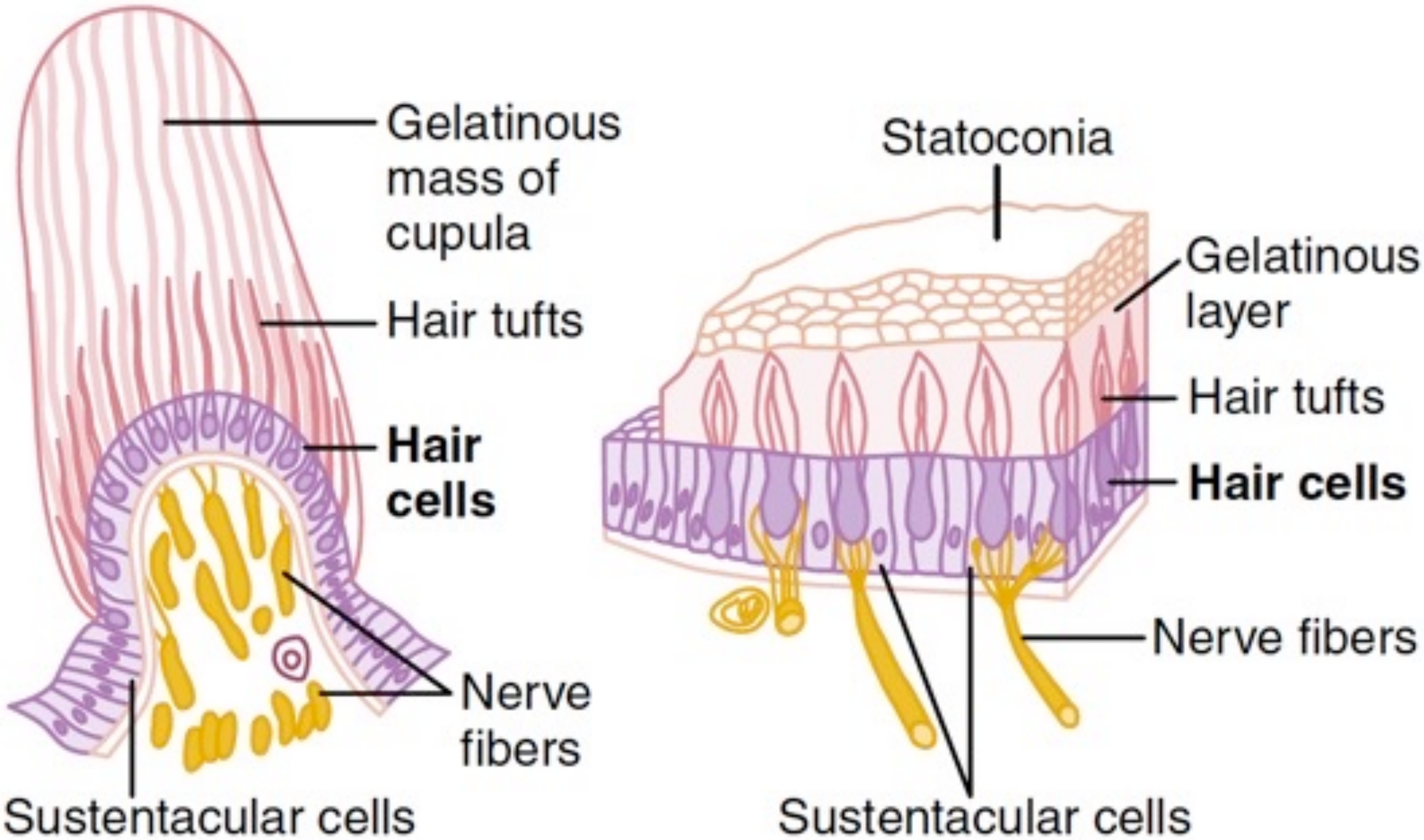
- This positioning permits detection of rotational acceleration or deceleration.

The semicircular ducts are filled with a fluid called endolymph

The primary function of the semicircular ducts is to detect rotational movements of the head



(a) Details of a crista



CRISTA AMPULLARIS AND MACULA

Semicircular Ducts

- When the head rotates, the attached semicircular ducts and hair cells move with it. However, the endolymph within the ampulla is not attached and lags behind due to inertia.

- The drag of the endolymph causes the cupula and the hair bundles that project into it to bend in the direction opposite to that of the head movement.

Here, we see the ampulla in resting state (figure A) & in rotational state (figure B)

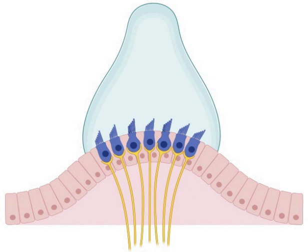


Figure A

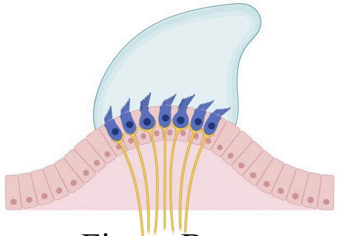
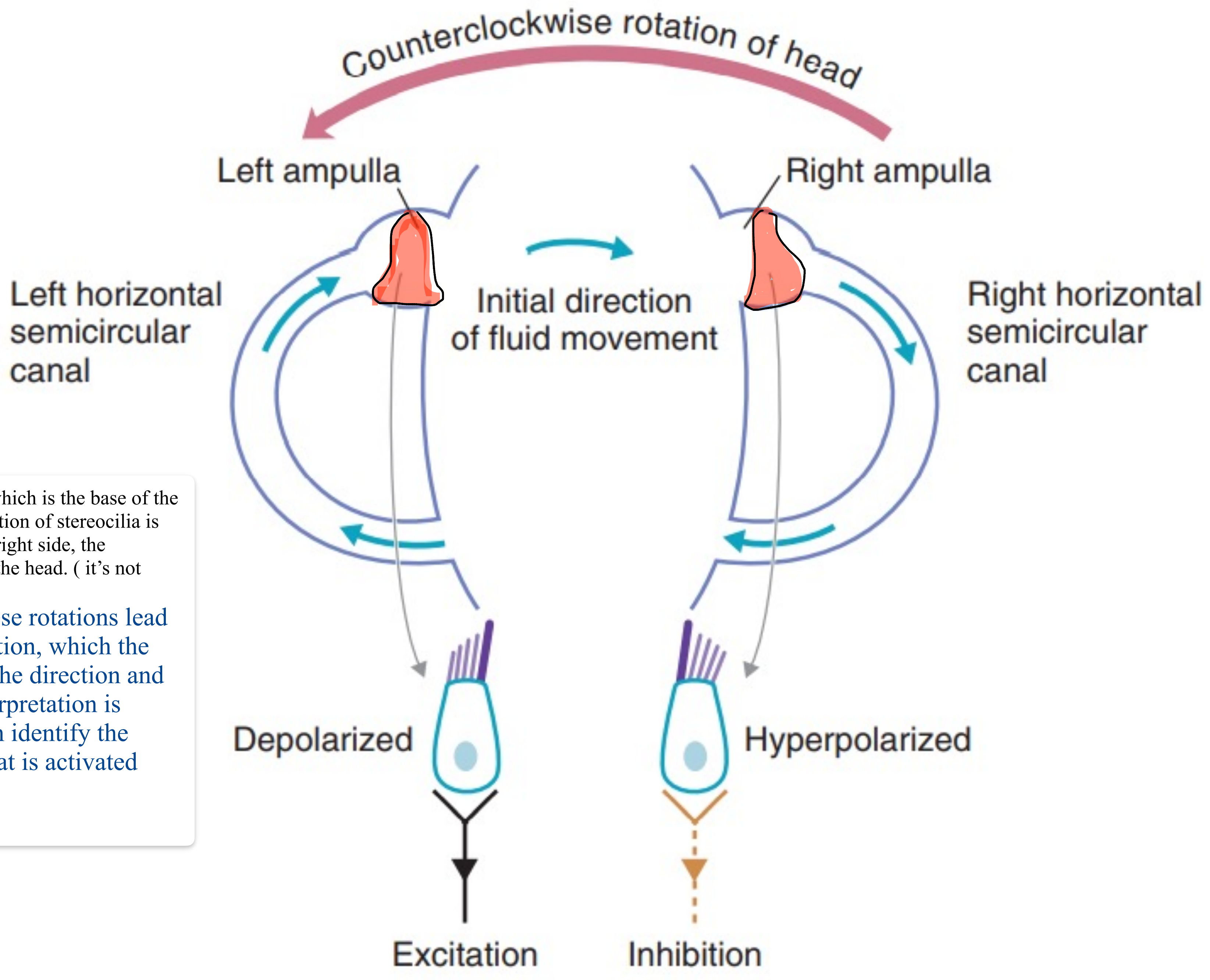


Figure B

Semicircular Ducts

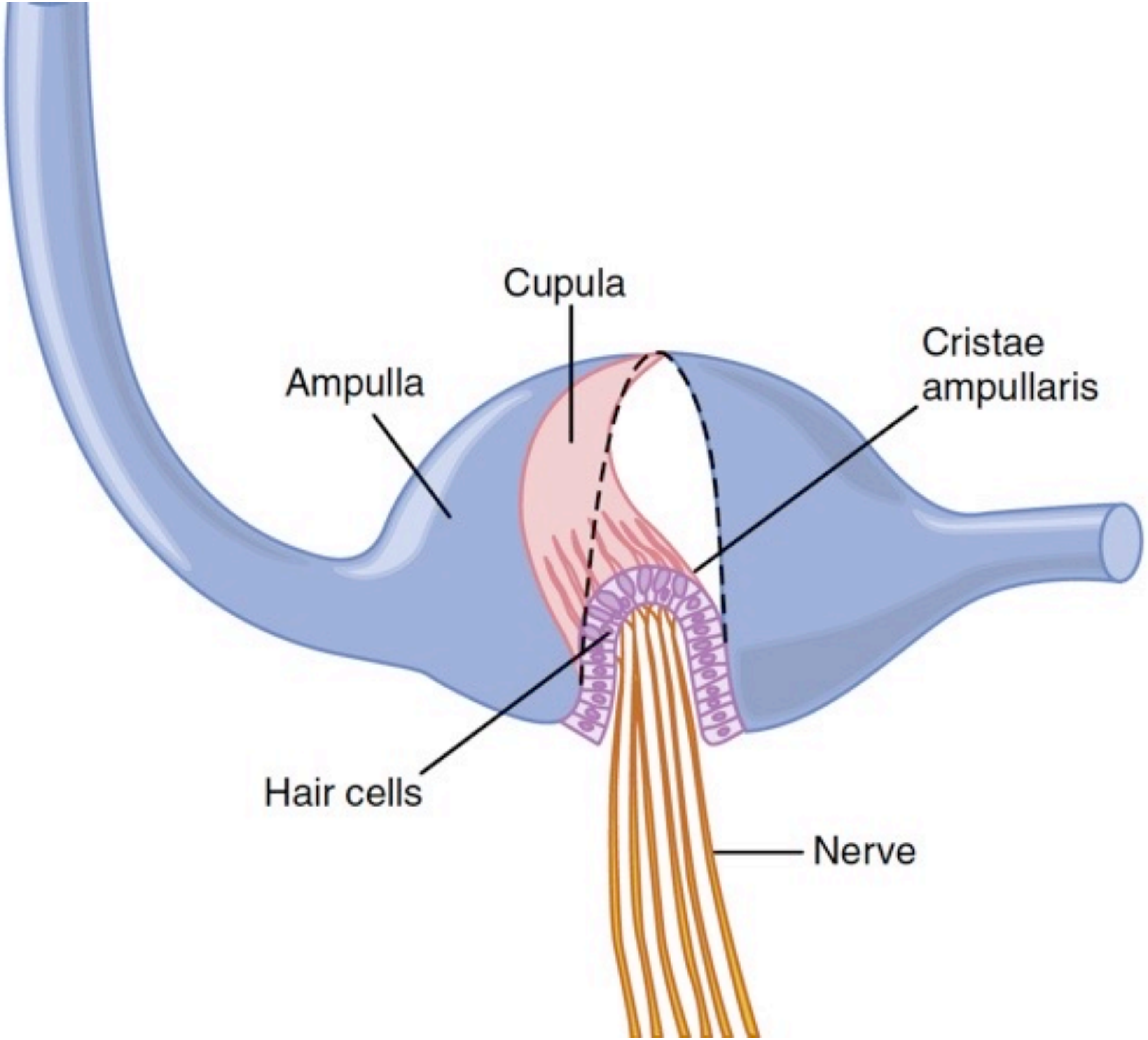
- Once the head stops moving, the endolymph temporarily keeps moving due to inertia, which causes the cupula and its hair bundles to bend in the same direction as the preceding head movement.

- At some point the endolymph stops moving and the cupula and its hair bundles return to their resting, unbent positions.



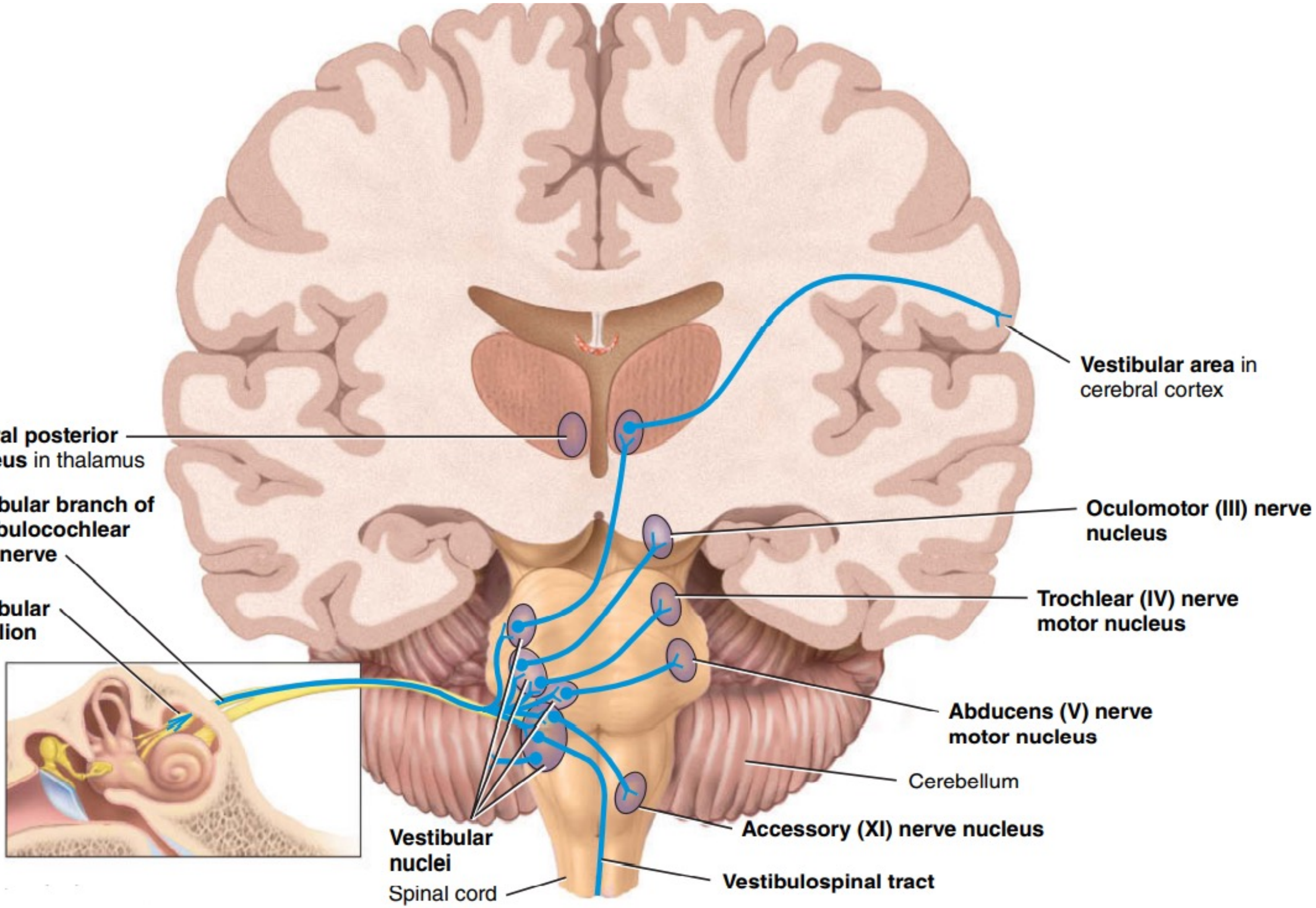
Rotation always initiates from the stem, which is the base of the receptor cells. In the left ampulla, the rotation of stereocilia is opposite to that of the head, while on the right side, the stereocilia rotate in the same direction as the head. (it's not required to know the directions)

- Its important to know that these rotations lead to varying degrees of stimulation, which the CNS interprets to determine the direction and plane of movement. This interpretation is possible because the CNS can identify the specific semicircular canal that is activated during the rotation.


Cupula
Cristae
ampullaris
Ampulla
Hair cells
Nerve

Semicircular ducts

- the semicircular duct mechanism predicts that disequilibrium is going to occur and thereby causes the equilibrium centers to make appropriate anticipatory preventive adjustments, which helps the person maintain balance before the situation can be corrected.


Vestibular area in cerebral cortex
Ventral posterior nucleus in thalamus
Vestibular branch of vestibulocochlear (VIII) nerve
Oculomotor (III) nerve nucleus
Vestibular ganglion
Trochlear (IV) nerve motor nucleus
Abducens (V) nerve motor nucleus
Cerebellum
Accessory (XI) nerve nucleus
Vestibular nuclei
Vestibulospinal tract
Spinal cord

Equilibrium pathways

- Most of the axons synapse with sensory neurons in vestibular nuclei in the medulla oblongata and pons.

- The vestibular nuclei also receive input from the eyes and proprioceptors, especially proprioceptors in the neck and limb muscles that indicate the position of the head and limbs.

- Some fibers pass directly to the brain stem reticular nuclei without synapsing and also to the cerebellar nuclei. The most important structure in terms of balance & coordination.

Equilibrium pathways

The vestibular nuclei integrate information from vestibular, visual, and somatic receptors and then send commands to:

(1) the nuclei of cranial nerves III, IV, and VI that control coupled movements of the eyes with those of the head to help maintain focus on the visual field. (vestibuloocular reflex ⇒ ensuring stable vision by generating compensatory eye movements in response to head rotations or movements).

(2) nuclei of the accessory (XI) nerves to help control head and neck movements to assist in maintaining equilibrium.

Equilibrium pathways

(3) the vestibulospinal tract, which conveys impulses down the spinal cord to maintain muscle tone in skeletal muscles to help maintain equilibrium.

(4) the ventral posterior nucleus in the thalamus and then to the vestibular area in the parietal lobe of the cerebral cortex to provide us with the conscious awareness of the position and movements of the head and limbs.

Loss of function

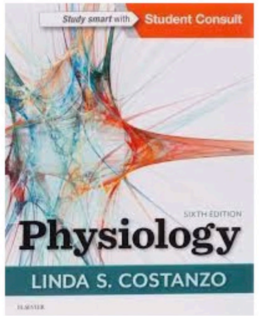
- After destruction of the vestibular apparatus, and even after loss of most proprioceptive information from the body, a person can still use the visual mechanisms reasonably effectively for maintaining equilibrium.
- Some people with bilateral destruction of the vestibular apparatus have almost normal equilibrium as long as their eyes are open, and all motions are performed slowly.
- However, when moving rapidly or when the eyes are closed, equilibrium is immediately lost.

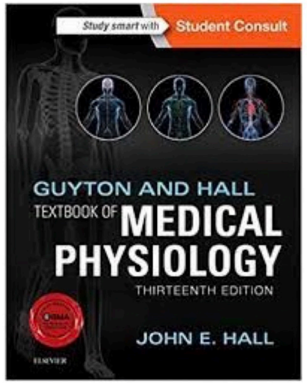
The foot integrate various sensory inputs, including proprioception, pressure, and tactile sensations. When standing upright, these inputs collectively provide information about foot movement through the stimulation of tactile receptors.

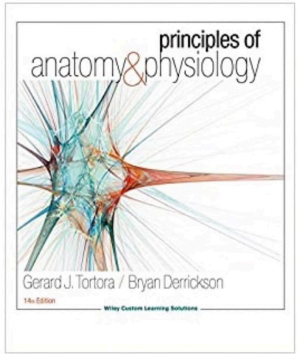
- it’s crucial to have coordination between the vestibular apparatus (signals), proprioceptors in the body & tactile sensations.

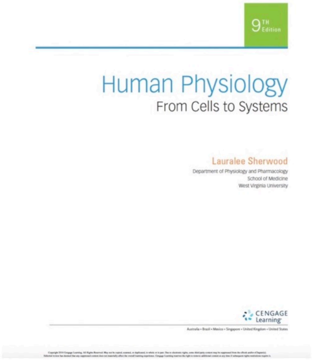
Reference

The Romberg test is a component of the neurological examination used to assess balance and proprioception. It involves having the patient stand with their feet together, eyes open, and then eyes closed. In a positive Romberg sign, the patient exhibits increased difficulty maintaining balance or an increase in unsteadiness when the eyes are closed compared to when they are open. This finding suggests impaired proprioception or **sensory ataxia**, where the patient relies heavily on visual cues for balance and coordination.









Thank you