Physiology of the Vestibular Apparatus

Calmette - AEC

Organisation of the Balance system

Input
- Vestibular
- Vision
- Proprioception / somatosensation

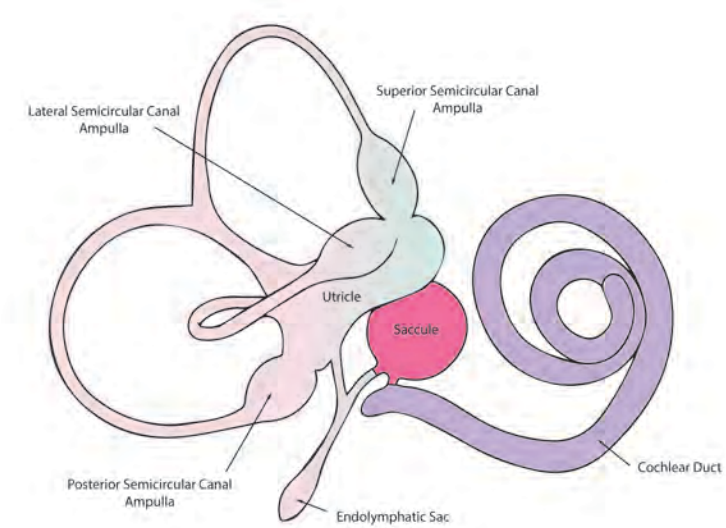
Integration
aka Central Processing
- 'Vestibular' nuclei and Cerebellum

Output
- Motor nerves
- Muscles
- Joints

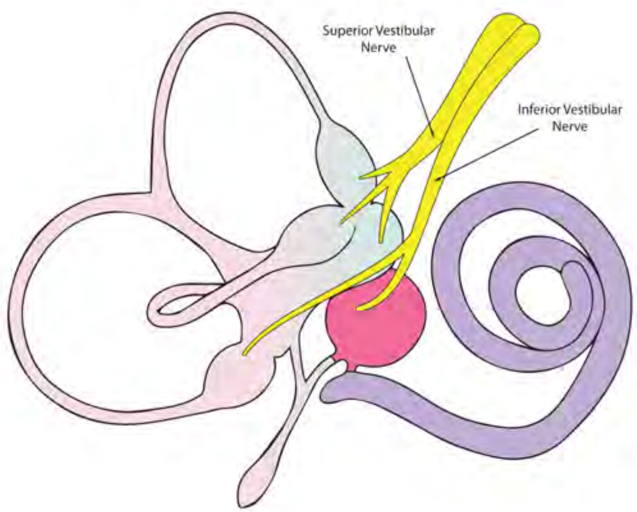
Vestibular Input to Balance

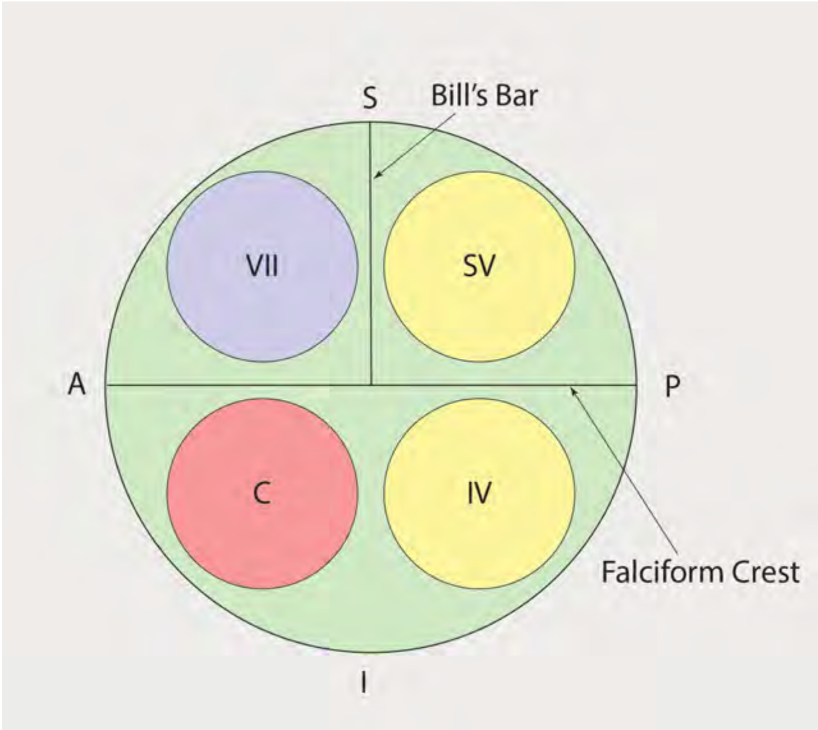
- The vestibular apparatus consists of the semicircular canals, the utricle and saccule.
- The semicircular canals are responsible for detecting rotational movements (head turns, looking up or down etc)
- The utricle and saccule detect linear movements (side-to-side, front-to-back) and gravity (up and down).

The Inner Ear – Membranous Labyrinth

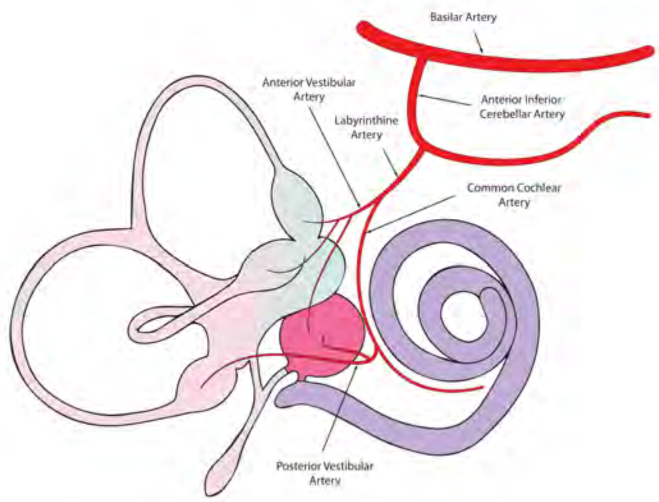


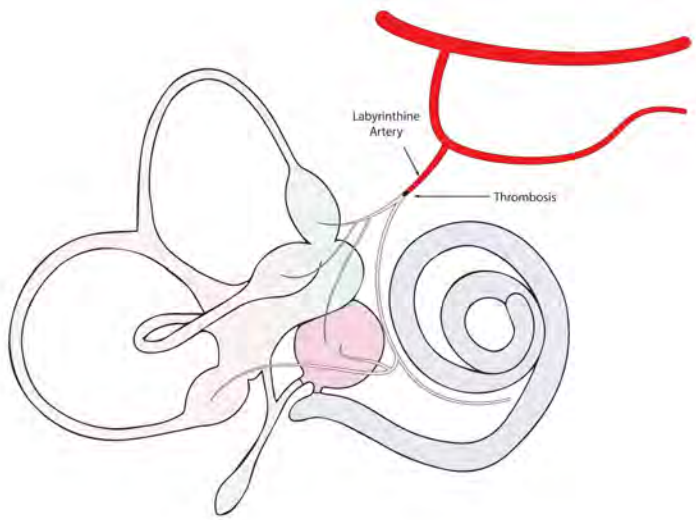
Neural Anatomy – 2 Vestibular nerves





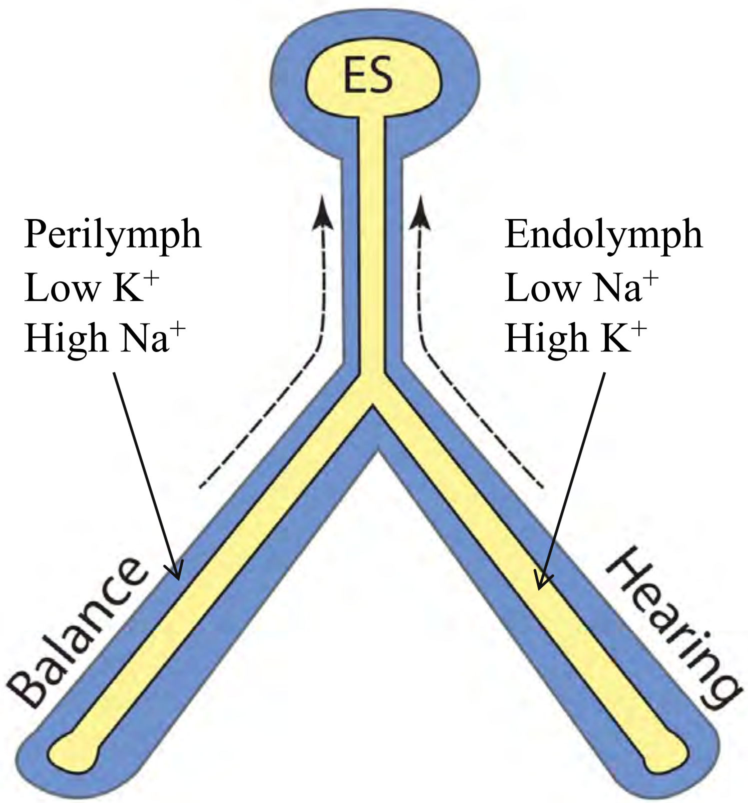
Vascular Anatomy – an End Artery system





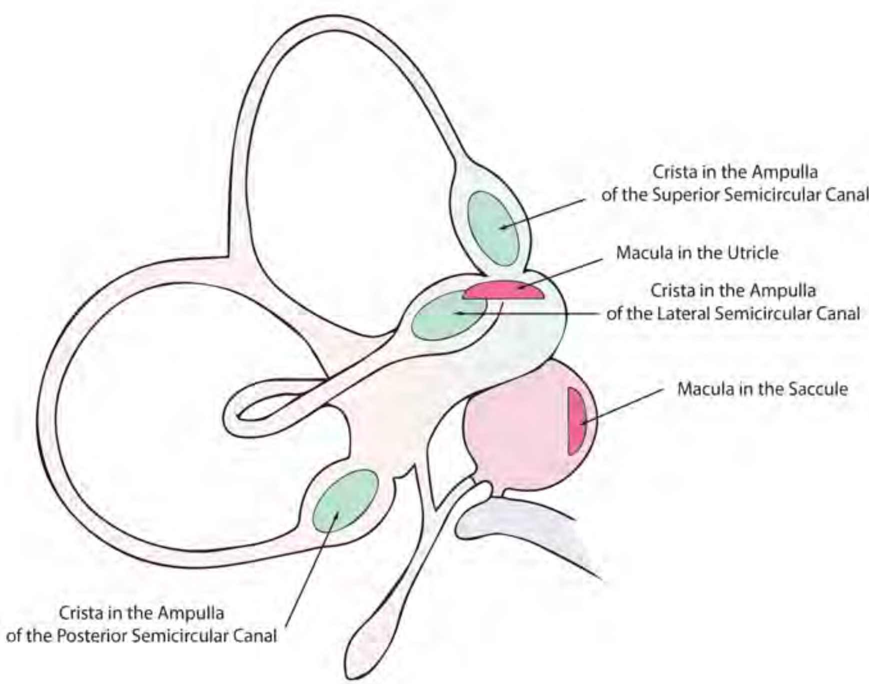
Obstruction of the labyrinthine artery causes vertigo AND sensory deafness

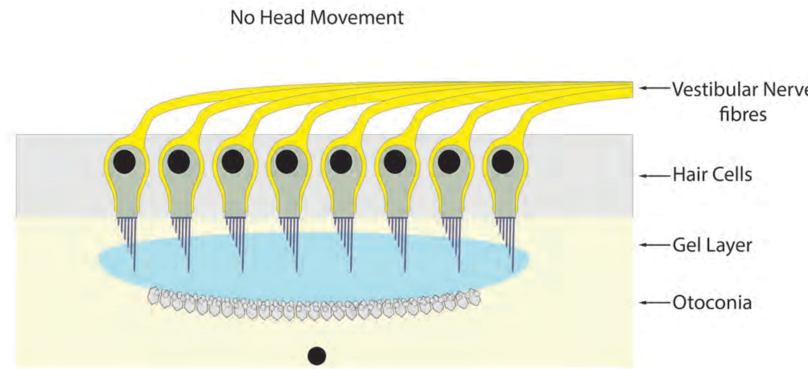
Inner Ear Physiology Simplified

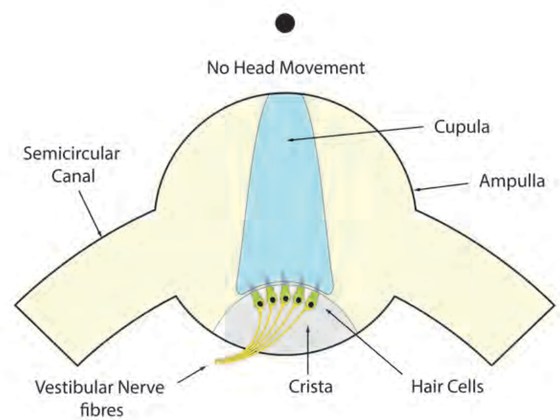


- Endolymph created by ‘dark’ cells
- Perilymph comes from CSF
- Maintained in composition and volume with help of endolymphatic sac

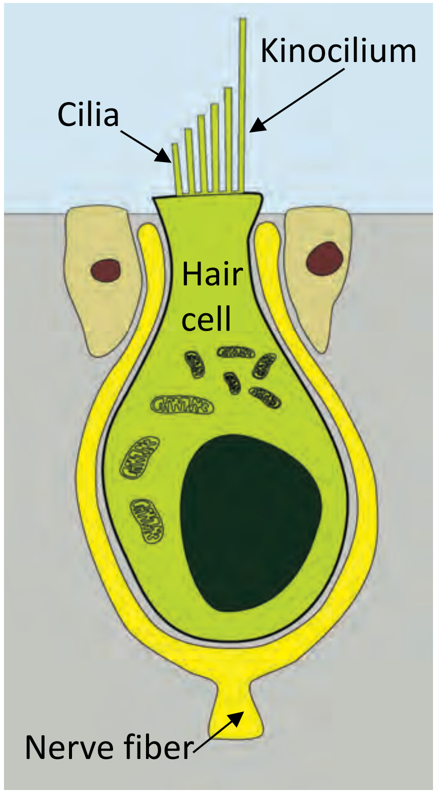
Crista and Maculae







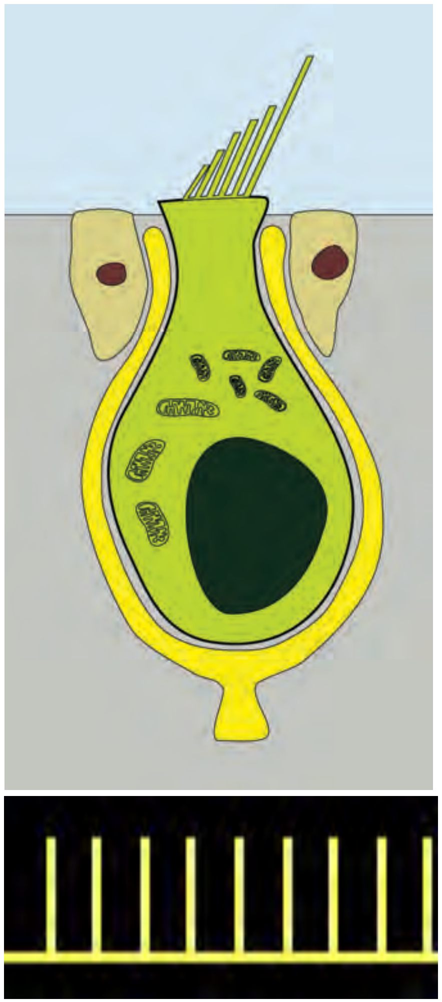
Physiology



Tonic firing rate

- Before starting to learn which stimuli are detected by the semicircular canals, utricle and saccule we must understand how the ear changes movement into neural activity.
- This is done in the hair cell. The hair cell has a cell body from which project cilia of varying length and a long kinocilium. The hair cell is closely related to a nerve fiber of the vestibular nerve.
- When the cilia are undistorted, the cell produces a continual stream of impulses. This is called a tonic discharge and is due to inherent leakiness of the cell membrane to K^+

Physiology

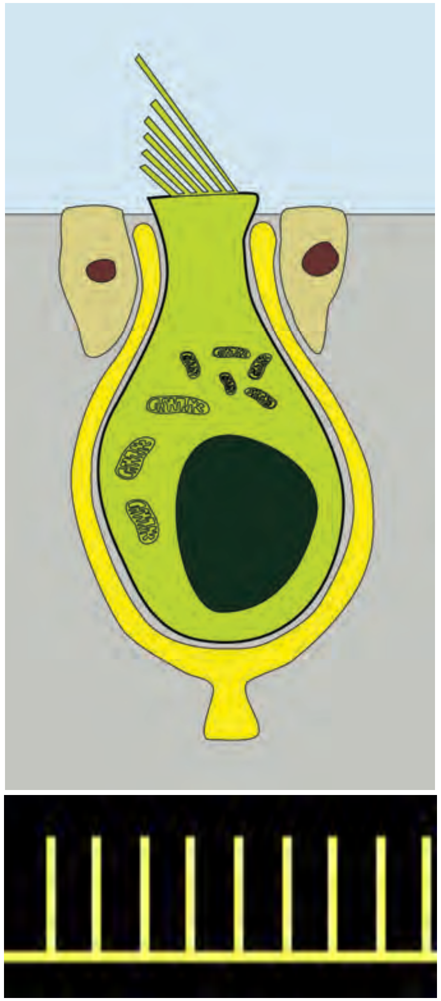


Firing rate increases

- When the cilia are distorted towards the longest cilium (known as the kinocilium) the firing rate in the nerve fiber increases.

- The molecular physiology of this is complex but in brief:
  - Movement opens membrane channels mechanically
  - K^+ moves along its electrical gradient into the cell
  - Ca^{2+} channels open
  - Neurotransmitter is released
  - The nerve fibre depolarises
  - A nerve impulse is set off

Physiology



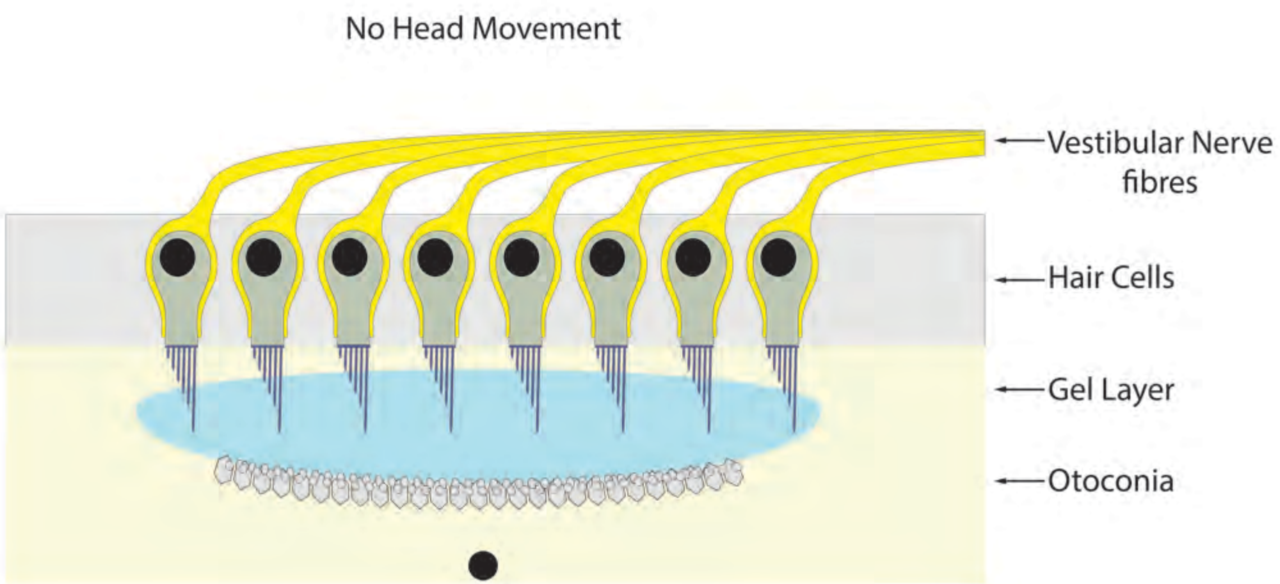
Firing rate decreases

- When the cilia are distorted away from the kinocilium the firing rate drops.
- Note that the firing rate is <u>modified</u> by movement of the cilia but that there is always some firing (except in pathological circumstances).
- The hair cells are clumped together to form a neuro-epithelium and vestibular nerves run from them.

The Macula

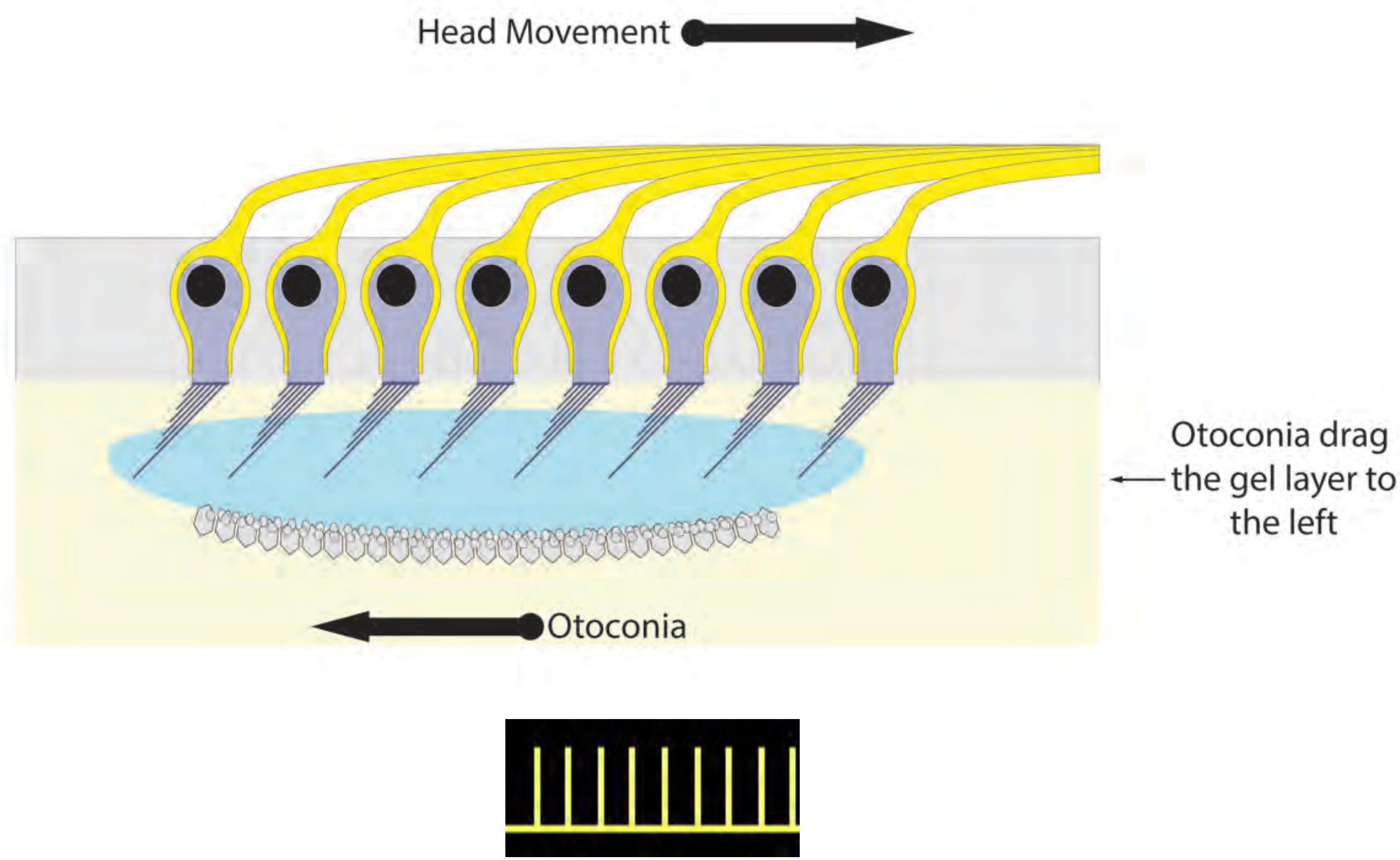
- The macula is a patch of cells clumped together, one in the utricle and one in the saccule.
- The clump is called a neuroepithelium.
- It consists of hair cells with cilia embedded in gel. The gel is coated in otoconia.
- Otoconia are calcium carbonate crystals that give the gel inertia.
- Stimulation of the macula is effected by linear movement only.

Physiology of the Macula



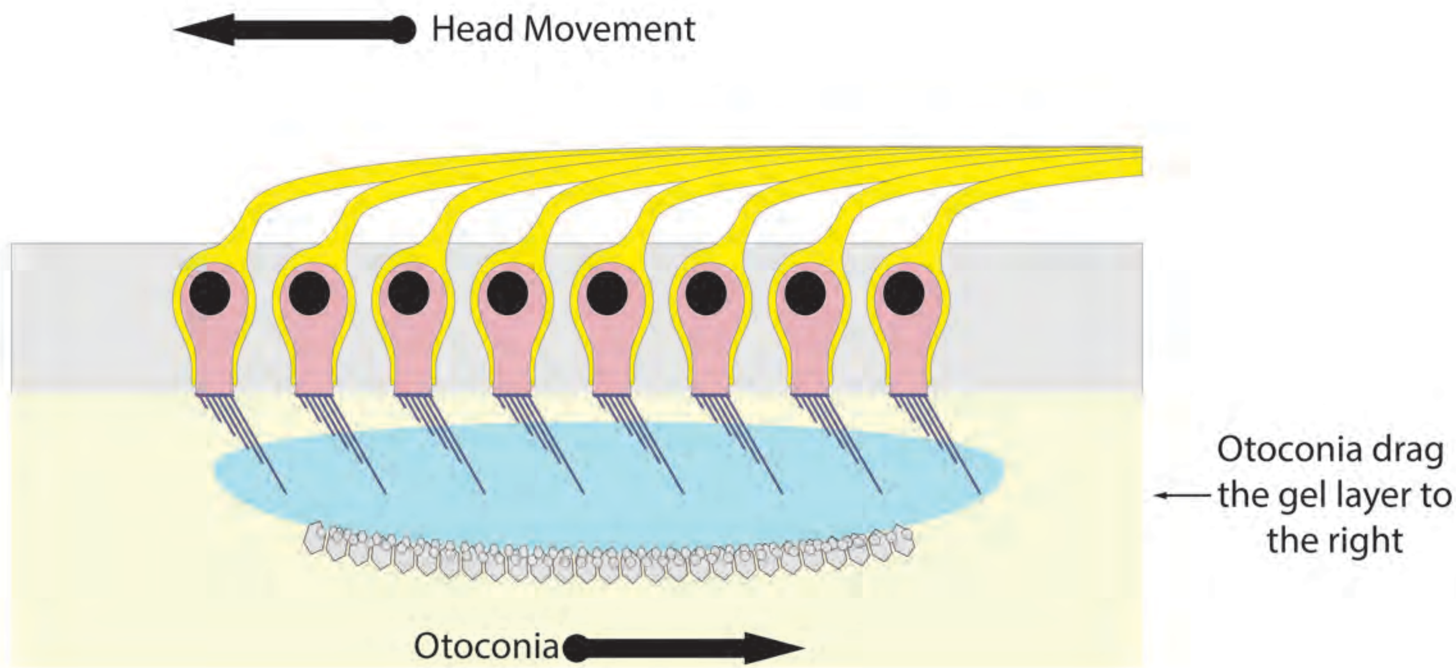
Tonic firing rate

Physiology of the Macula



Firing rate falls

Physiology of the Macula

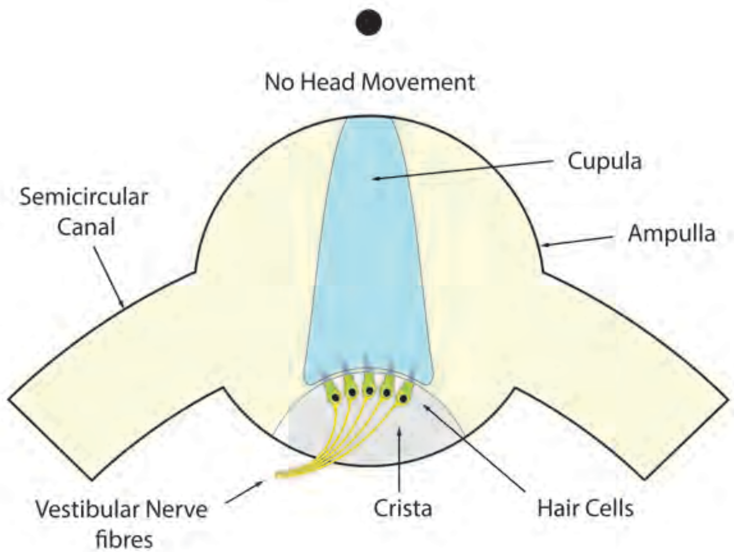


Firing rate rises

The Crista

- The cristae lie in the ampullae of the semicircular canals; one in each of the three.
- It consists of a clump of hair cells called a neuroepithelium.
- It has cilia embedded in gel. The gel is <u>not</u> coated with otoconia.
- The gel is called the cupula.
- The crista is stimulated by rotatory movements only.

Physiology of the Crista

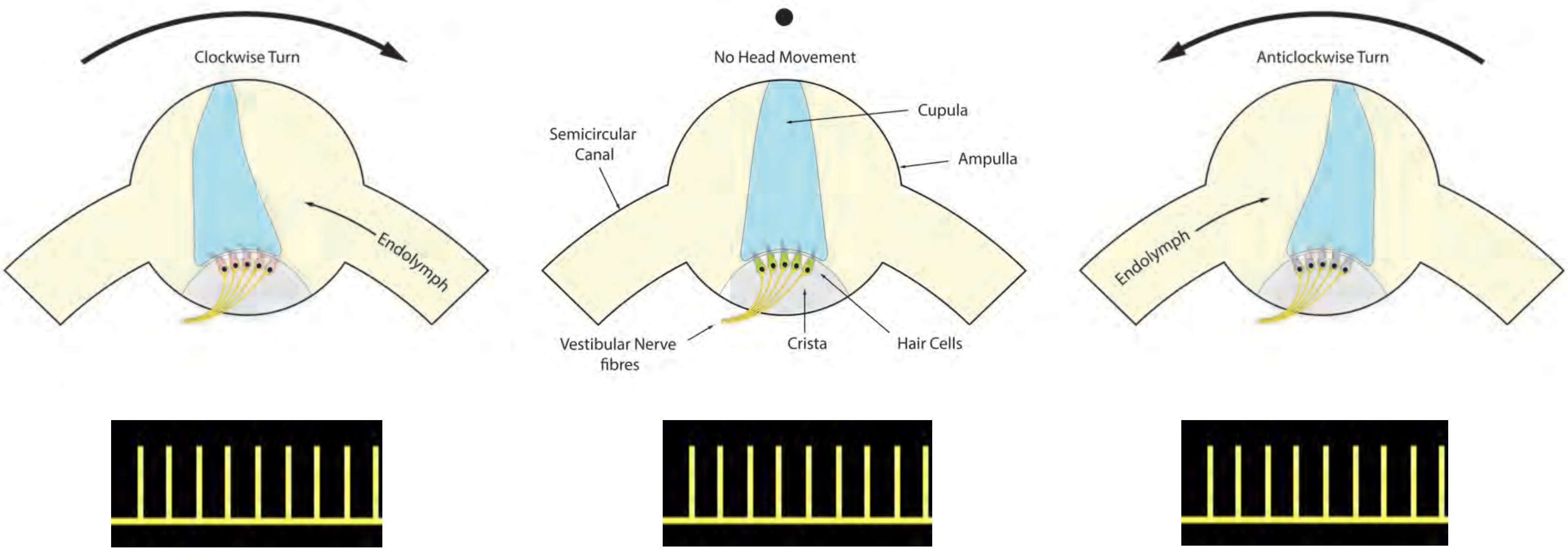


Tonic firing rate

Physiology of the Crista

- Rotation of the head in one direction caused the fluid in the semicircular canal to lag behind and push against the cupula.
- This distorts the hair cells in the crista.
- When the cupula bends one direction it will move the cilia towards the kinocilium and the firing rate will increase.
- When it bends in the other direction by rotation in the opposite direction it will cause a decrease in firing of the crista.

Physiology of the Crista

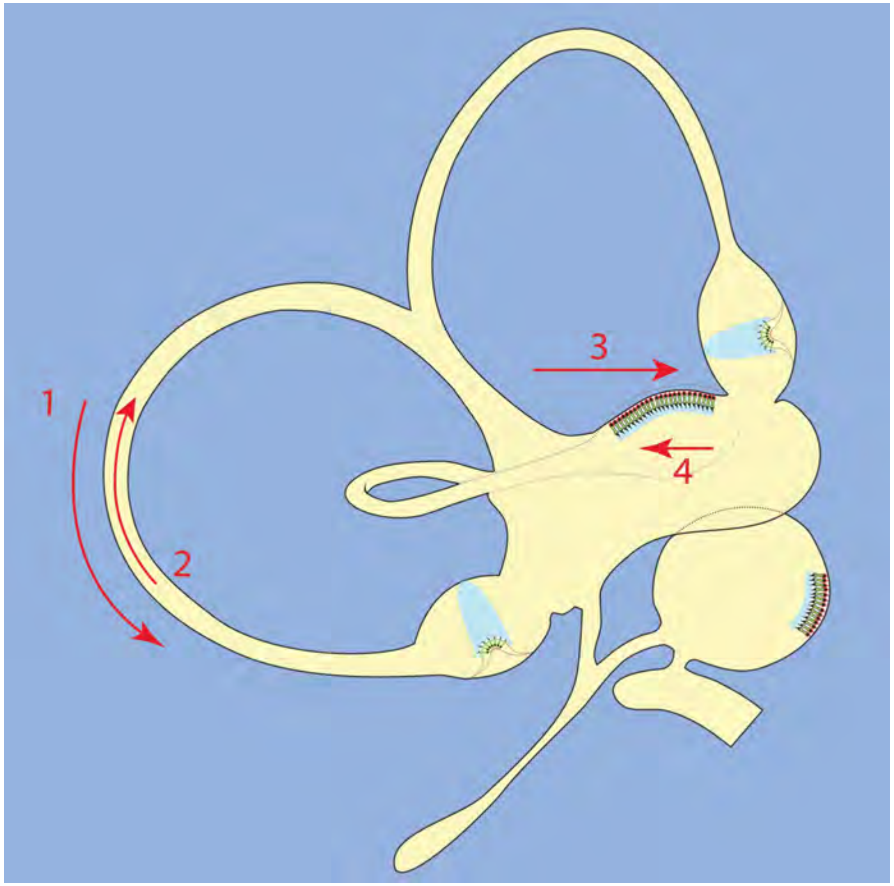


Firing rate increases

Tonic firing

Firing rate decreases

Physiology Roundup



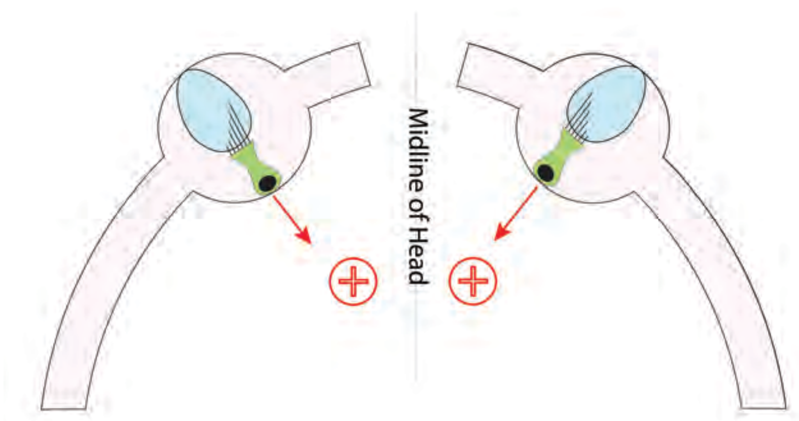
Utricle, saccule, posterior and superior semicircular canals. The lateral canal is transparent to show macula in utricle.

- This diagram summarises the types of movement that stimulate the semicircular canals and the maculae of the utricle and saccule.
- Rotational movements (turning head, nodding etc) stimulate the semicircular canals (1 and 2).
- Linear movements (moving forwards, sideways etc) are detected by the maculae (3 and 4). These can detect movements in all three planes also.

Functional Pairs

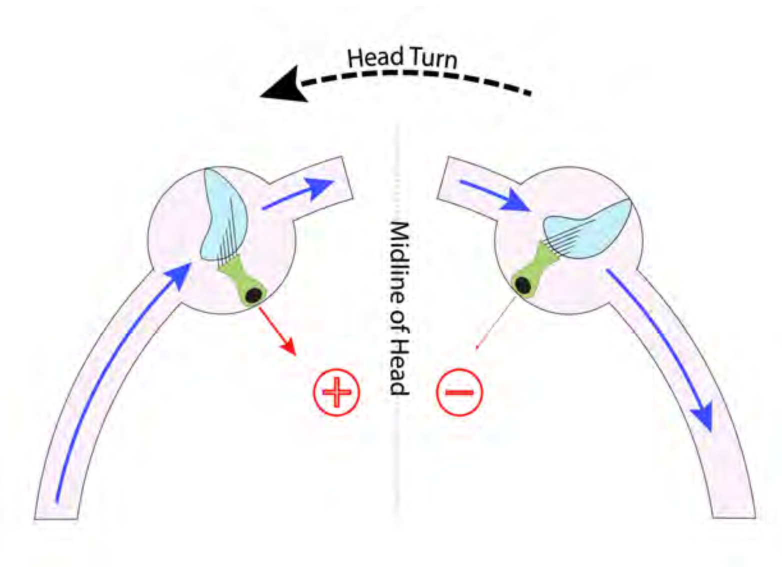
- We have balance organs on both sides of our heads – they are a mirror image of each other.
- As you will see, any movement that increases activity in the balance organ on one side will inhibit activity on the other side.
- Let’s start by looking at what happens in the lateral semicircular canal when we turn our heads to the left.

Mirror Symmetry



- These are the lateral canals shown from above looking down. Instead of a whole neuroepithelium a single hair cell represents the crista.
- Note that the one side is a mirror image of the other.
- The kinocillia are nearest the midline

Functional Pairing

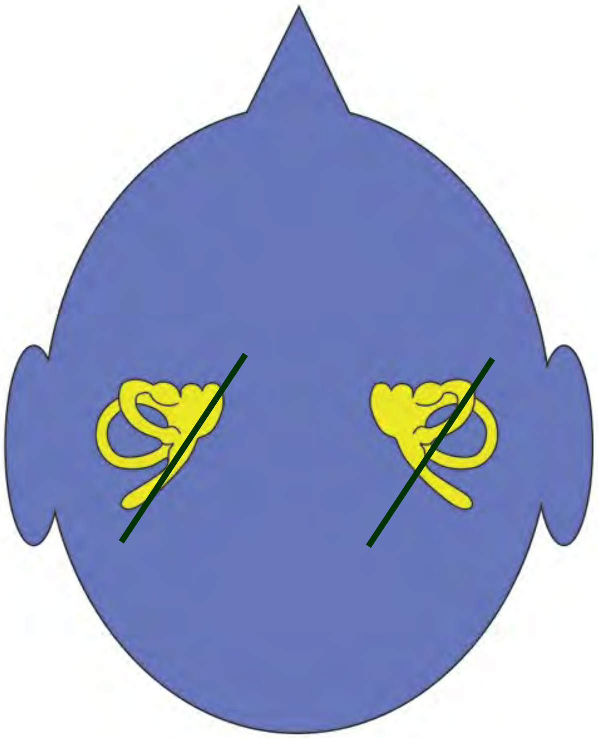


- We are looking down onto the head at the lateral (horizontal) semicircular canals only.
- The head turns to the left (anticlockwise) and the fluids in the canal lag to the right (clockwise).
- On the left the cupula moves so as to move the cilia towards the kinocillium and firing rate increases.
- On the right the opposite happens and firing rate falls.
- This is because the canals are mirror images of one another.
- This is a fixed system and it always behaves the same way.

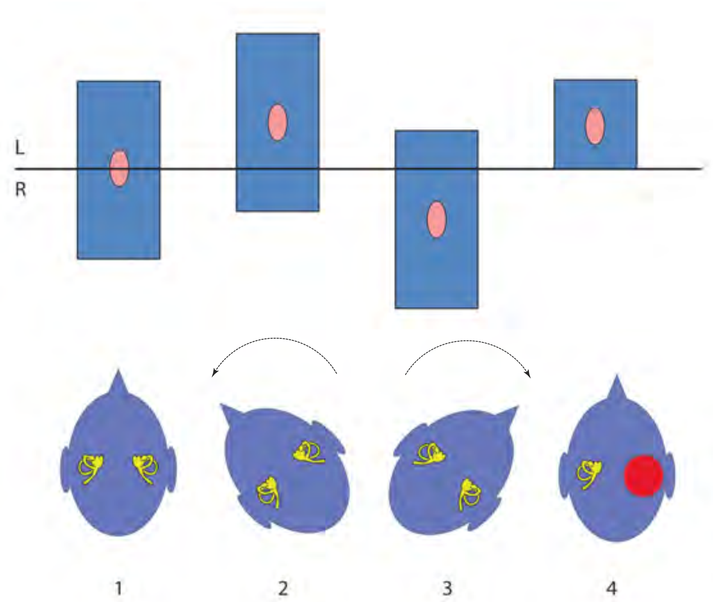
Functional Pairing

- All of the semicircular canals are paired:
  - The left lateral with the right lateral
  - The left superior with the right posterior
  - The left posterior with the right superior

- When the activity in one goes up the activity in its paired canal goes down.

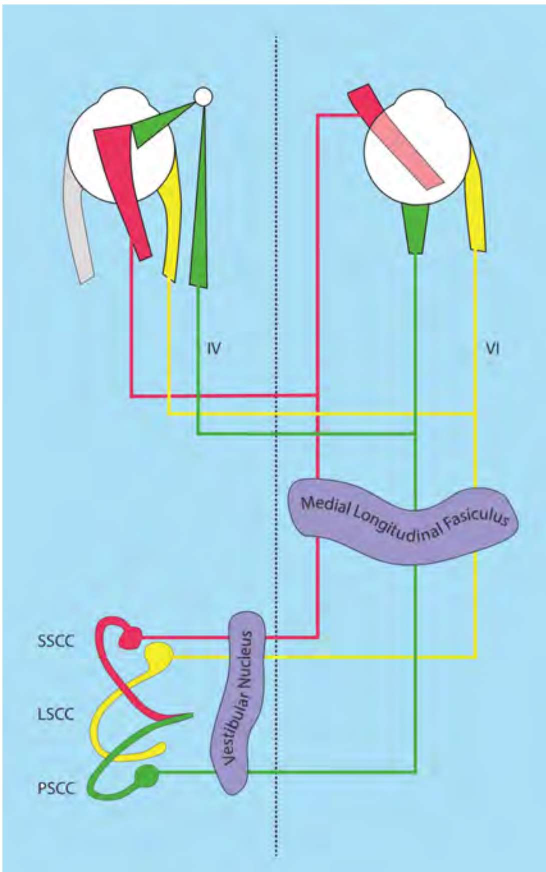


The brain compares the activity on the left with that on the right. When both sides are discharging tonically it compares them and finds them the same. There is no net activity on either side. This is the situation when there is no head movement.



- When the head turns left the left activity rises and the right falls. The brain interprets this as turning to the left because there is net activity on the left.
- When one ear fails (red) the brain believes that the head is turning because there is net activity on the left.
- Vestibular neuritis, Labyrinthitis, Ménière's Disease all do this

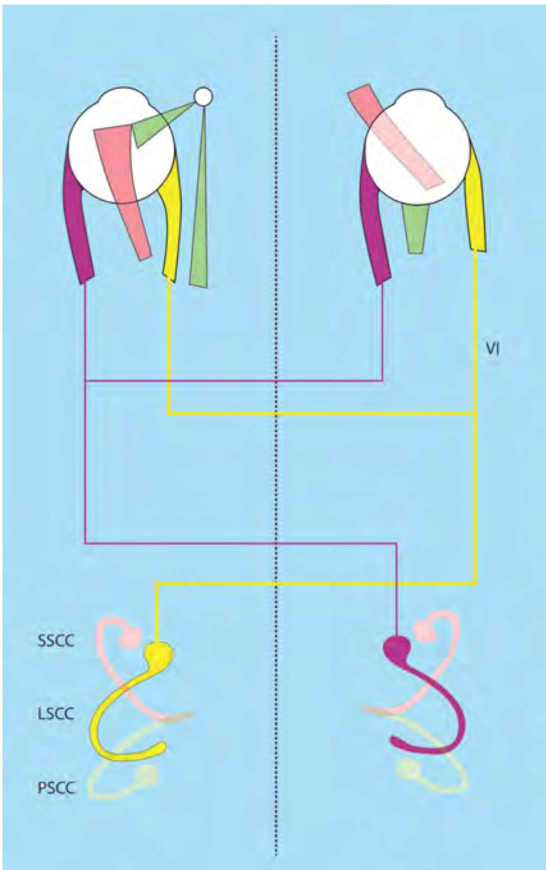
Semicircular canals and eye muscles



SSCC = anterior canal (superior canal),
PSCC = posterior canal, LSCC = lateral canal

- Look at the ‘wiring’ diagram opposite
- See how each canal is connected to a pair of extra-ocular muscles
- This diagram is complex especially when you realize that the right ear connections are not included. Nor are the inhibitory ones.
- Let us consider the lateral canal and its connections only

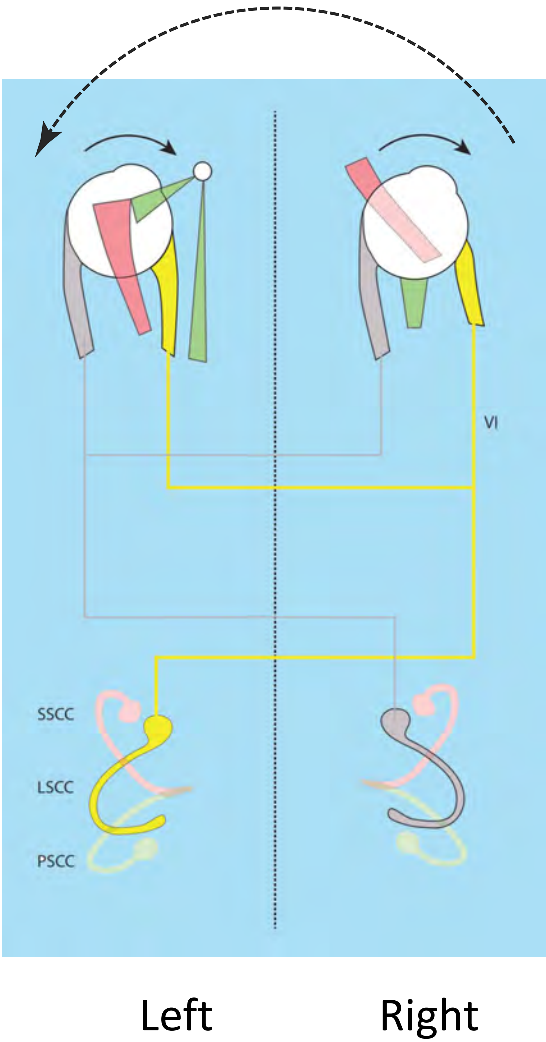
The lateral canals



Left Right

- The lateral canals are wired up to the muscles that move the eye laterally
- Both the canals supply tonic activity to the muscles so that those muscles are continually in a state of contraction
- All canals do this and all the extra ocular muscles are in a state of contraction
- This gives the eye posture and stops it swiveling around uncontrollably

The lateral canals



- The lateral canal on the left side will increase it's firing when the head turns to the left
- Increased firing will lead to an increase in activity within the nerves that innervate the lateral rectus muscle of the right eye and the medial rectus of the left eye.
- The opposite side will decrease its activity and the antagonistic muscles will relax.
- The effect will be to turn the eyes to the right.

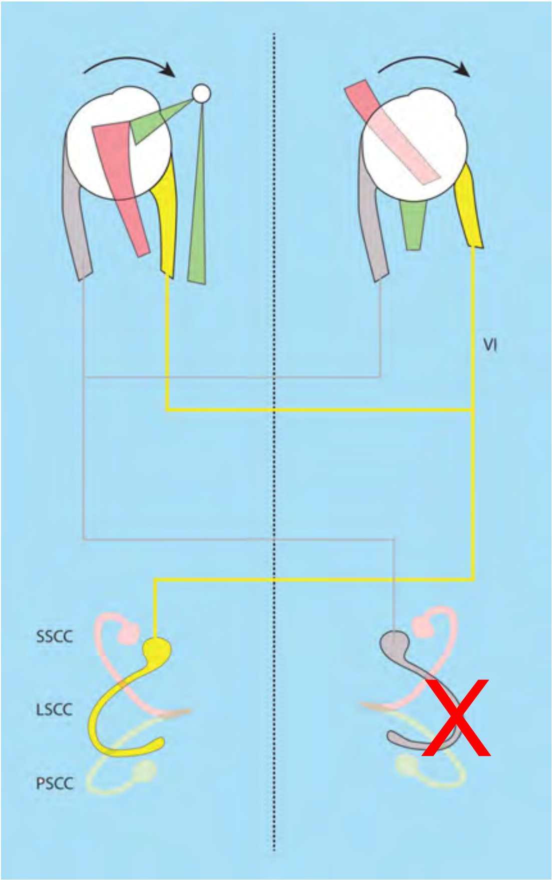
The lateral canals

X

- Try this: look at the ‘X’ and quickly turn your head to the left. Your eyes move to the right to keep fixated on the ‘X’.
- This is your lateral canals in action
- We test lateral canals with a head impulse test

Head Impulse test

The Lateral Canals and Nystagmus



Left Right

- What would happen if one of the ears was damaged and sent no information to the brain and the eye muscles?
- In this diagram the right lateral canal is weak and sending little information to the brain and eye muscles.
- The effect is that the eyes drift towards the right because of the unopposed action of the muscles innervated by the left canal (yellow).
- This is the pathological phase of nystagmus. Soon central correction will occur, and the eyes will snap back into place. Thus, there is a slow phase and a fast phase with nystagmus.

Nystagmus in Ear Disease

- Nystagmus has a slow phase towards the diseased ear followed by a fast phase away from the diseased ear.

- Nystagmus is traditionally defined by its fast phase so the description 'left beating nystagmus' means nystagmus with a fast phase to the left.

- In ear disease the eyes beat away from the underactive labyrinth. So left nystagmus implies that the right labyrinth is underactive and vice versa.

- Nystagmus obeys Alexander's Law and we will discuss this when we look at skills training in vestibular disease.

Nystagmus – Left Beating