The Vestibular System and Equilibrioception

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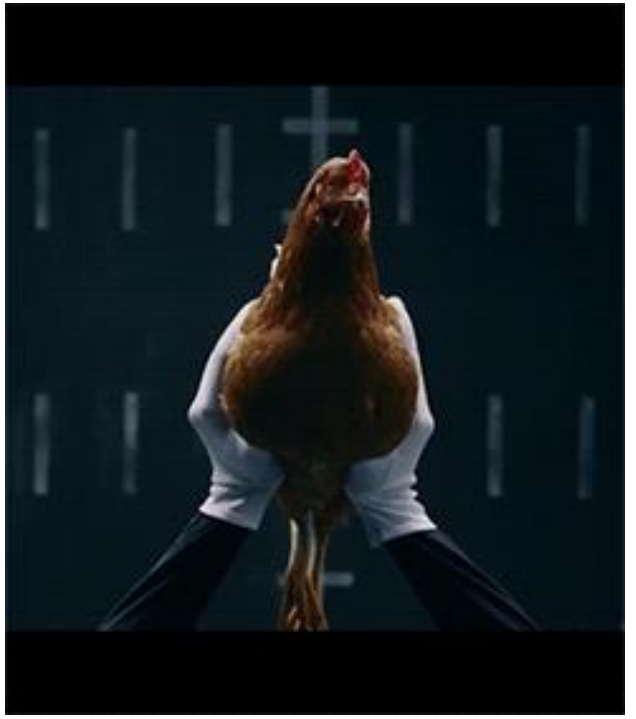


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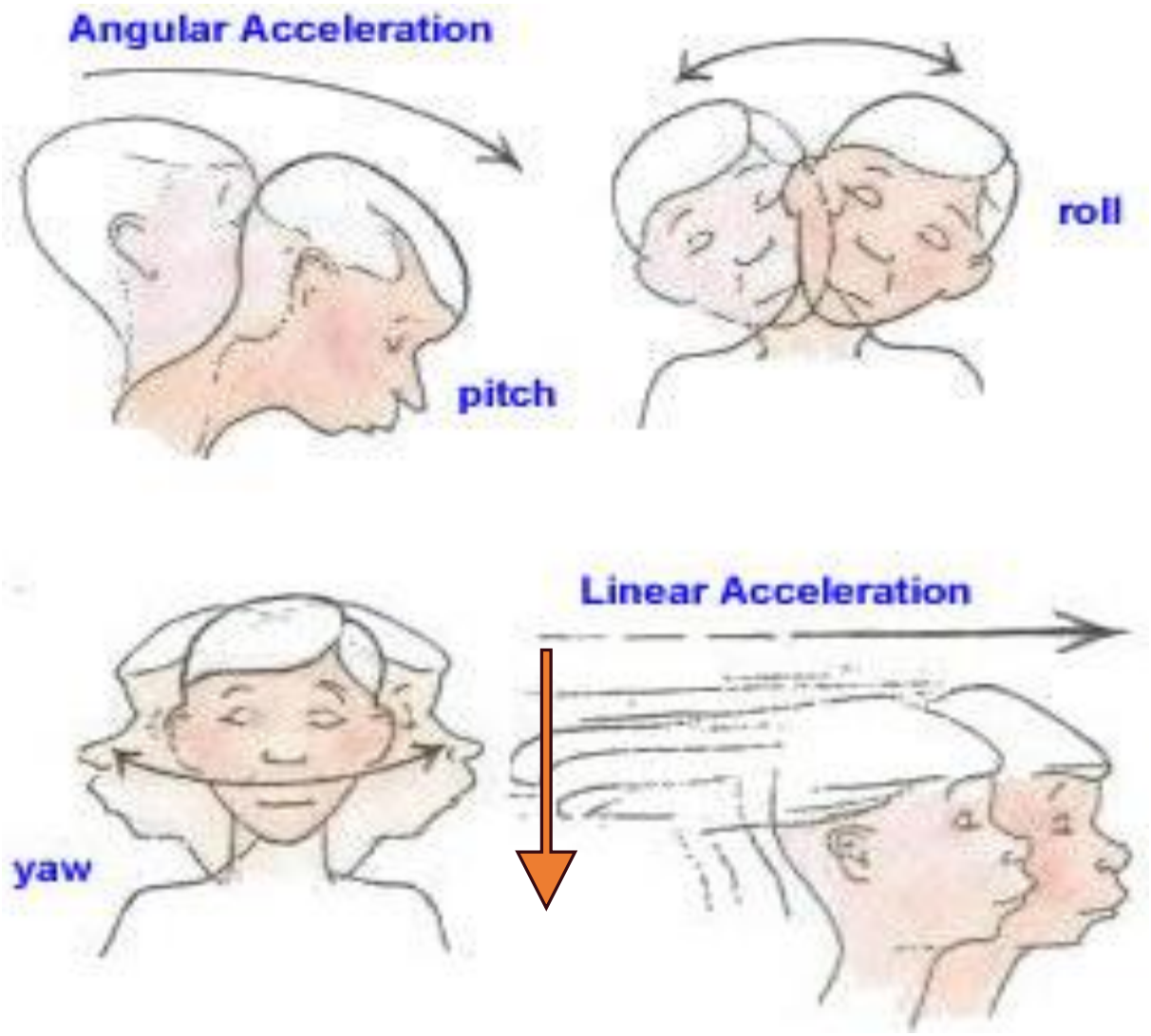
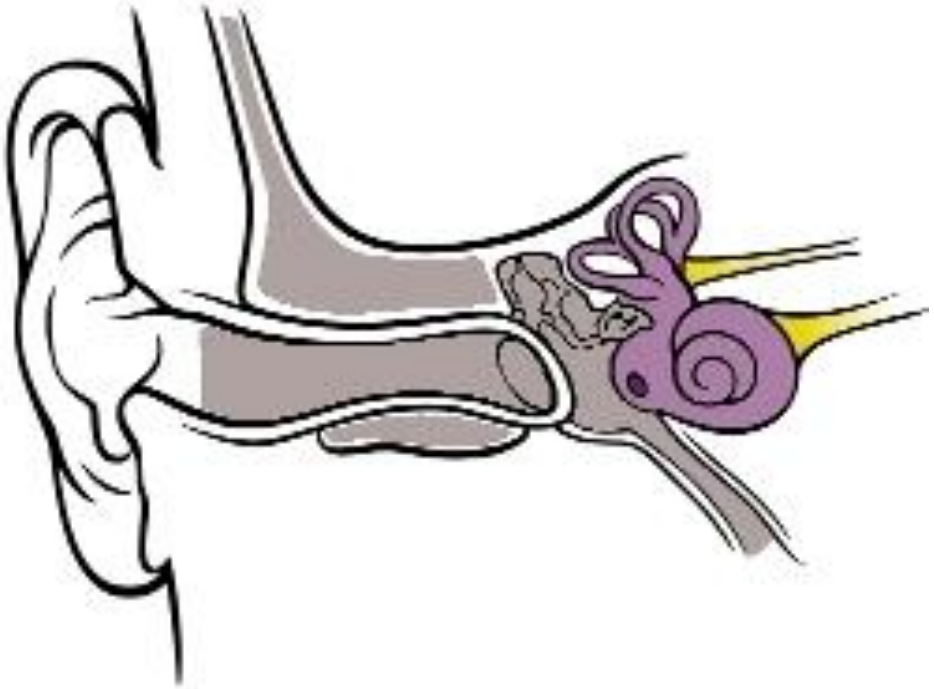
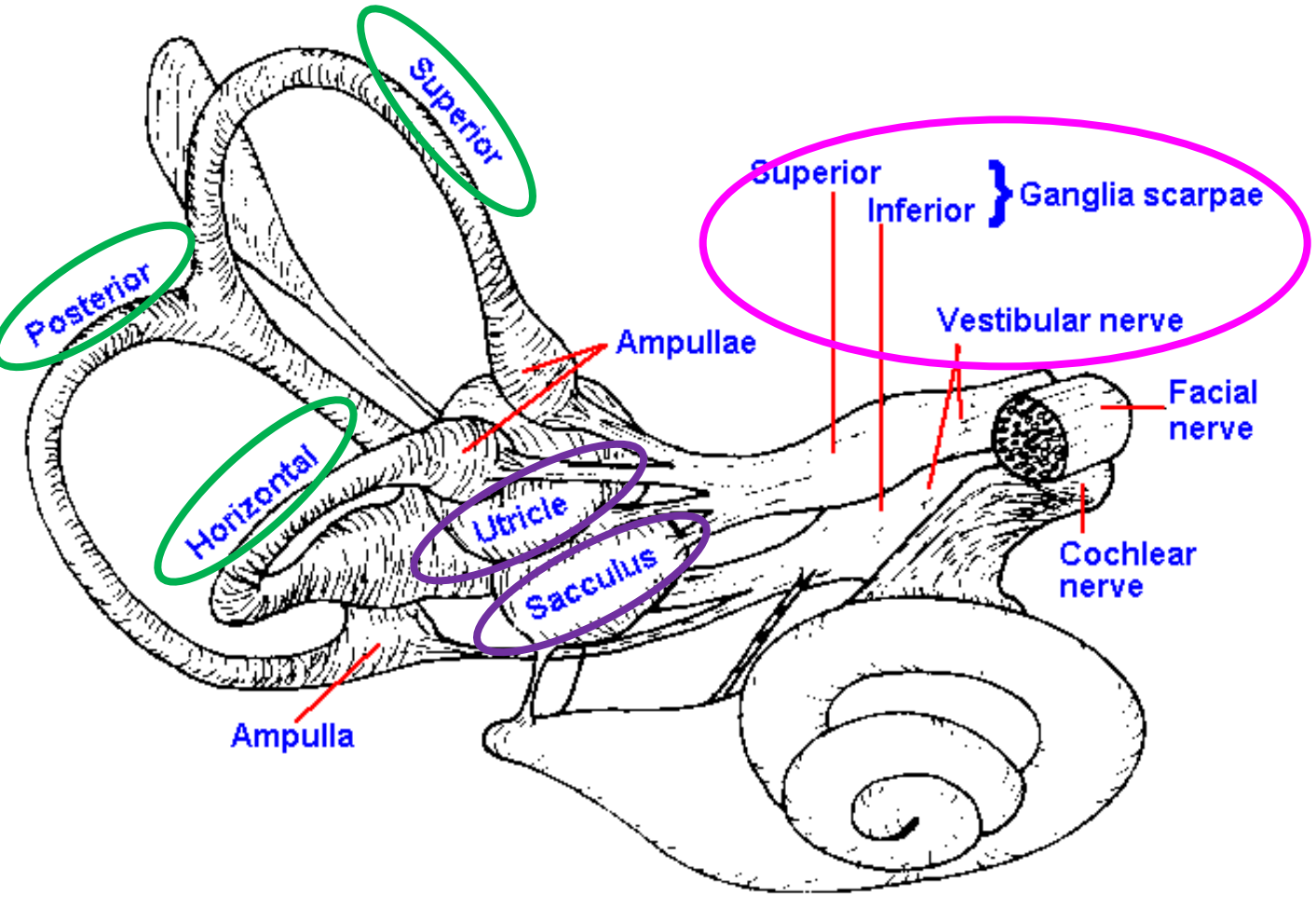


Head motions, in the form of <u>angular and linear accelerations</u> relative to the gravity vector, is detected by the vestibular system in the inner ear.



The Vestibular Inner Ear

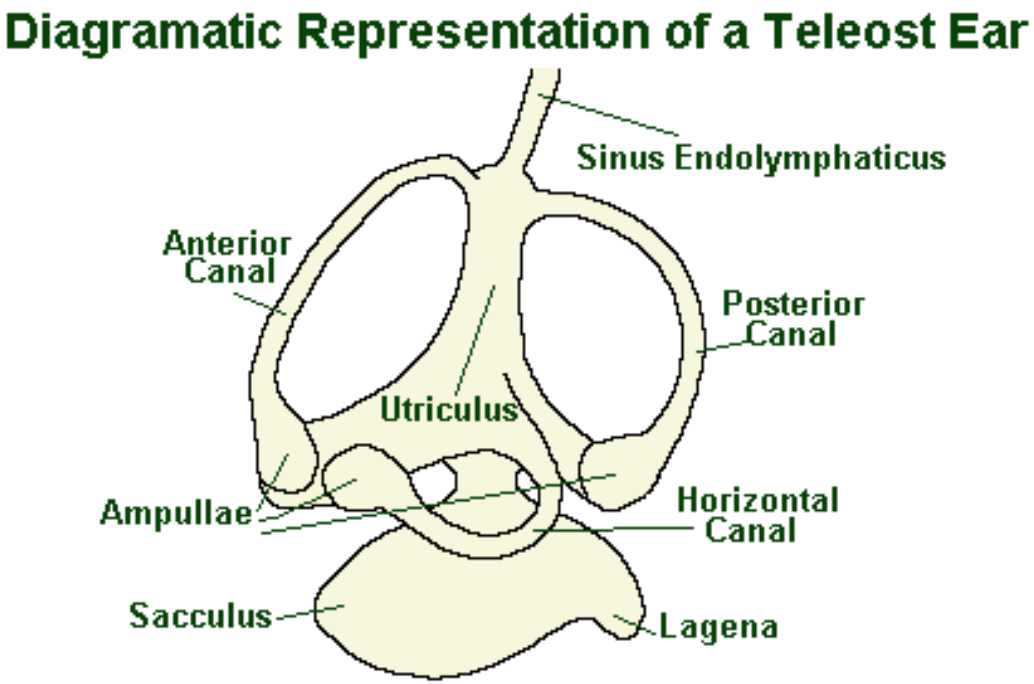


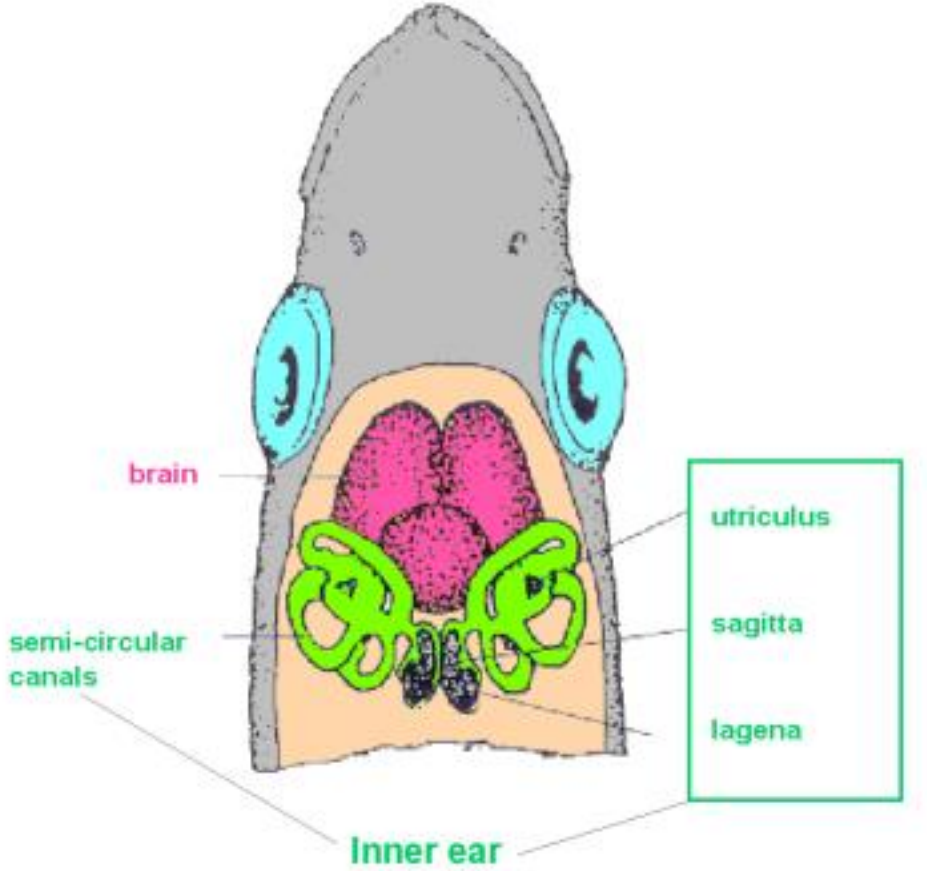
- Vestibular labyrinth: 5 vestibular organs per ear
  - (3) Semicircular canals: Angular acceleration detectors; superior, posterior and horizontal arranged in three different planes.
  - (2) Otolith organs: Linear acceleration; utricle and saccule arranged in two different planes.
  - Vestibular nerve: innervate the 5 organs; superior and inferior ganglia converge with spiral ganglia to form VIII (vestibulocochlear) cranial nerve

Otolith means ear rock!

In fish: no cochlea, but similar balance organs

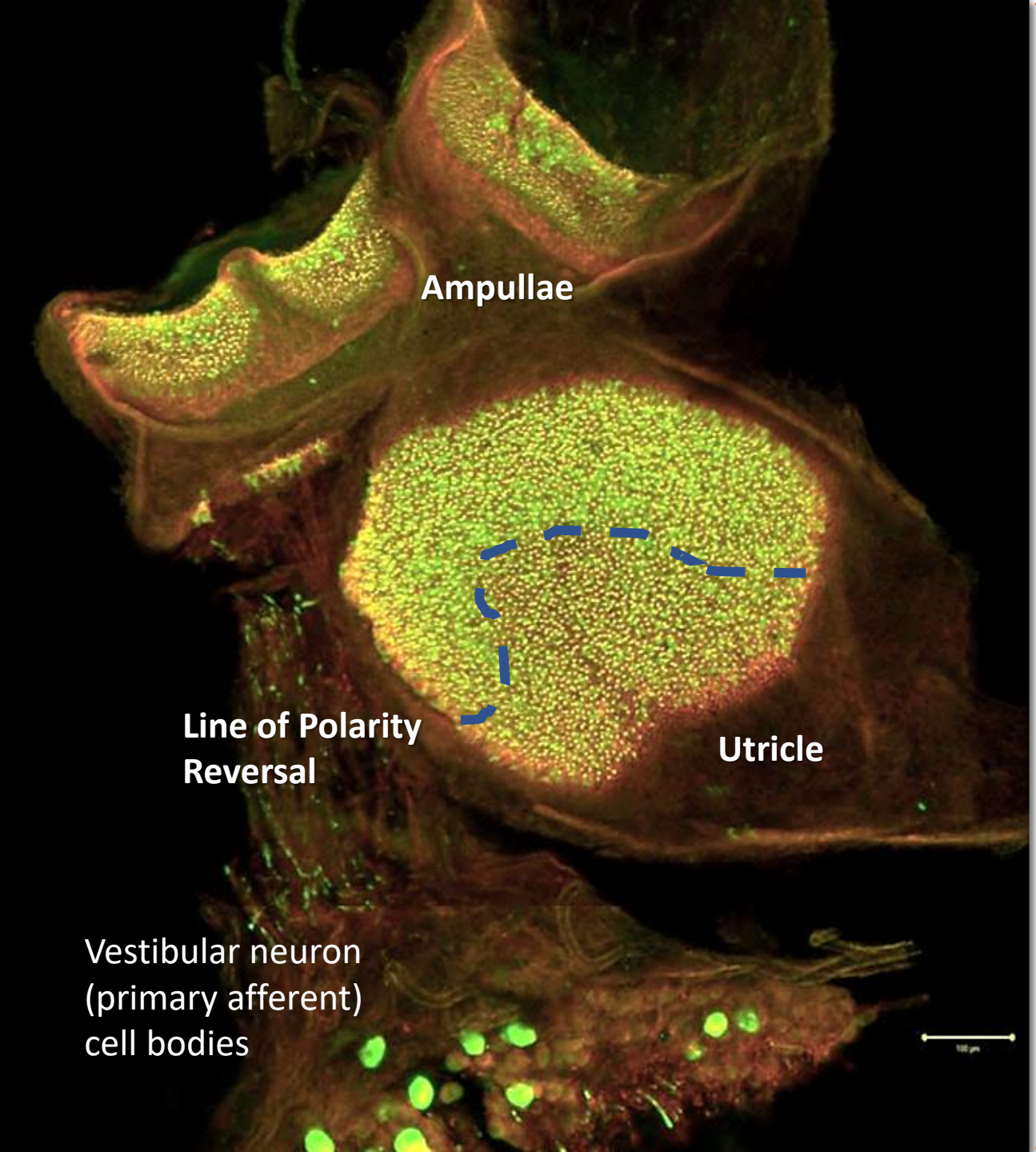
Sound travels further and faster in water than it does in the air, about 4.4 times as fast

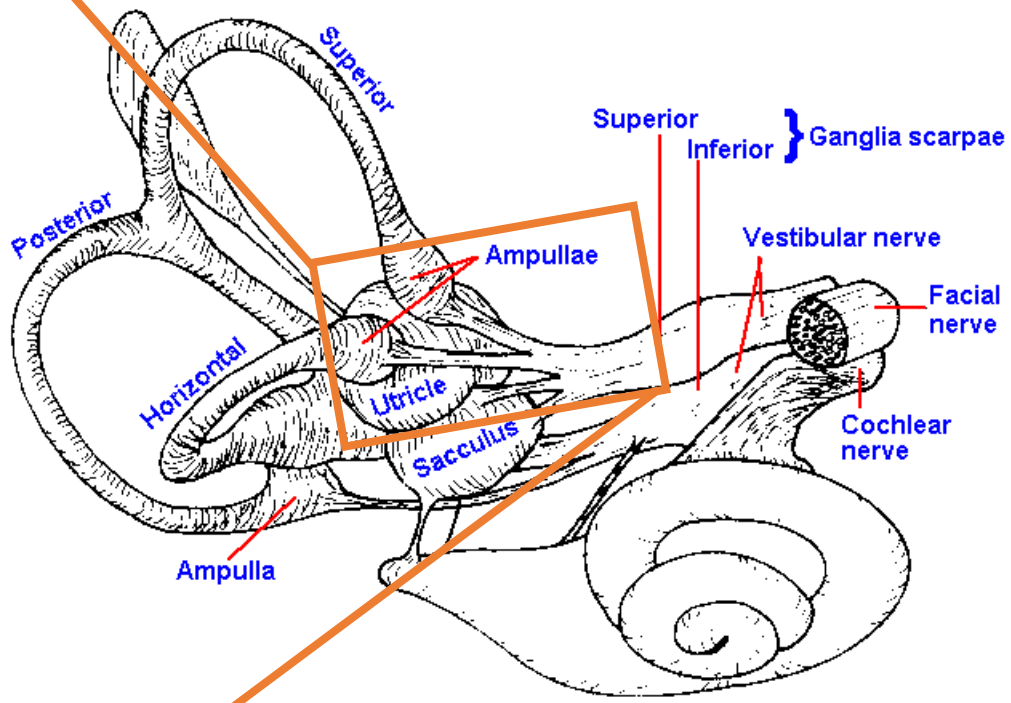




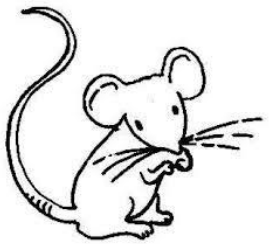
The 'utriculus', the 'sacculus', and the 'lagena' each contain a single otolith; scientists can often identify a species of fish just from the otoliths.

Mammalian Vestibular Organ IRL





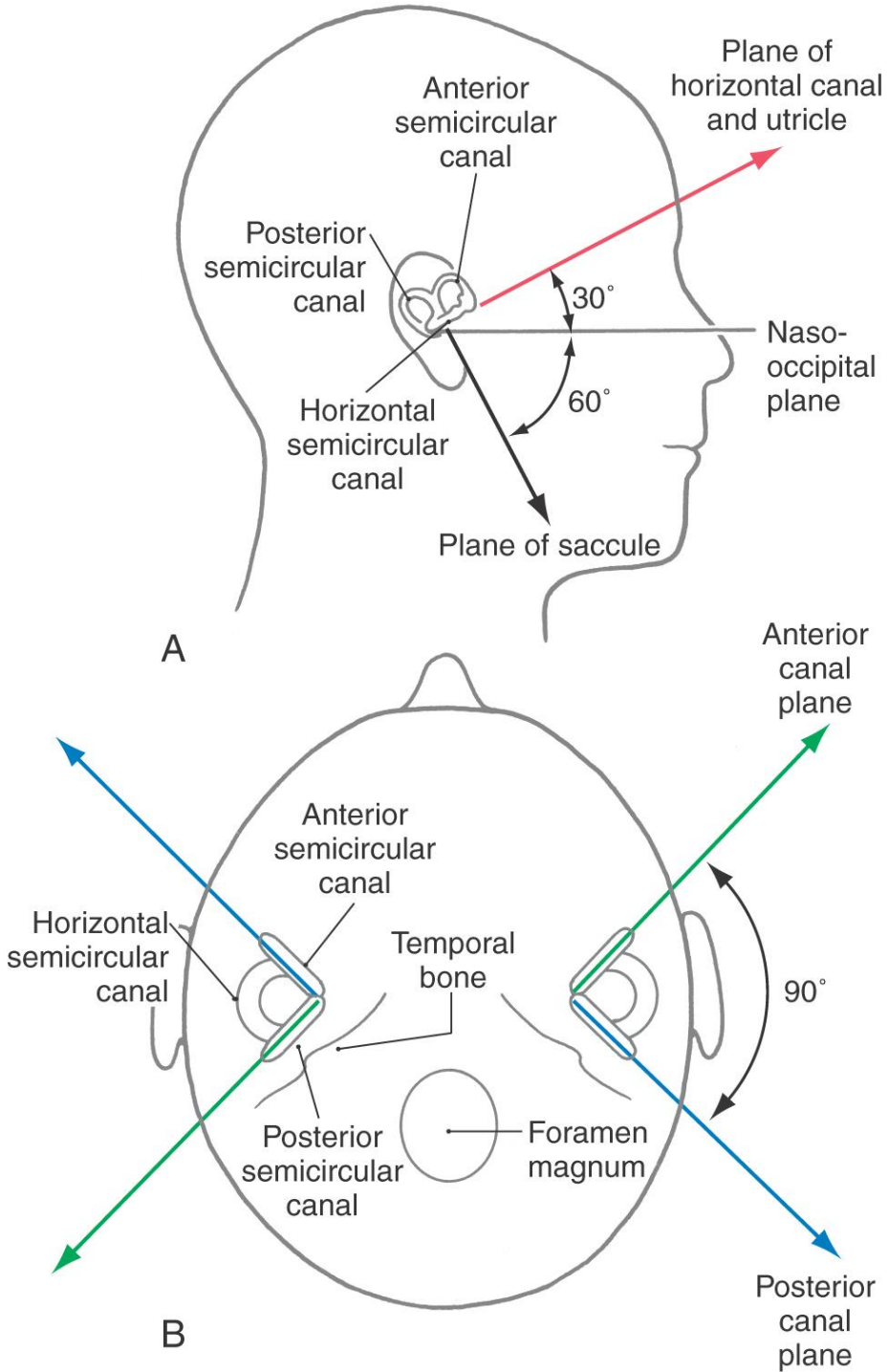
Part of vestibular organ dissected from a mouse and stained with neural markers (from Jingbing Xue, Eatock Lab)



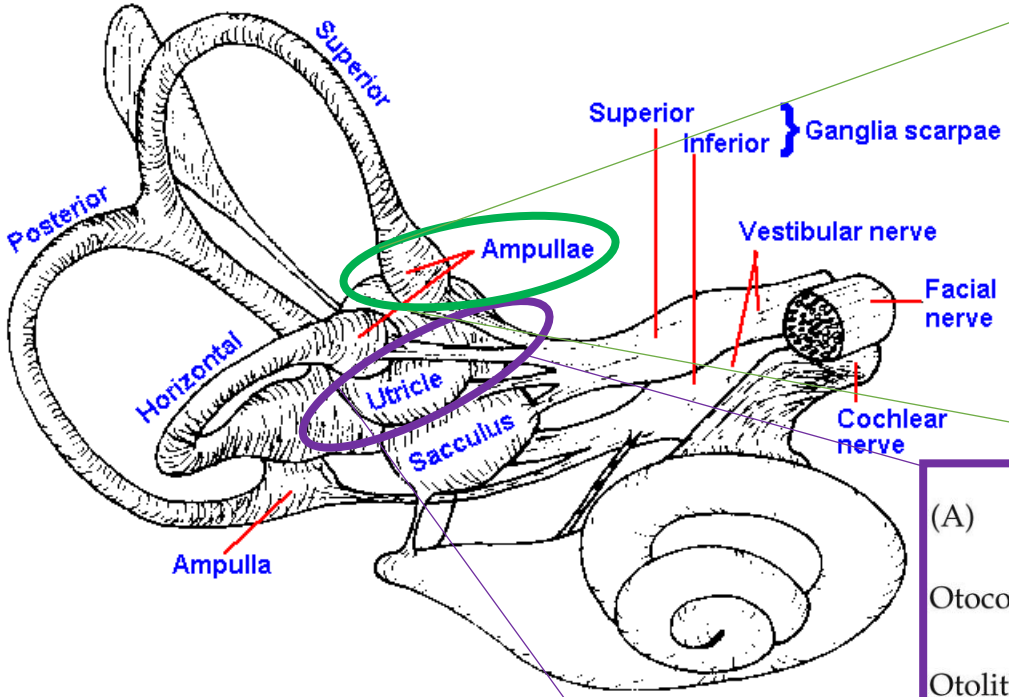
Note that the sensory epithelia are angled at specific orientations in your head

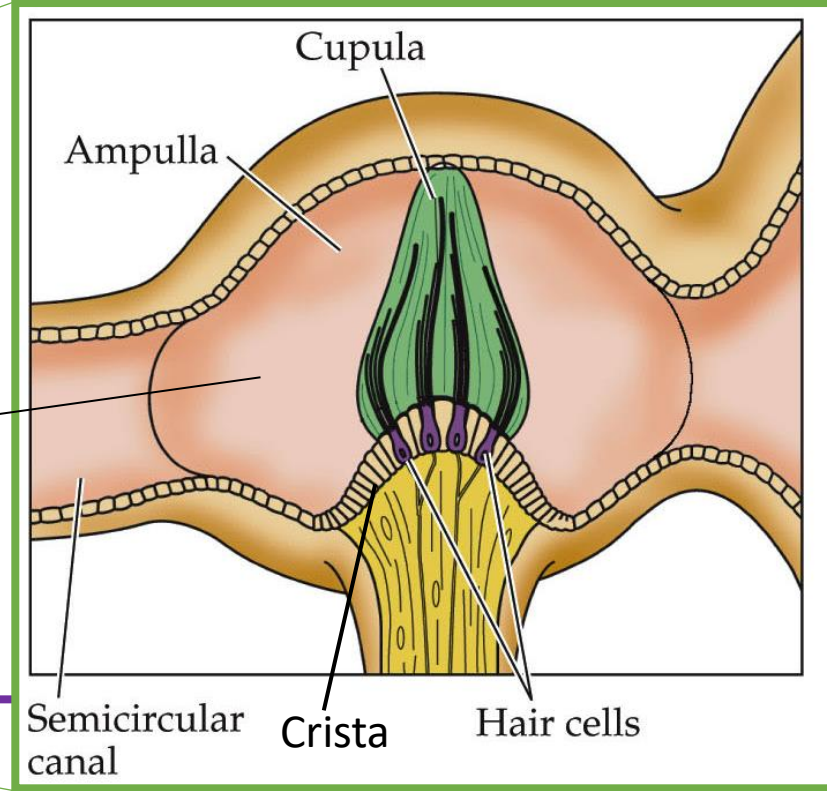
<u>Otolith organs:</u>
Utricle: horizontal plane
Saccule: vertical plane

<u>Semicircular canals:</u>
Horizontal canal: horizontal plane
Anterior & posterior canals: rotational angles 90 deg to each other.

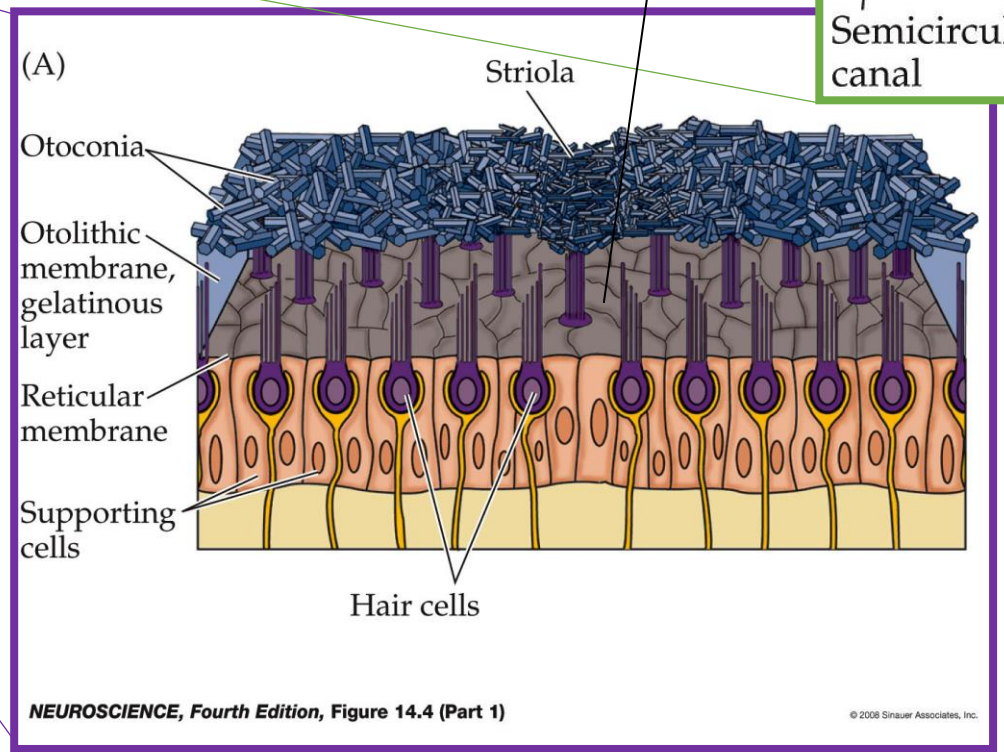


Hair cells do the “sensing”





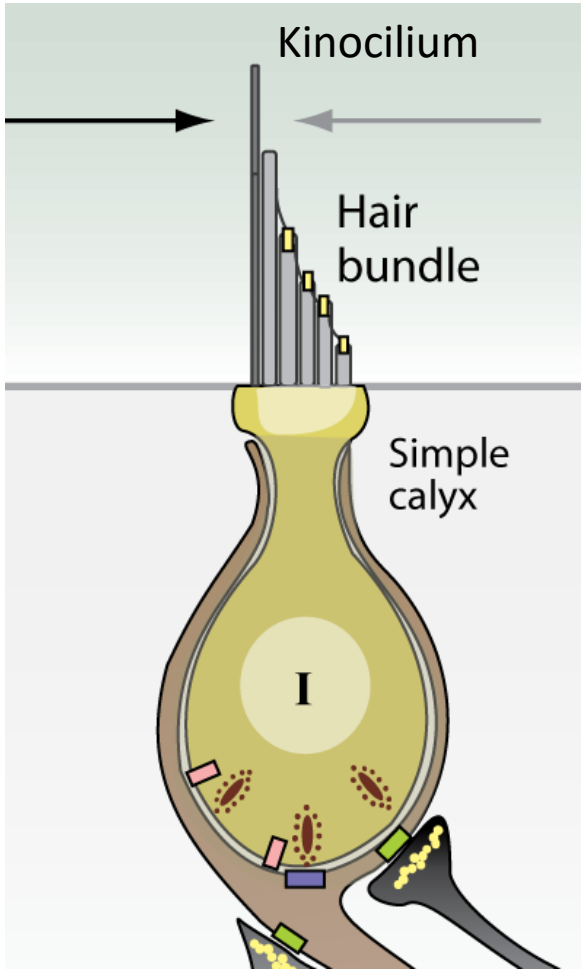
K+ rich Endolymph

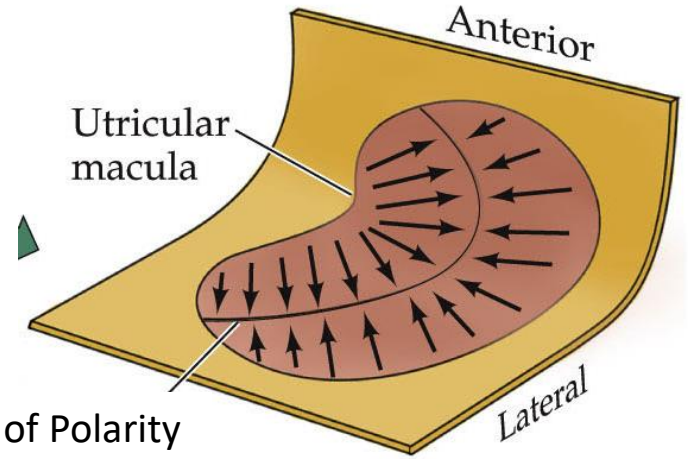


In semicircular canals, hair cells are in the crista and hair bundles (in cupula) are deflected by fluid motion of endolymph.

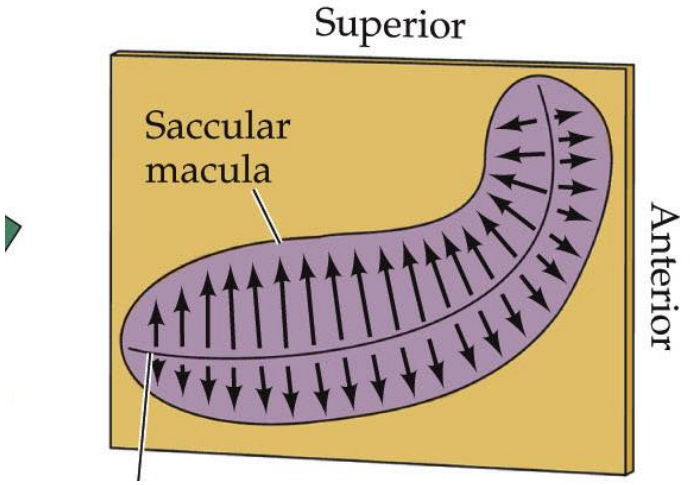
In otolith organs (utricle & saccule), hair cells are embedded in sensory epithelia (macula) and hair bundles are deflected by otolith gel matrix

- Hair cells can be deflected in positive and negative directions
- Firing rate of the vestibular neuron increases or decreases along a baseline firing rate
- Direction of hair bundles changes along line of polarity reversal in otolith organs, but NOT in ampullae of semicircular canals
- Incredibly sensitive; but how sensitive is sensitive?
  - ~10 nm, shorter for longer hair bundles



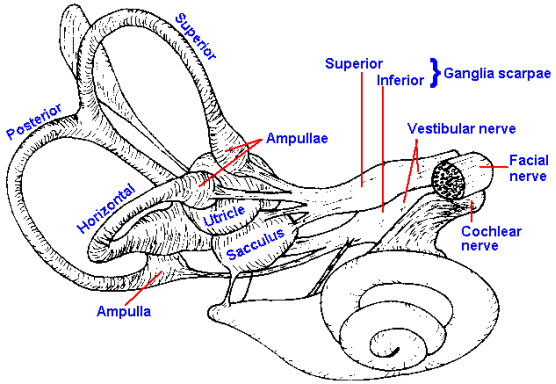


Line of Polarity Reversal

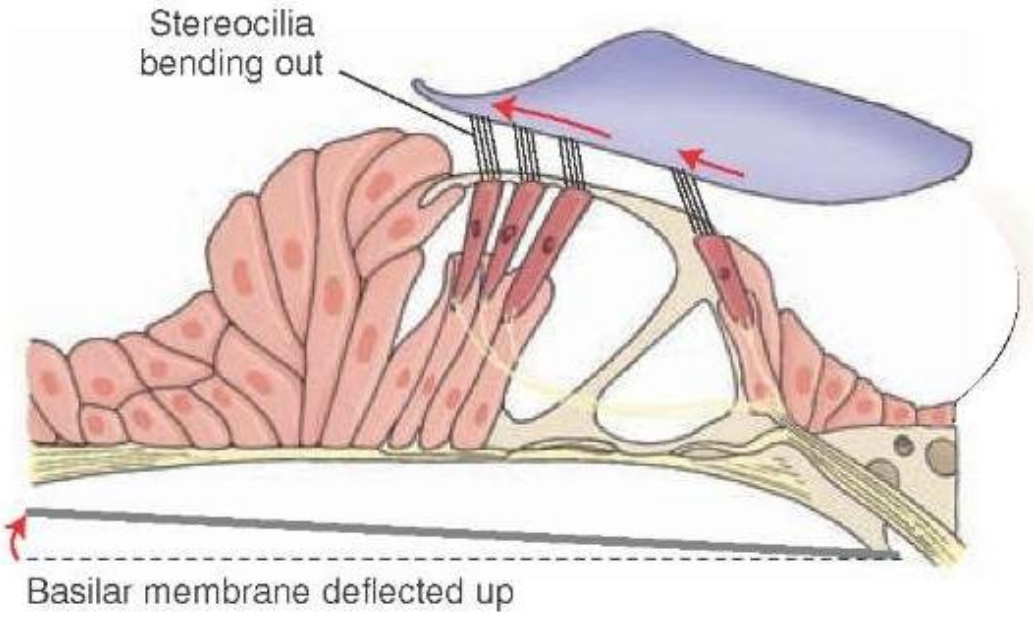


Line of Polarity Reversal

What's faster?

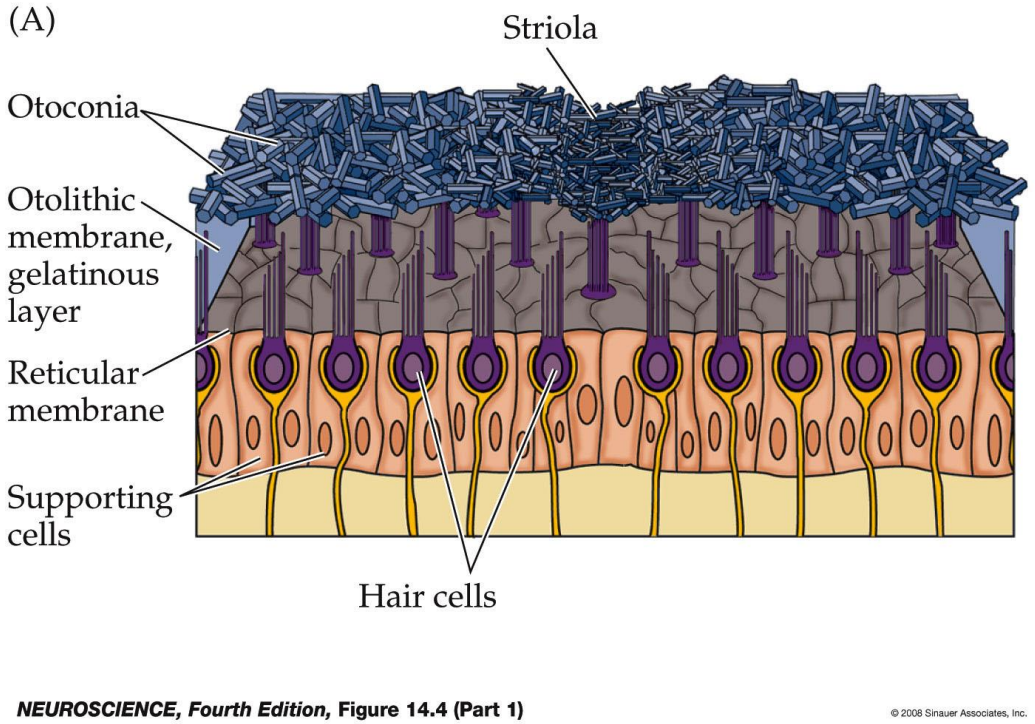


Auditory inner hair cells



OR

Saccular hair cells

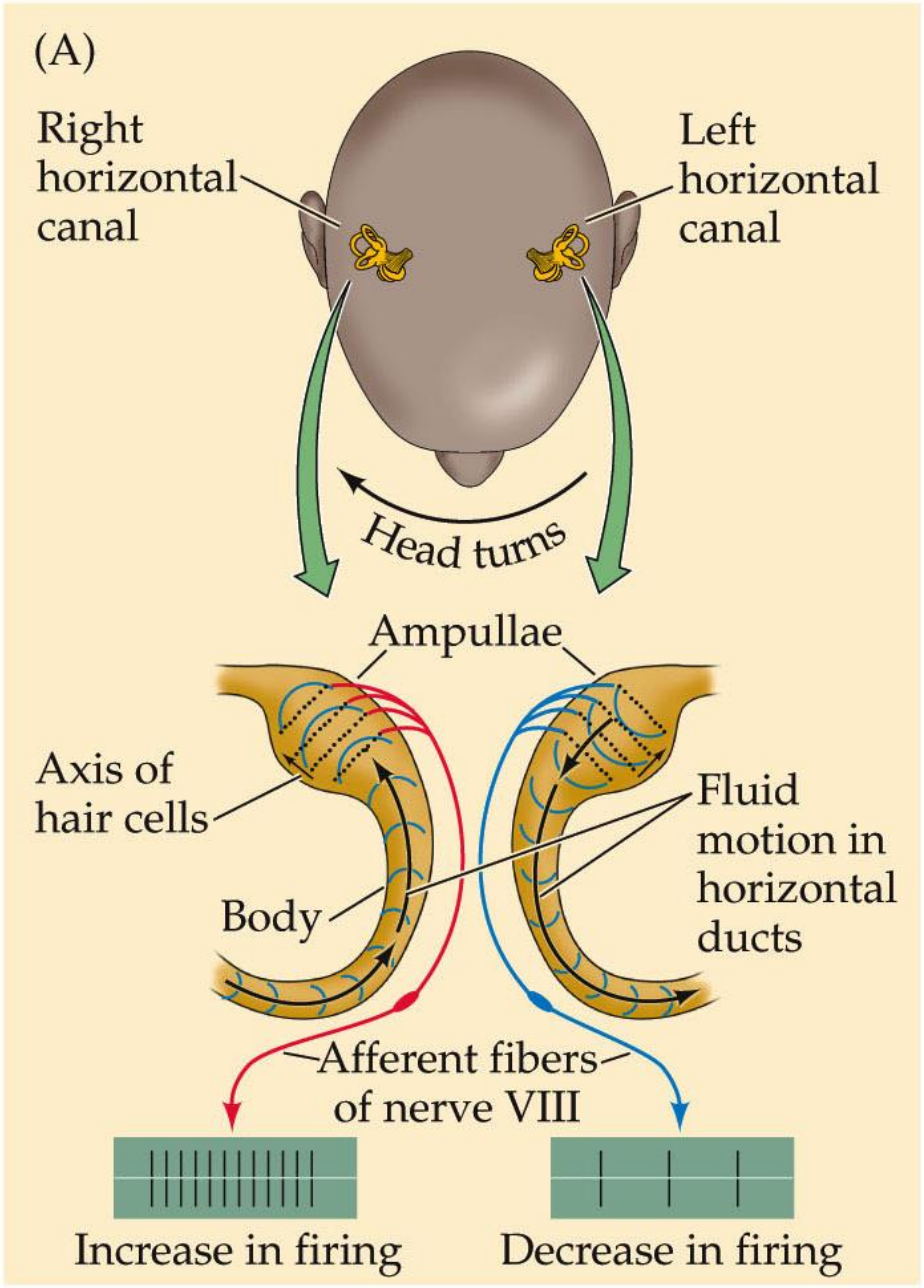


NEUROSCIENCE, Fourth Edition, Figure 14.4 (Part 1)

In response to acoustic clicks (800 Hz at >80 dB), auditory fibers had 1.0 ms latency while saccular fibers showed 0.7 ms latency (McCue & Guinan, *J Neuro*, 1994).

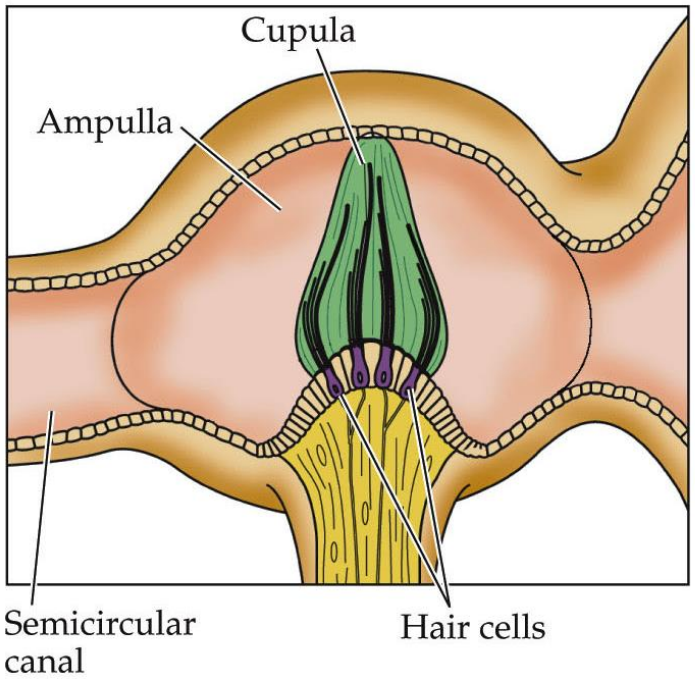
Bottom line: peripheral vestibular processing is FAST!

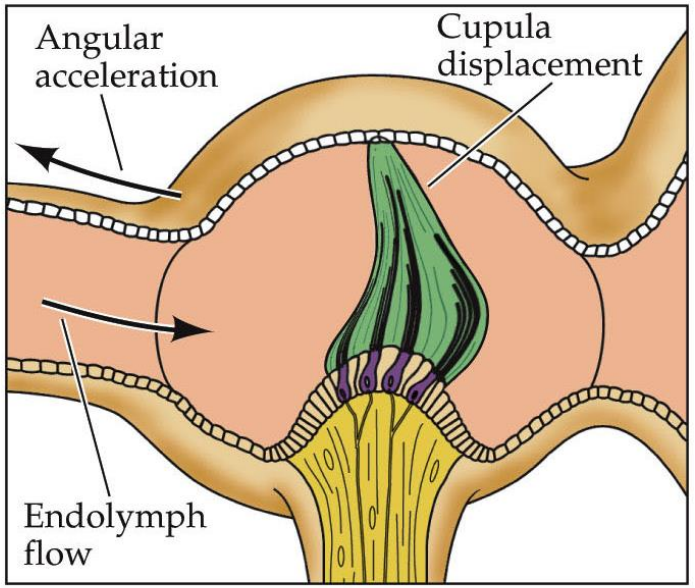
How does it work?



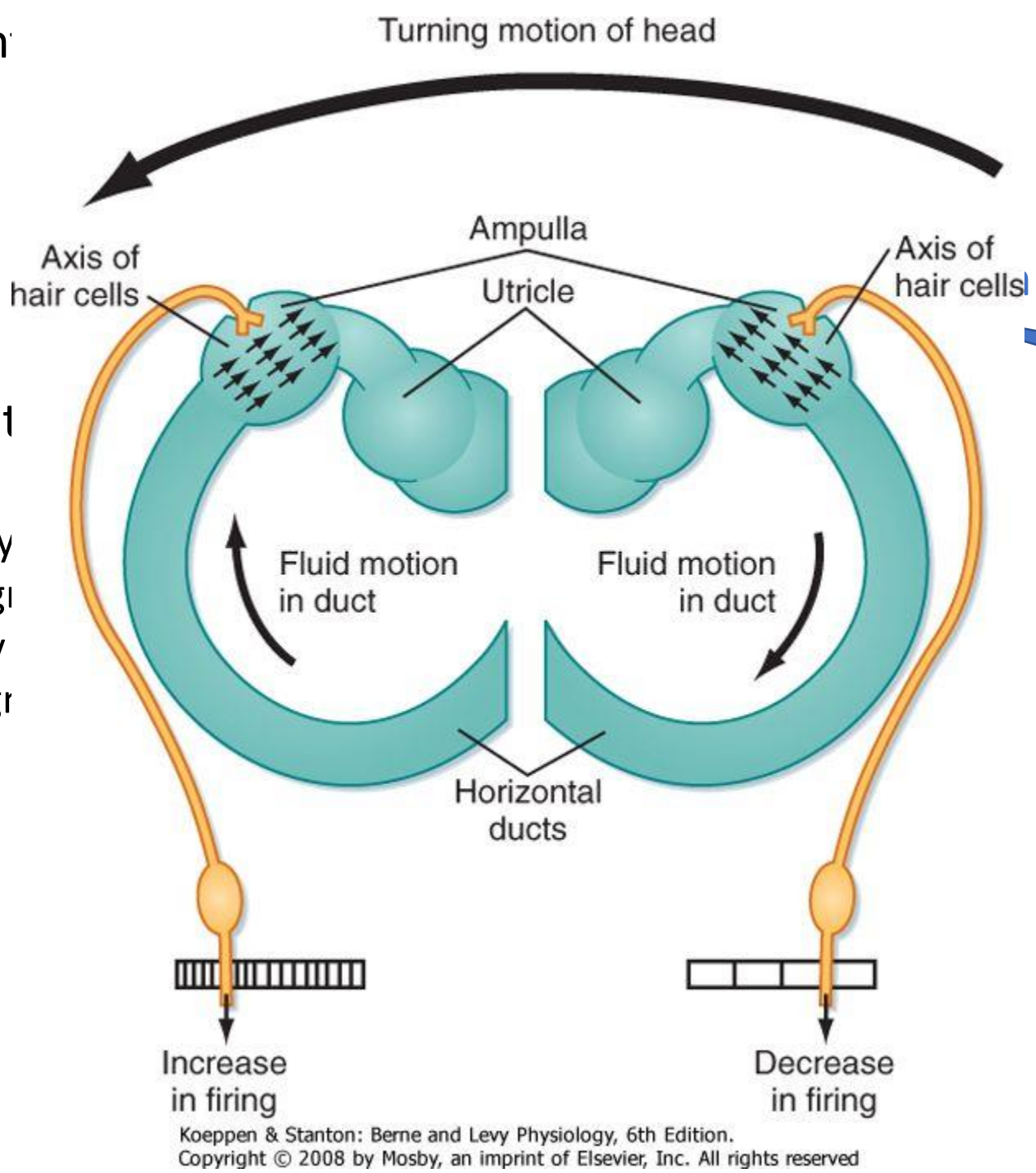
In the semicircular canal:

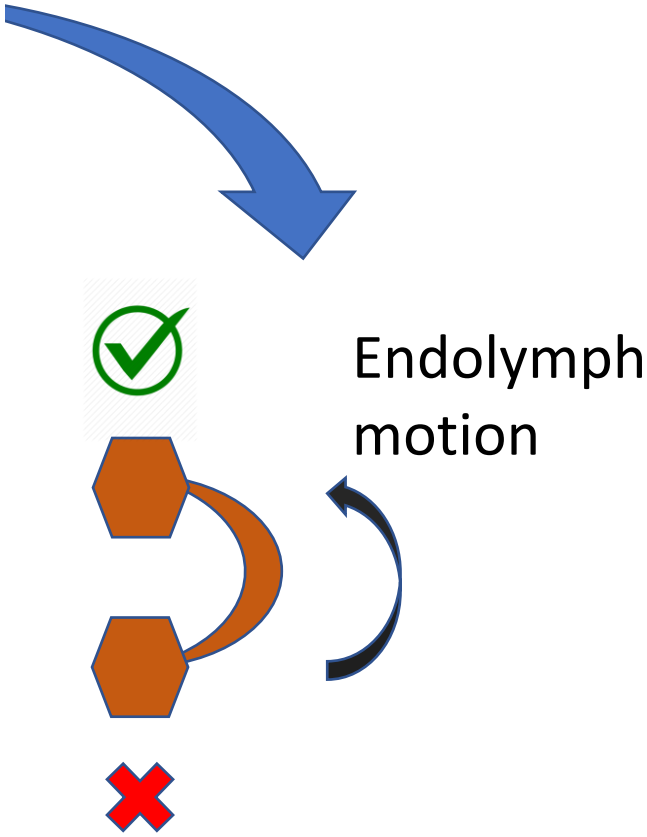
Rotations of the head in the plane of a semicircular canal causes movement of the endolymph fluid which applies force to cupula. Hair cells in base of cupula encode the magnitude of cupula deflection.





1) Head turns to the righ
2) Endolymph fluid in canals experience inertial lag relative to head motion
3) This flow deflects the cupula, which stimulat hair cells
   a) Right canal is positively stimulated (excitatory sig
   b) Left canal is negatively stimulated (inhibitory sig

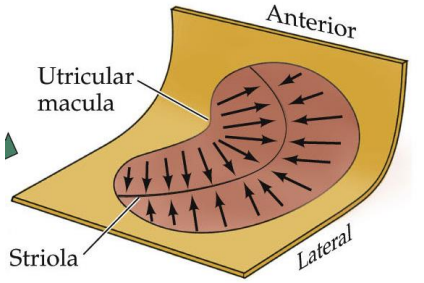


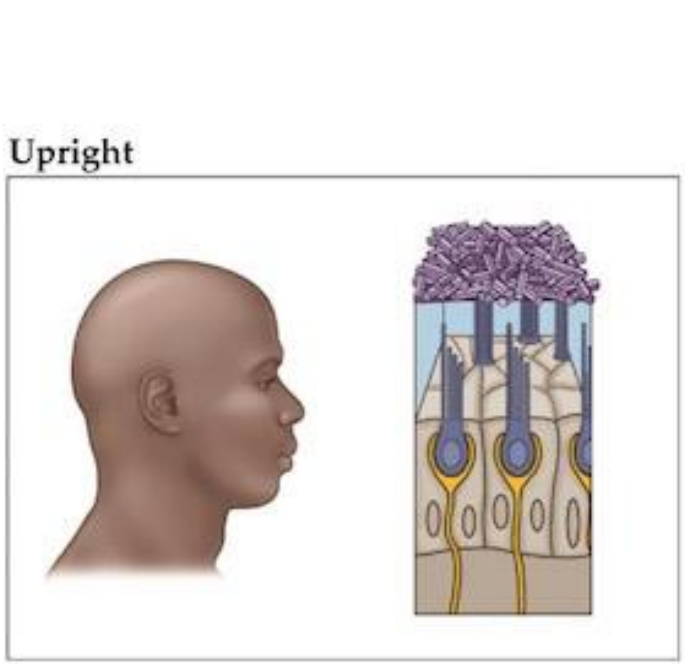


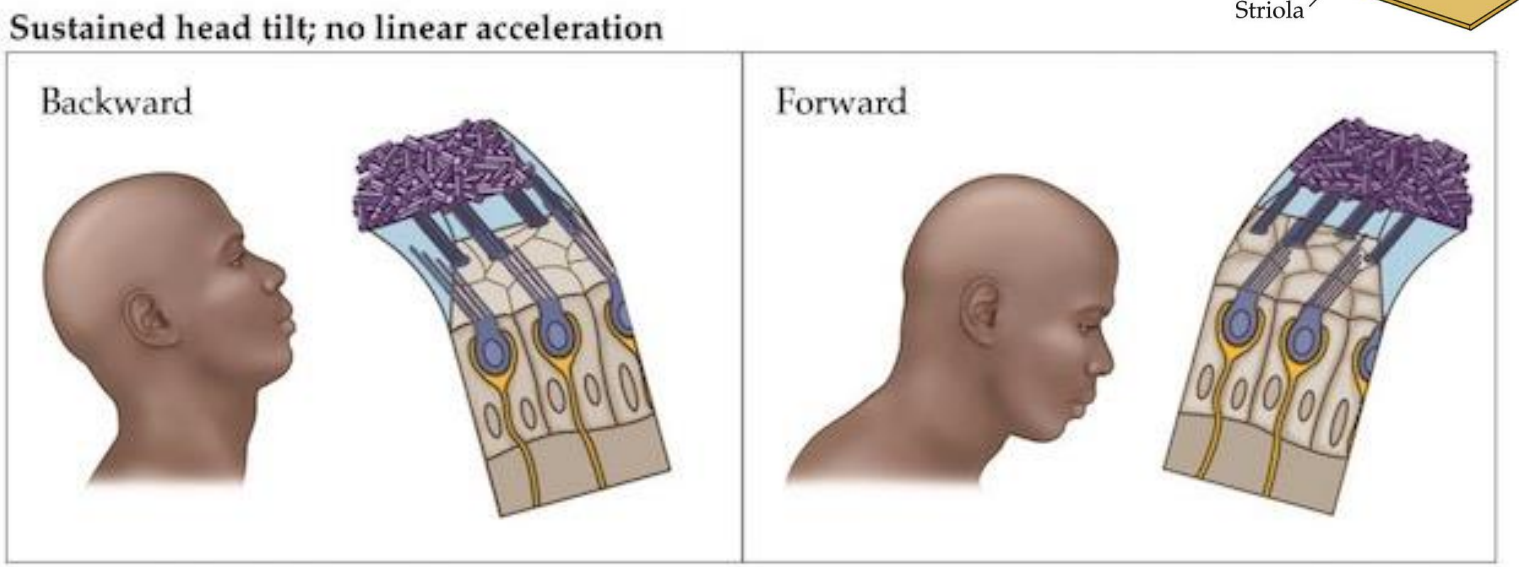
Endolymph motion

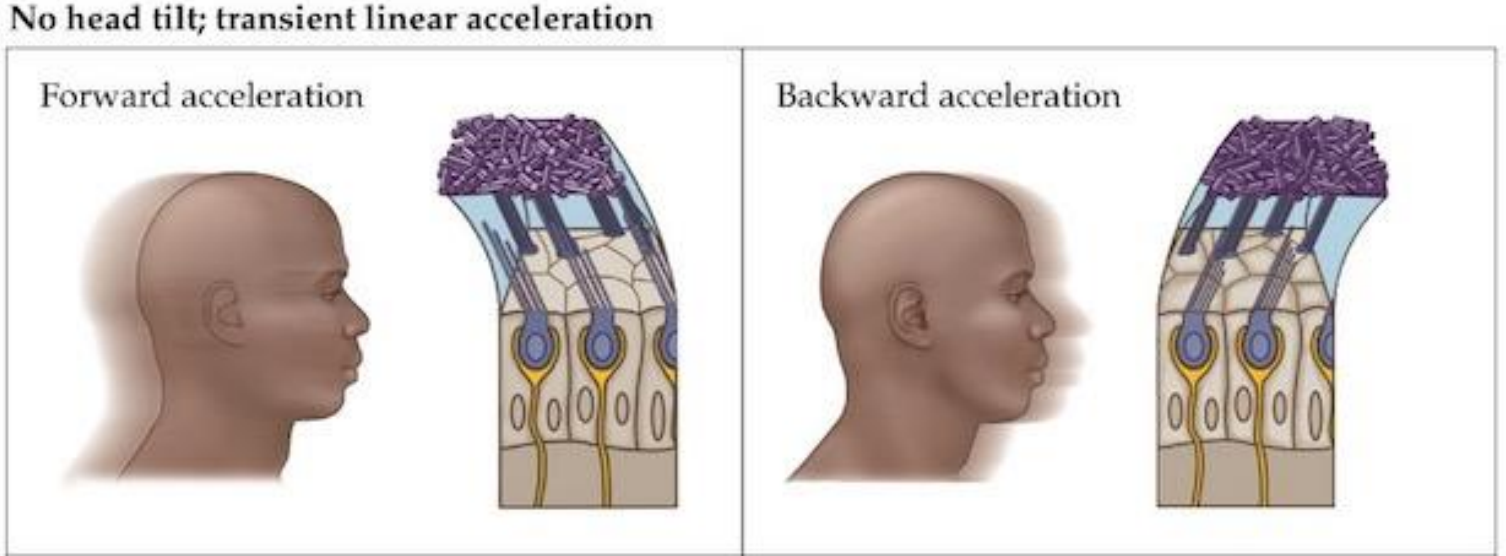
In otolith organs:

Displacement of otolithic membrane by inertial force stimulates hair cells.







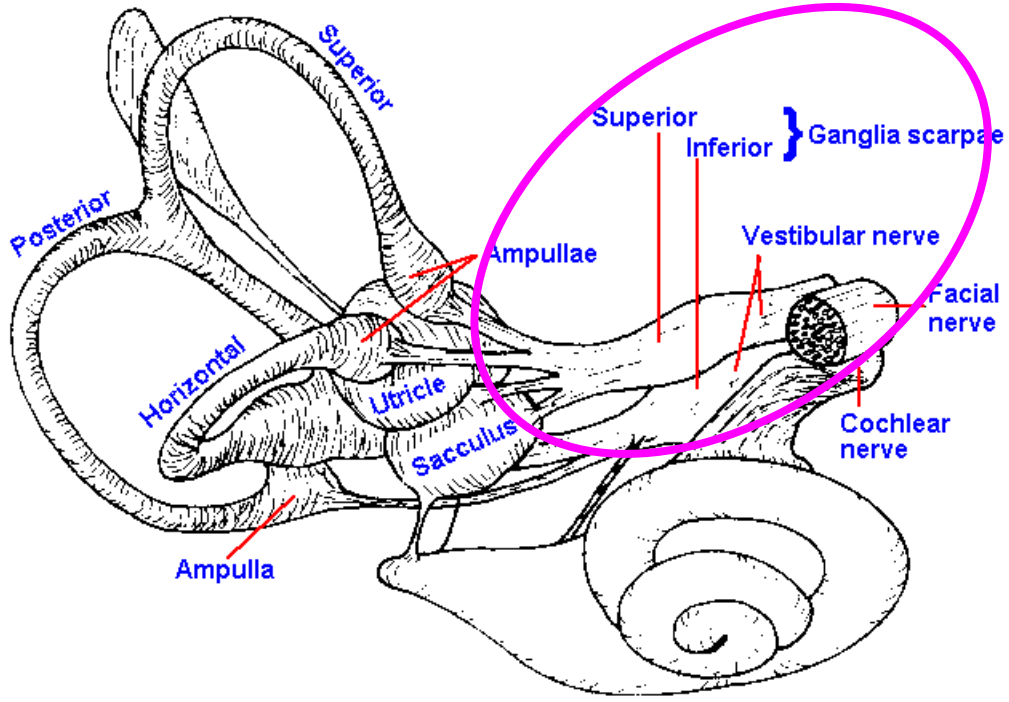


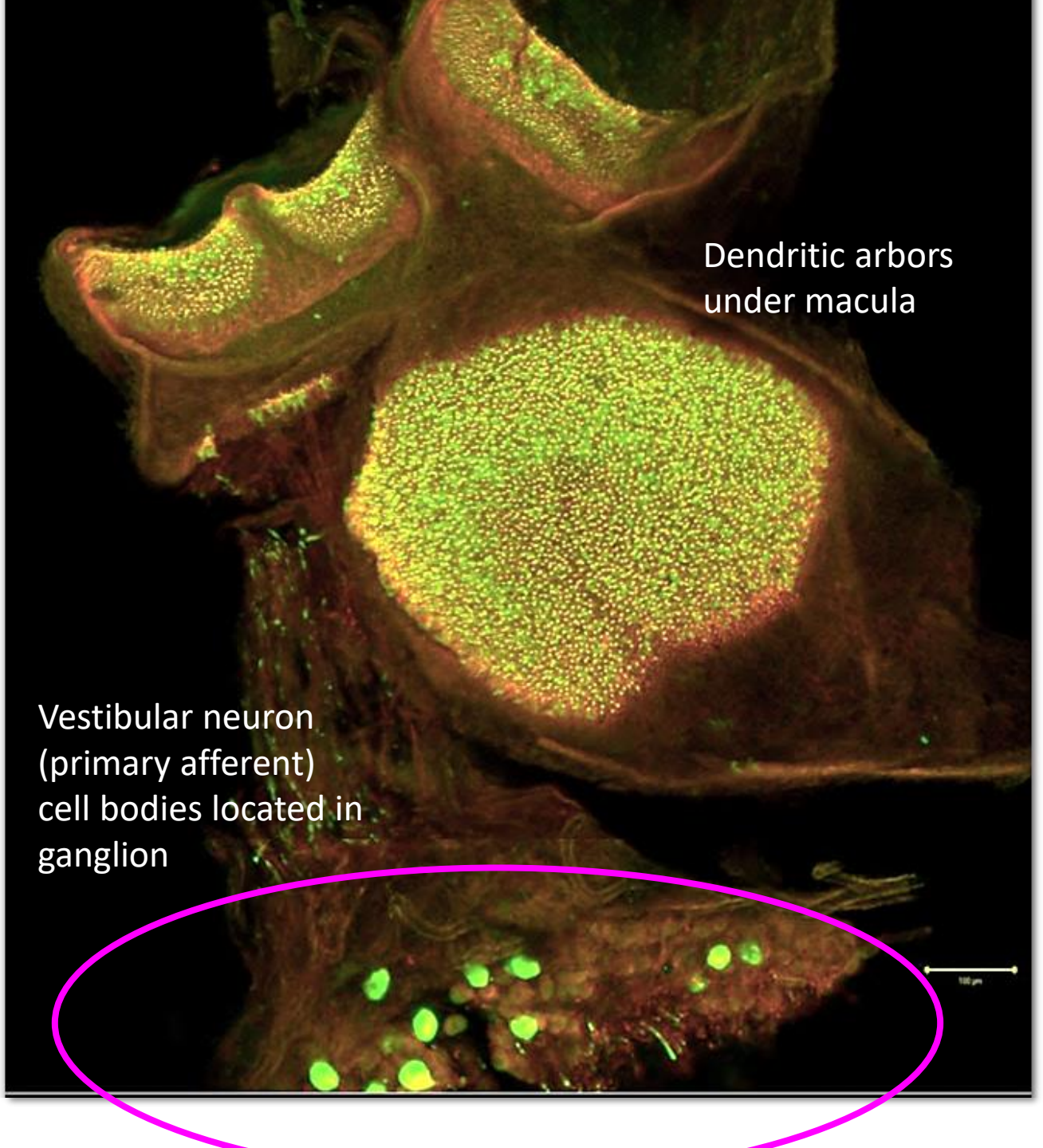
Are y’all with me so far?

- What specific vestibular organ is likely to sense motion of an elevator?
  - The abrupt stop of a car?
  - Shaking head side to side?

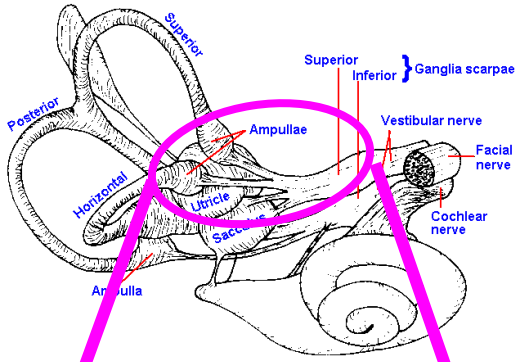
Primary vestibular afferents

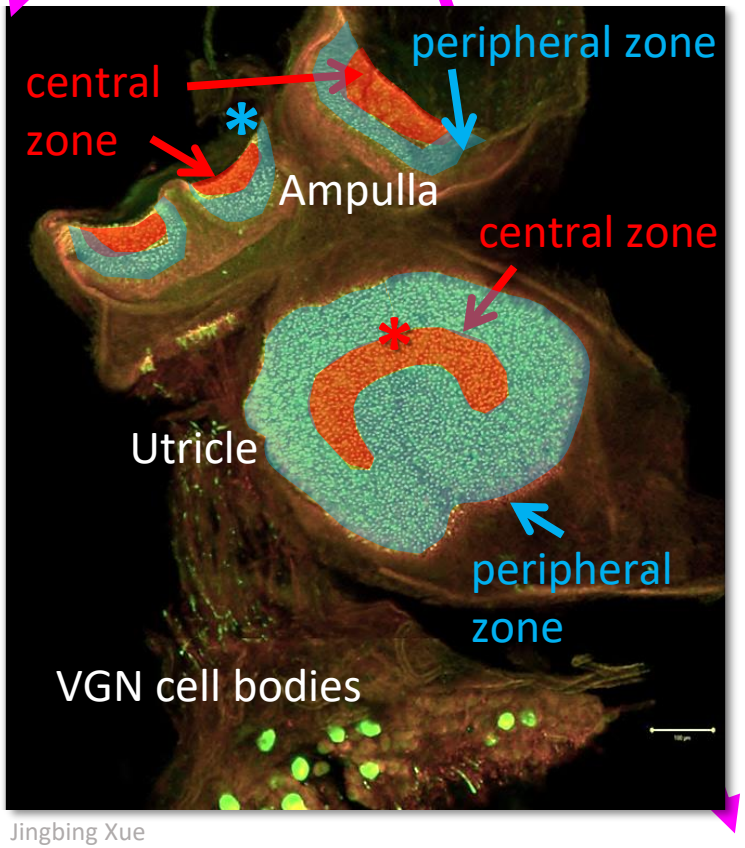
The vestibular nerve is made up of the primary vestibular afferents that take information from hair cells in the semicircular canals and otolith organs to the brainstem





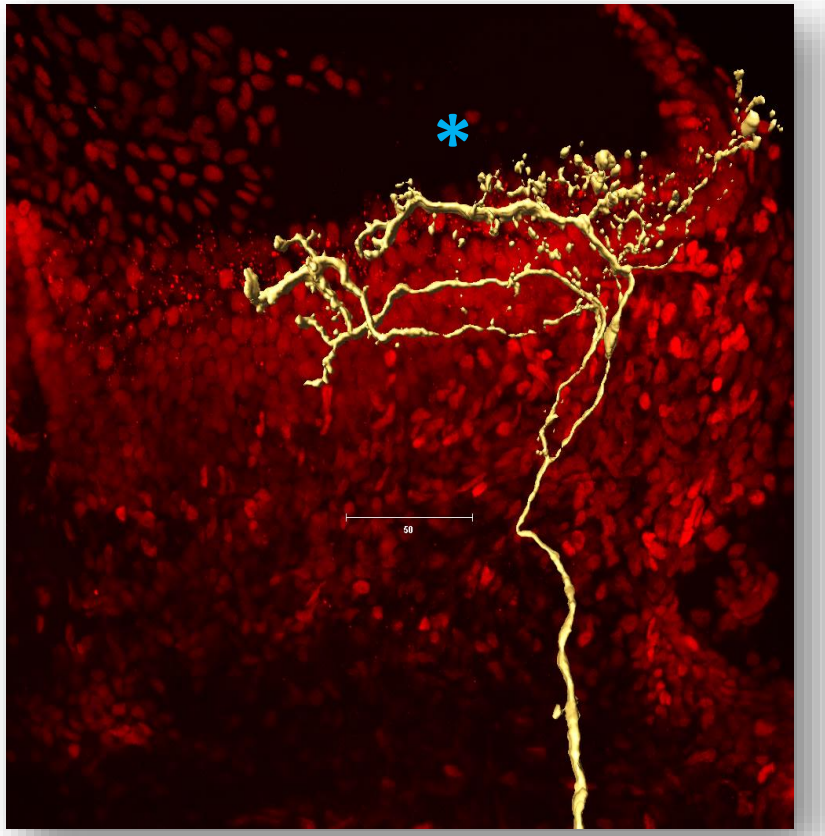
Vestibular afferents can have diverse dendritic morphology



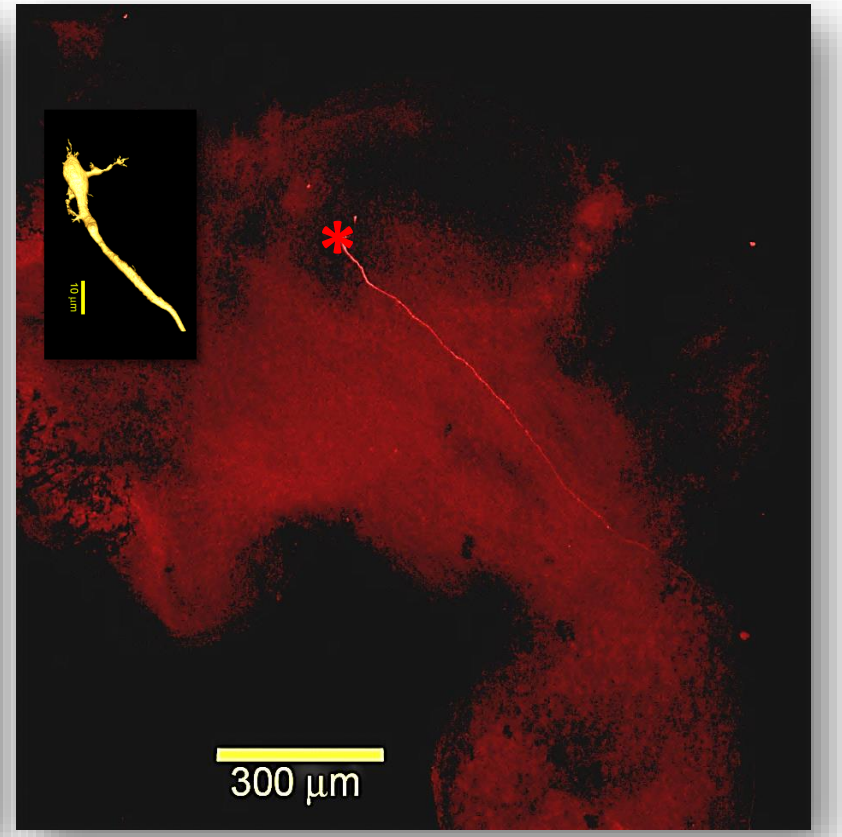


Jingbing Xue

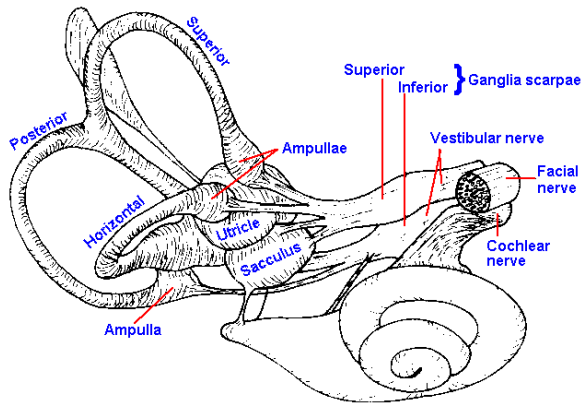
Peripheral terminal (crista)
Regular spike timing

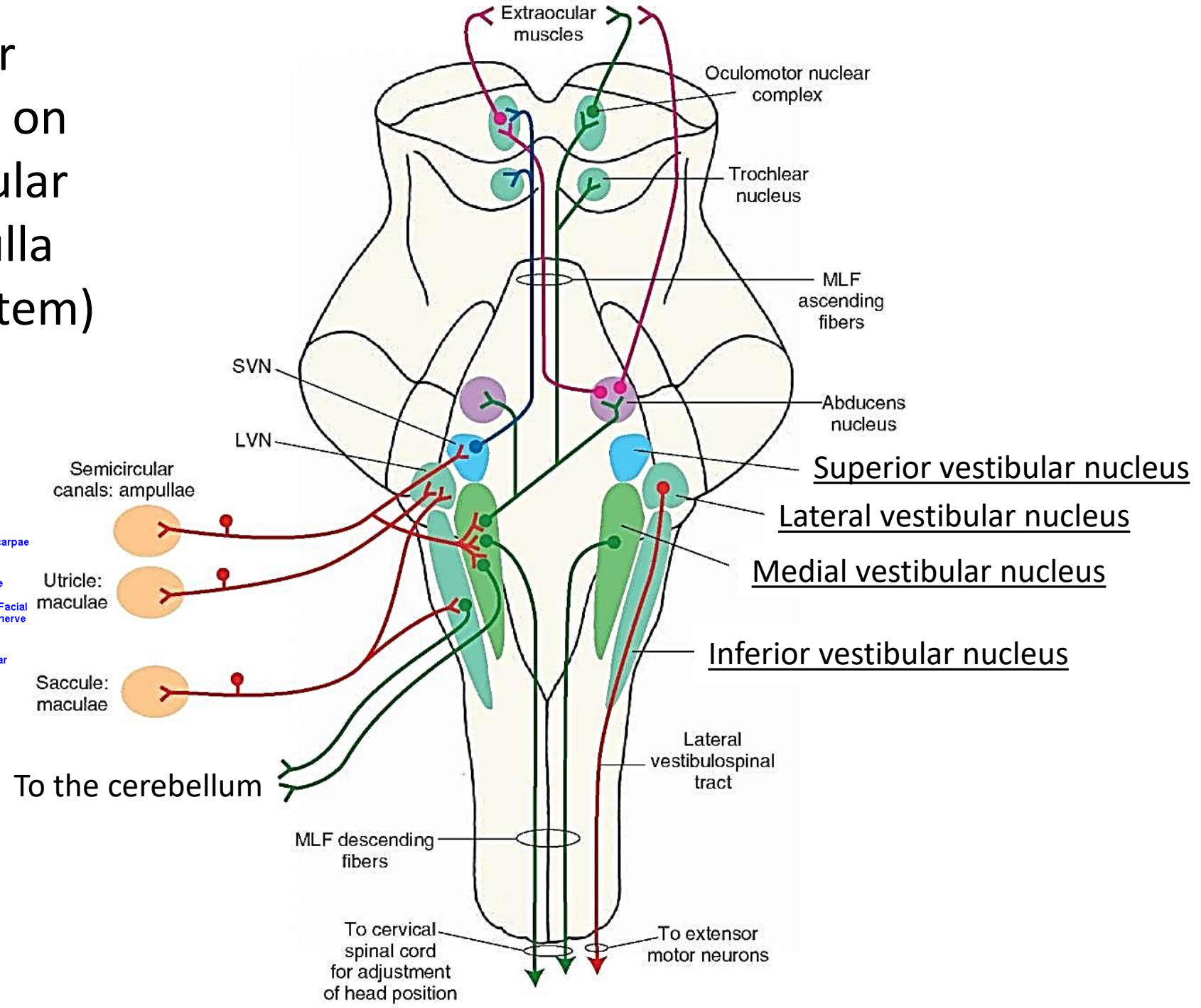


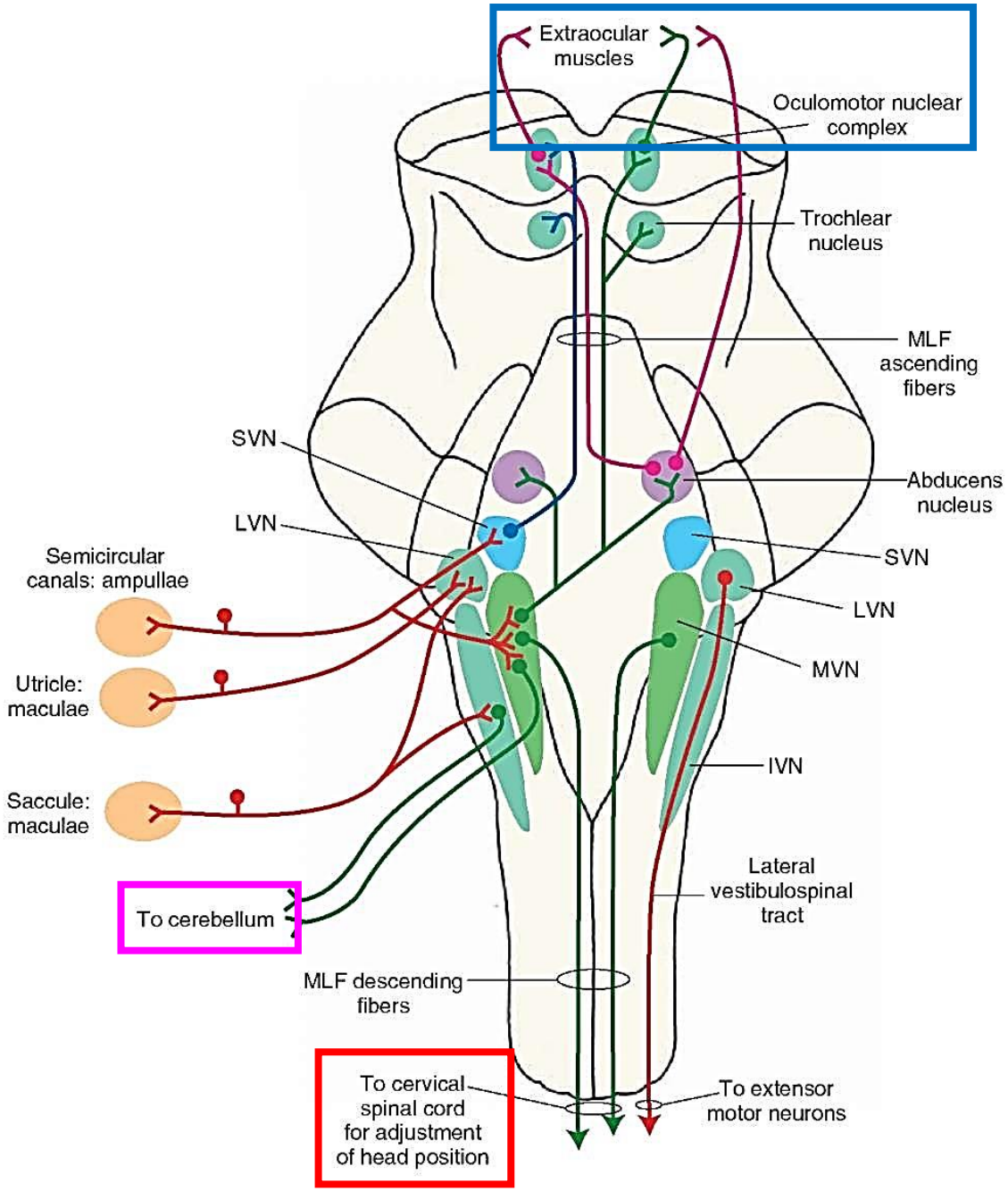
Striolar terminal (utricle)
Irregular spike timing



Primary vestibular afferents synapse on secondary vestibular afferents in medulla and pons (brain stem)







Information goes along to

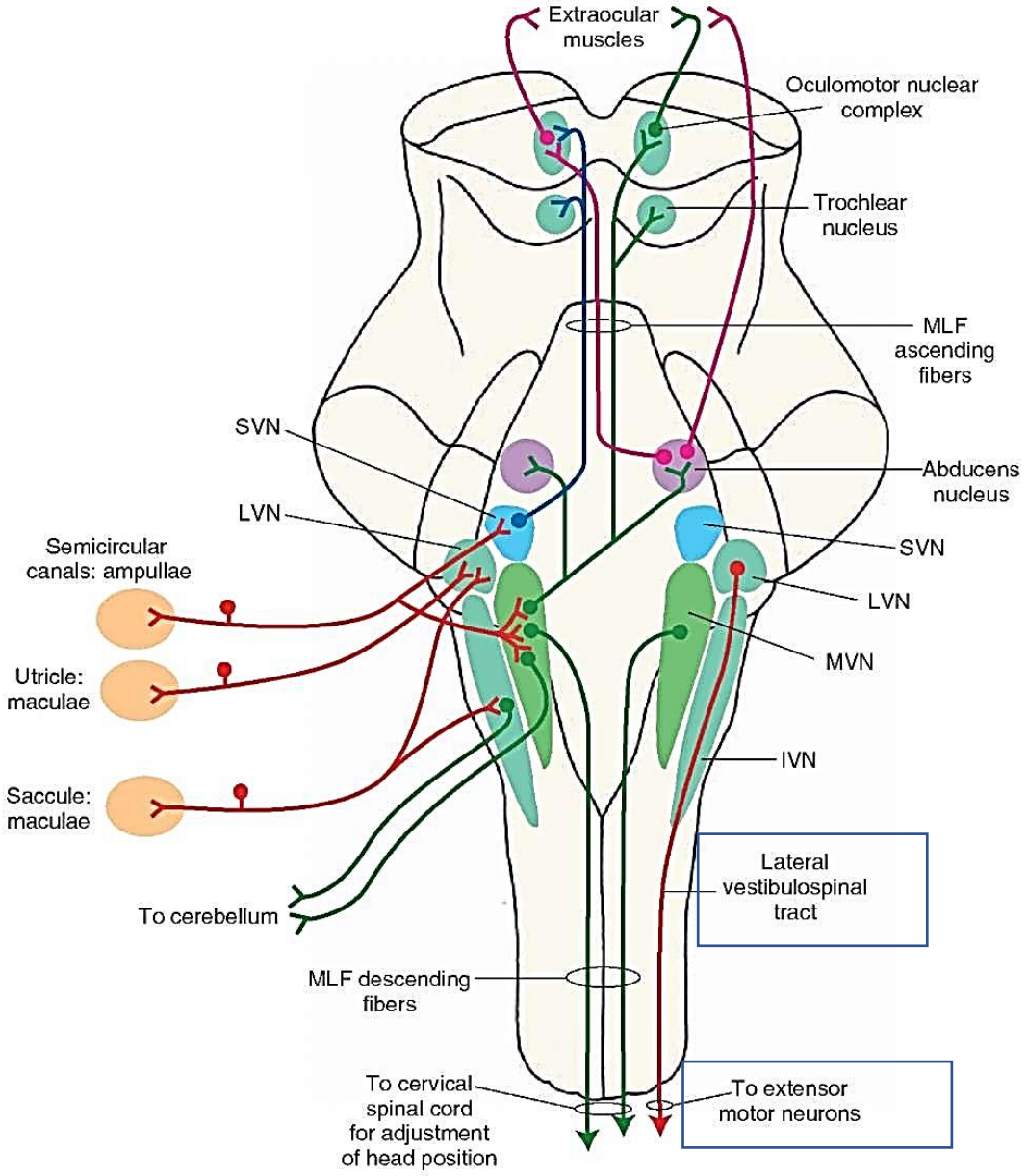
1) Cerebellum: corrective adjustments to motor cortex for maintenance of balance and posture.
2) Cranial nerves: control coupled movement of eyes, focus the visual field.
3) Accessory nerves: head motion and equilibrium
4) Thalamus and cortex: conscious awareness of position and movement of head

Reflexes

- Vestibulospinal reflexes
  - Postural support; sensing falling/tipping and prepares limbs for **life saving measures**
- Vestibulo-ocular reflexes
  - Stabilize visual image during head motion
- Vestibulocollic reflexes
  - Neck musculature to stabilize head during body motion

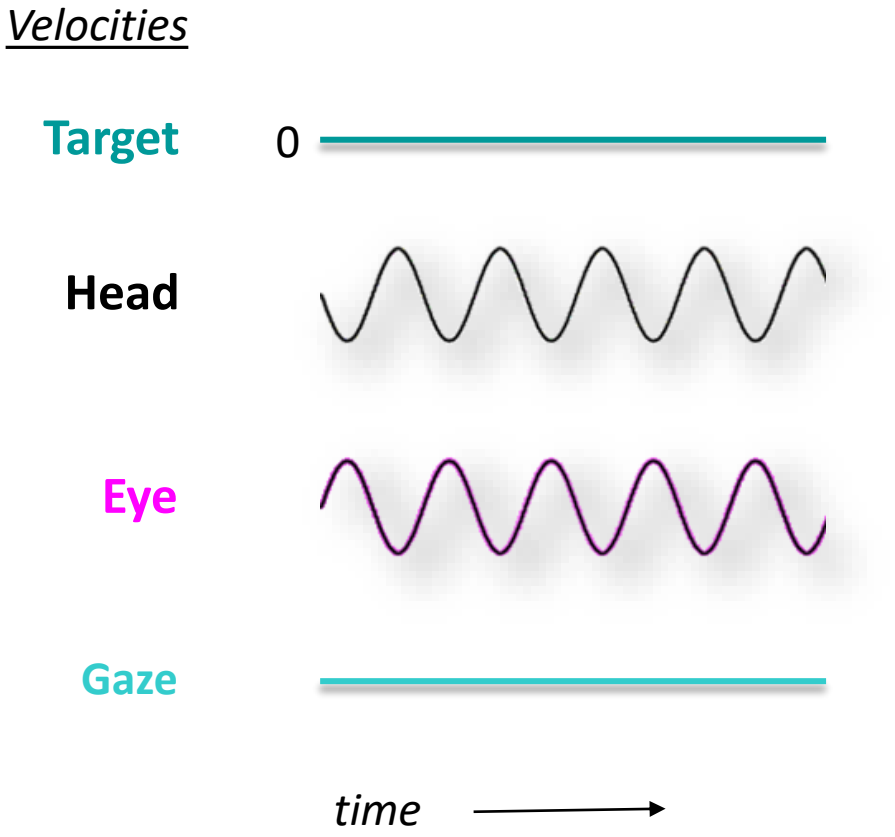
THE FASTEST REFLEXES IN YOUR BODY (JUST SAYING)

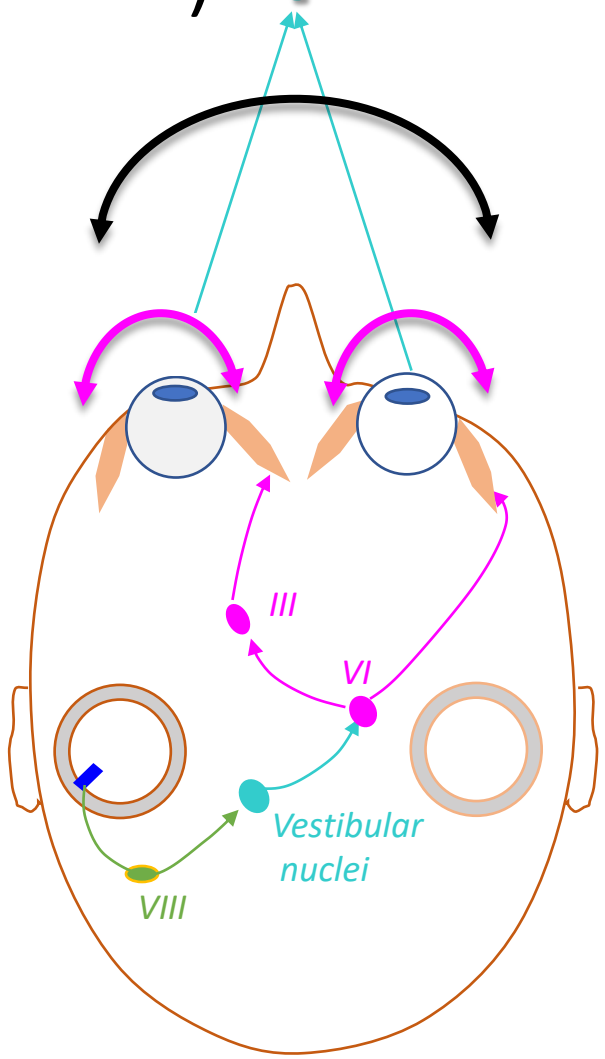
Vestibulospinal Reflexes (VSR)



Vestibulospinal tracts carry canal and otolith information from medial and lateral vestibular nuclei to modulate spinal interneurons and motorneurons.

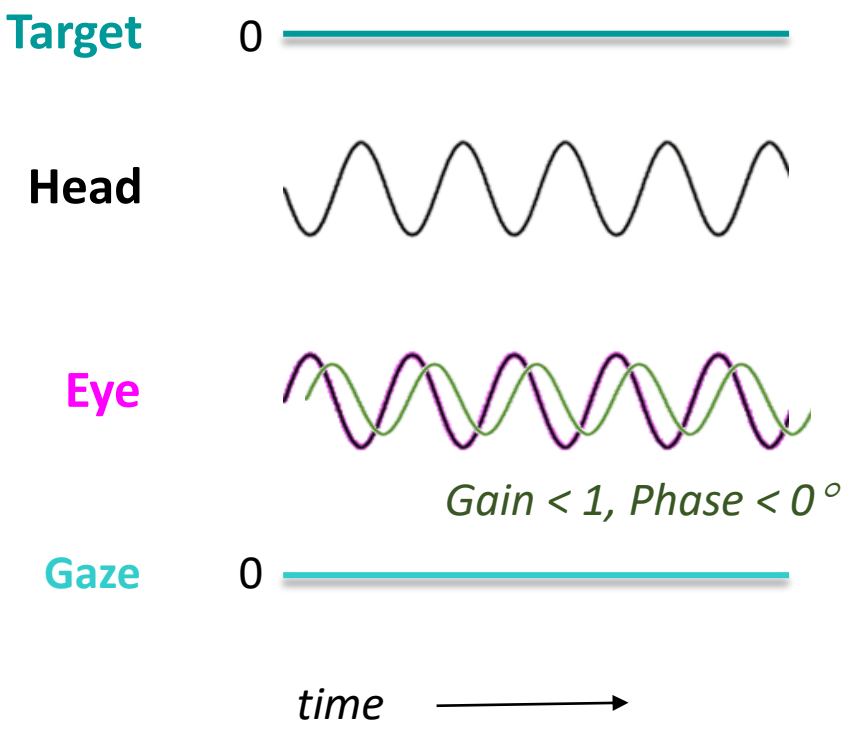
Vestibulo-ocular reflex (VOR) *

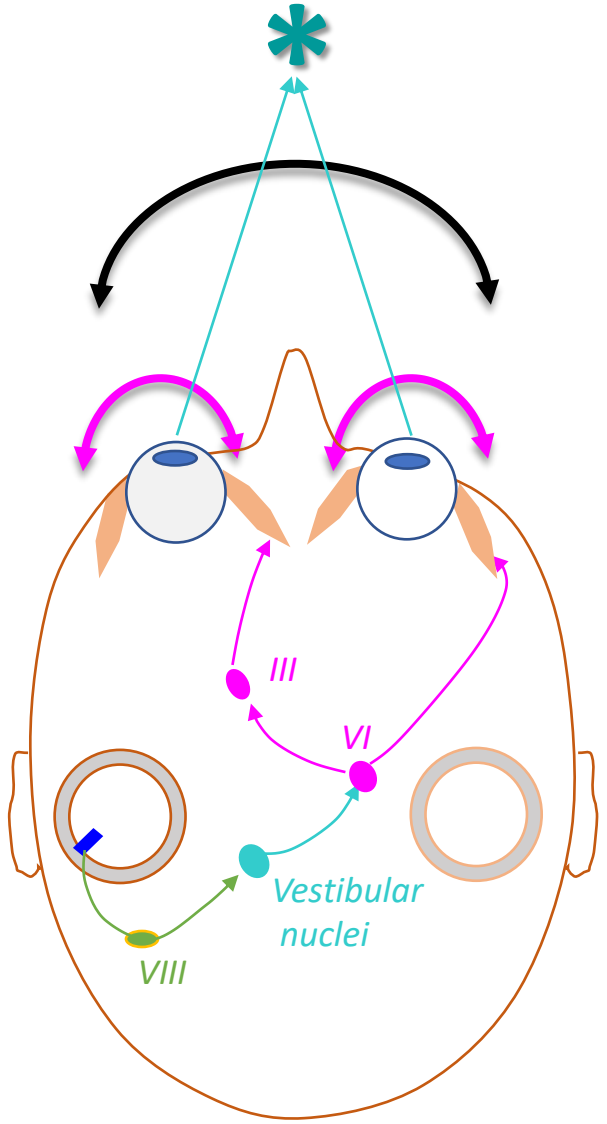




VOR stabilize gaze during head motions

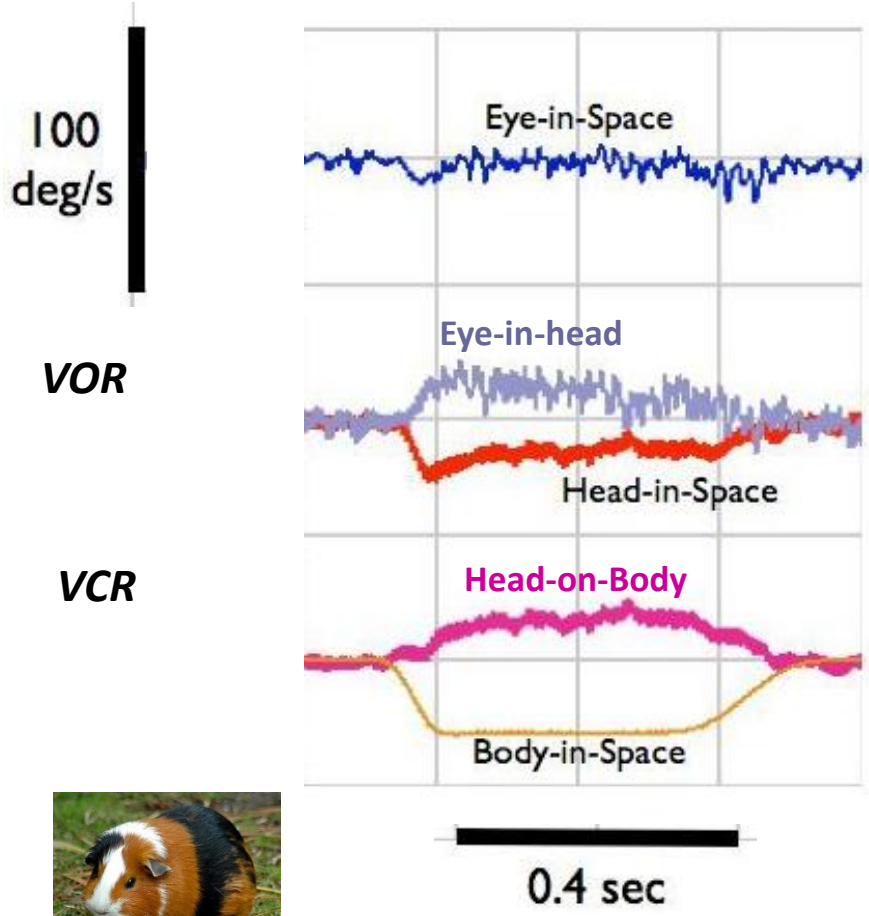
Velocities





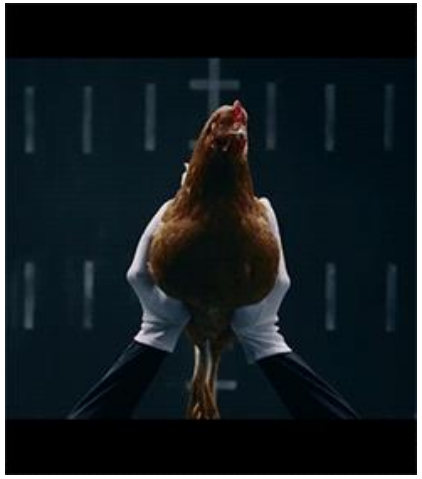
Vestibulocollic reflex (VCR)

During large head motions, VOR and VCR work together to stabilize gaze



Michael King

http://www.khri.med.umich.edu/research/king_lab/vor_gpig.php

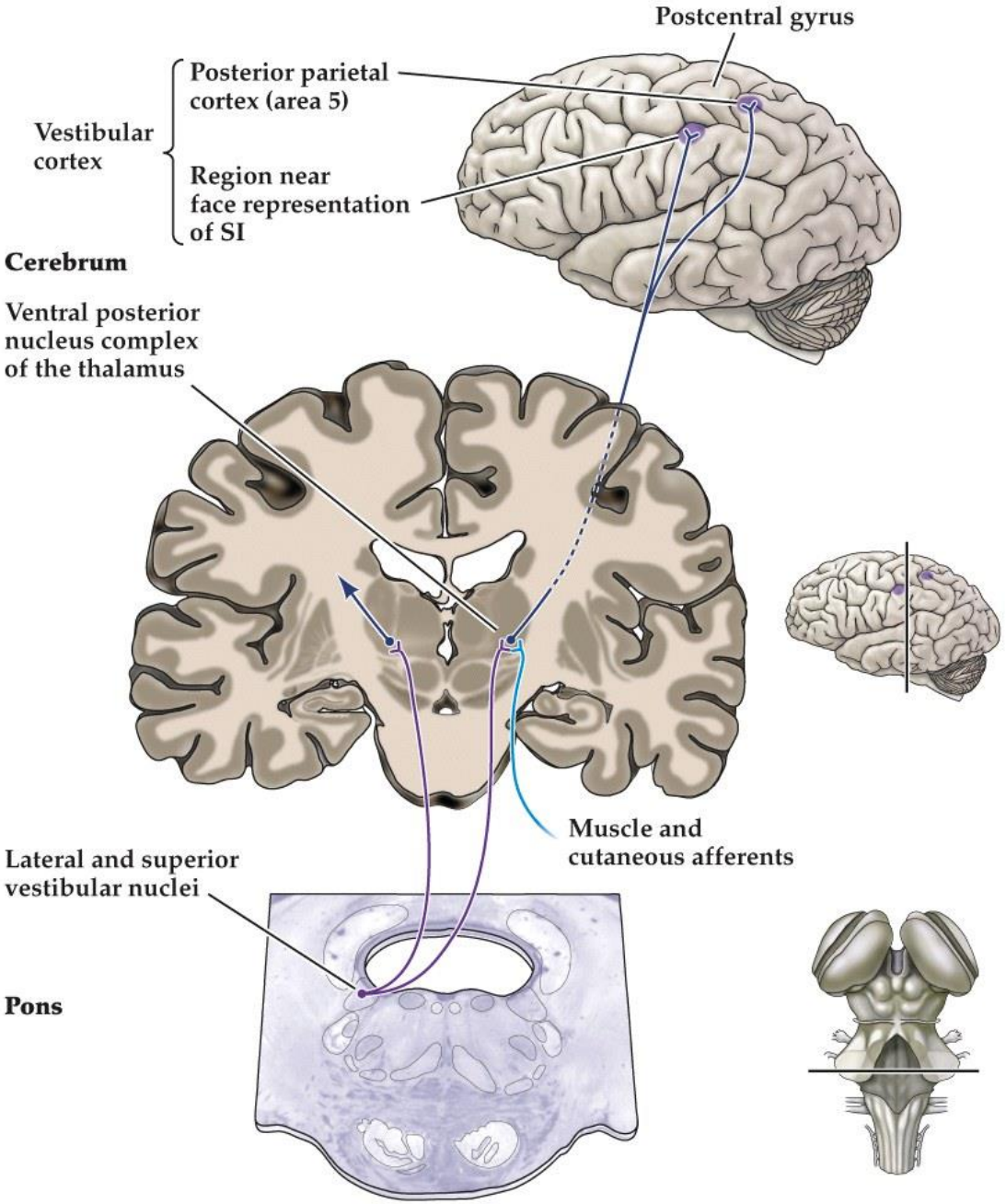


Central Vestibular Projections

Thalamocortical pathways carrying vestibular information. Unlike other sensory systems discussed so far, there is not a single cortical region dedicated to vestibular processing. Instead, a “vestibular cortical system” composed of parietal and insular cortical areas are key sites.

Parietoinsular vestibular cortex: integrates vestibular and proprioceptive inputs to for “head centered” spatial representations.

Other key cortical processing sites include ventral premotor cortex and cingulate motor area.

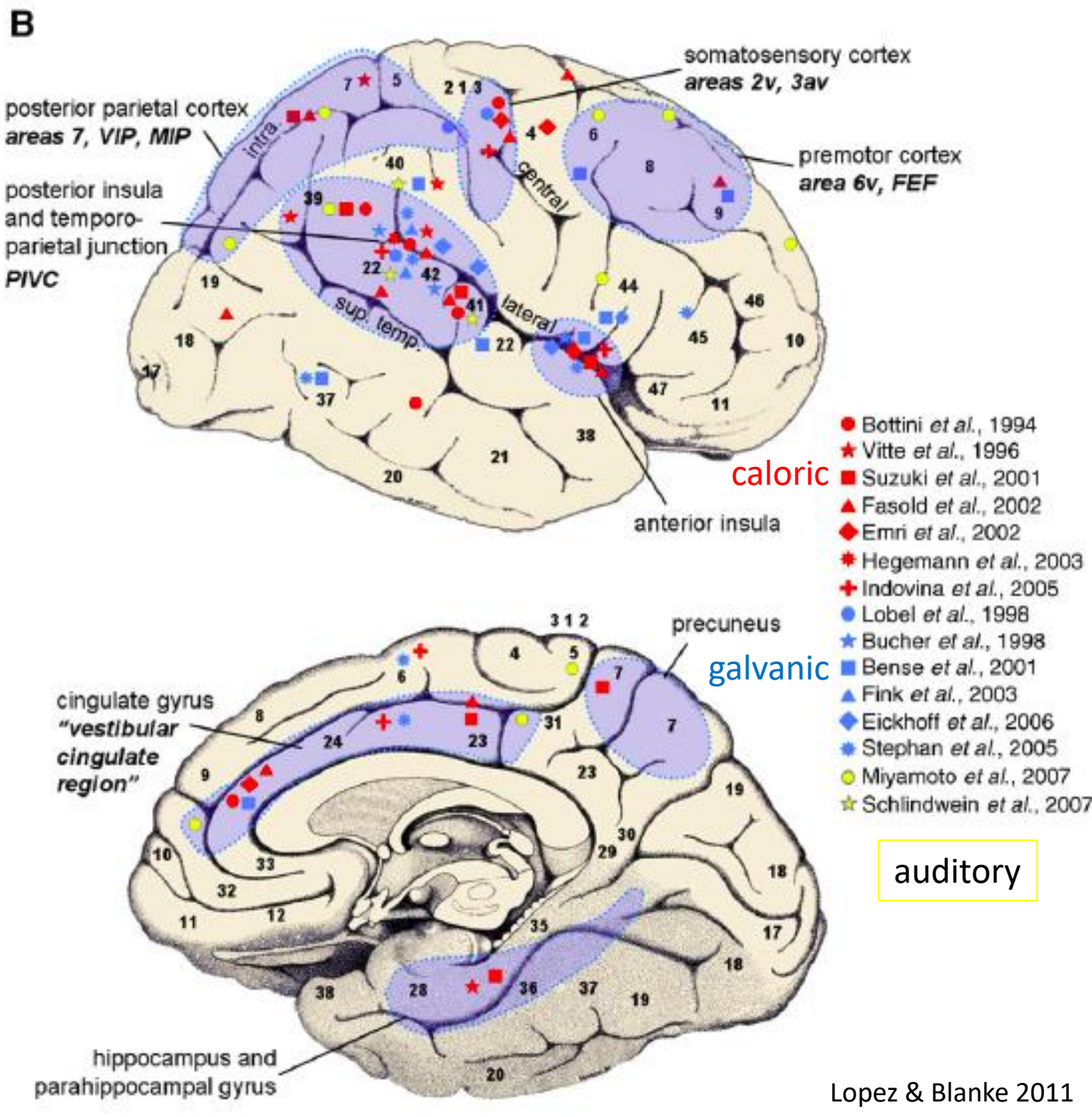


***NEUROSCIENCE 5e*, Figure 14.12**

Vestibular projections to cortex in humans (from neuro-imaging)

Stimulate vestibular system via caloric response (water in your ear evokes convection currents), galvanic (external electrical) stimulation, or auditory stimulation.

Notice the wide spread projections; the vestibular input impacts a variety of systems.

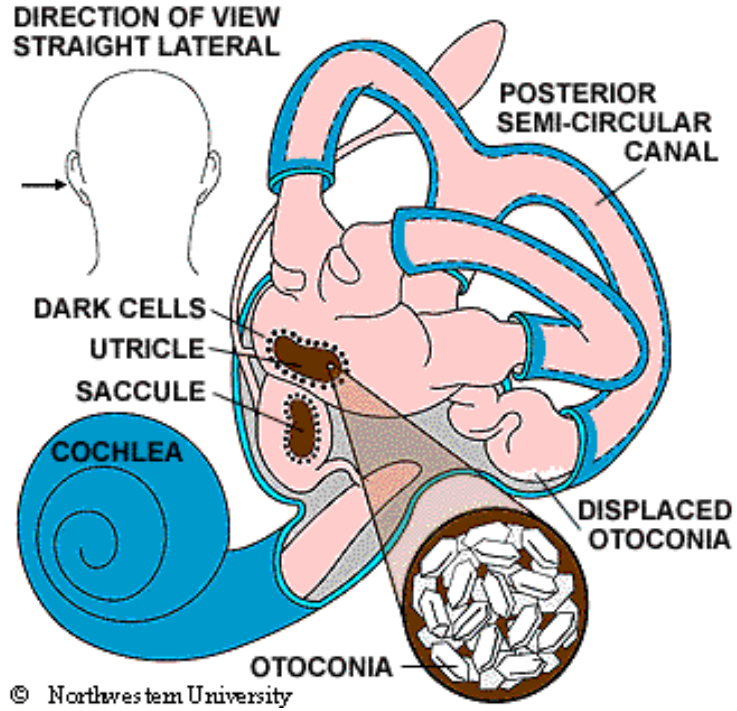


Lopez & Blanke 2011

Clinical disorders

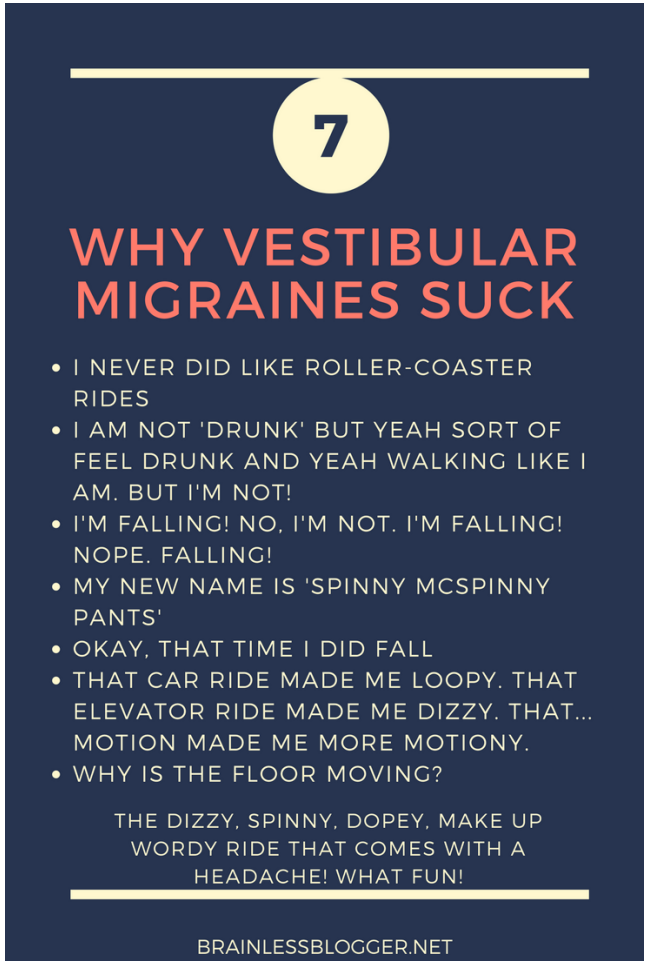
- Nystagmus: eyes make repetitive, uncontrolled movements. These movements often result in reduced vision and depth perception and can affect balance and coordination

- Benign paroxysmal positional vertigo (BPPV): sensation of spinning, dizziness, prevalent in older adults (60+)

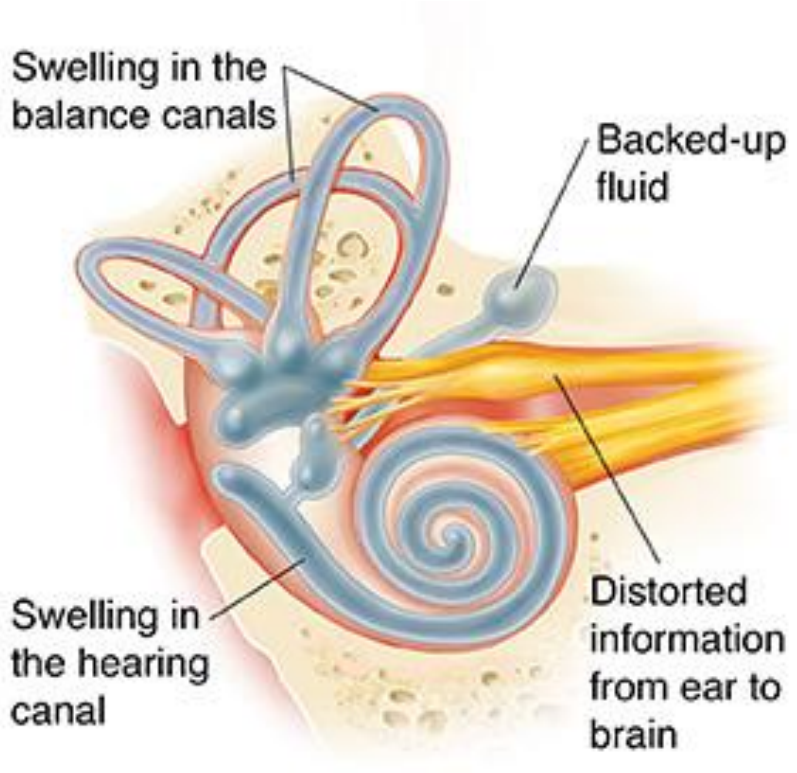


Clinical disorders

- Vestibular migraines: repeated dizziness (or vertigo) in people who have a history of migraine symptoms



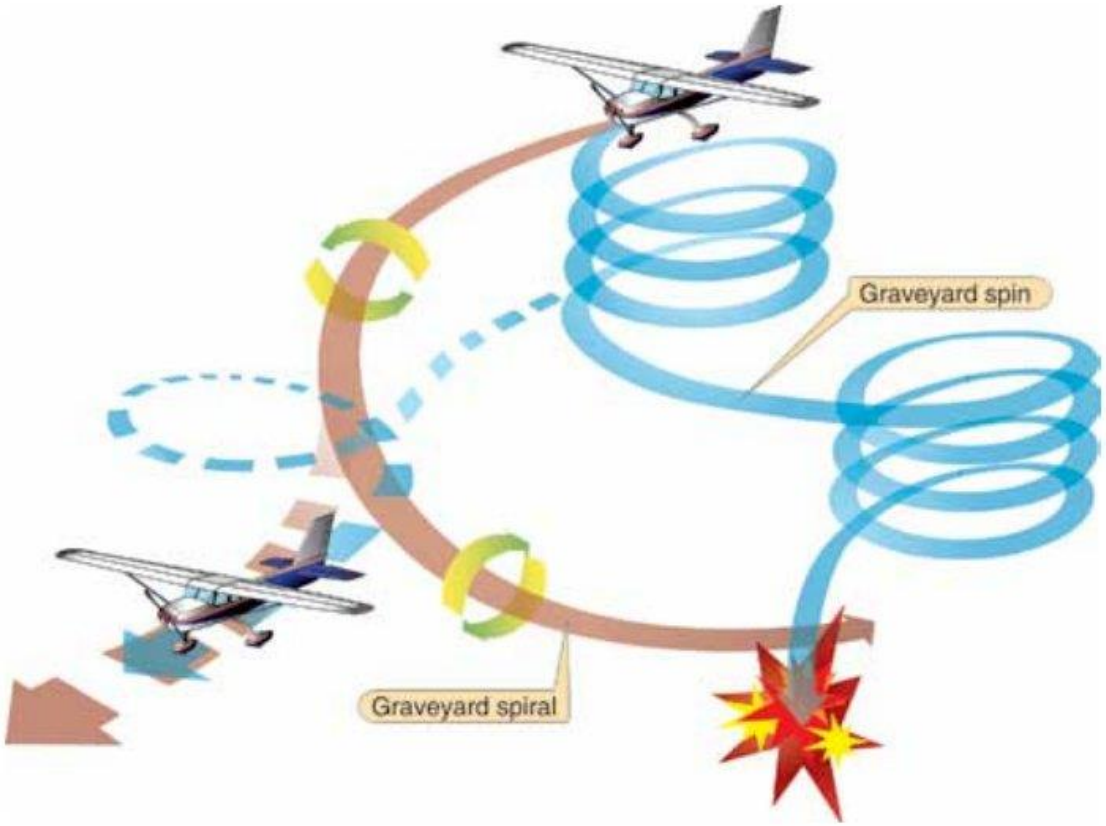
- Meniere's Disease: pressure or pain in the ear, severe cases of vertigo, hearing loss and a ringing or roaring noise (tinnitus)



Sensory illusions in aviation

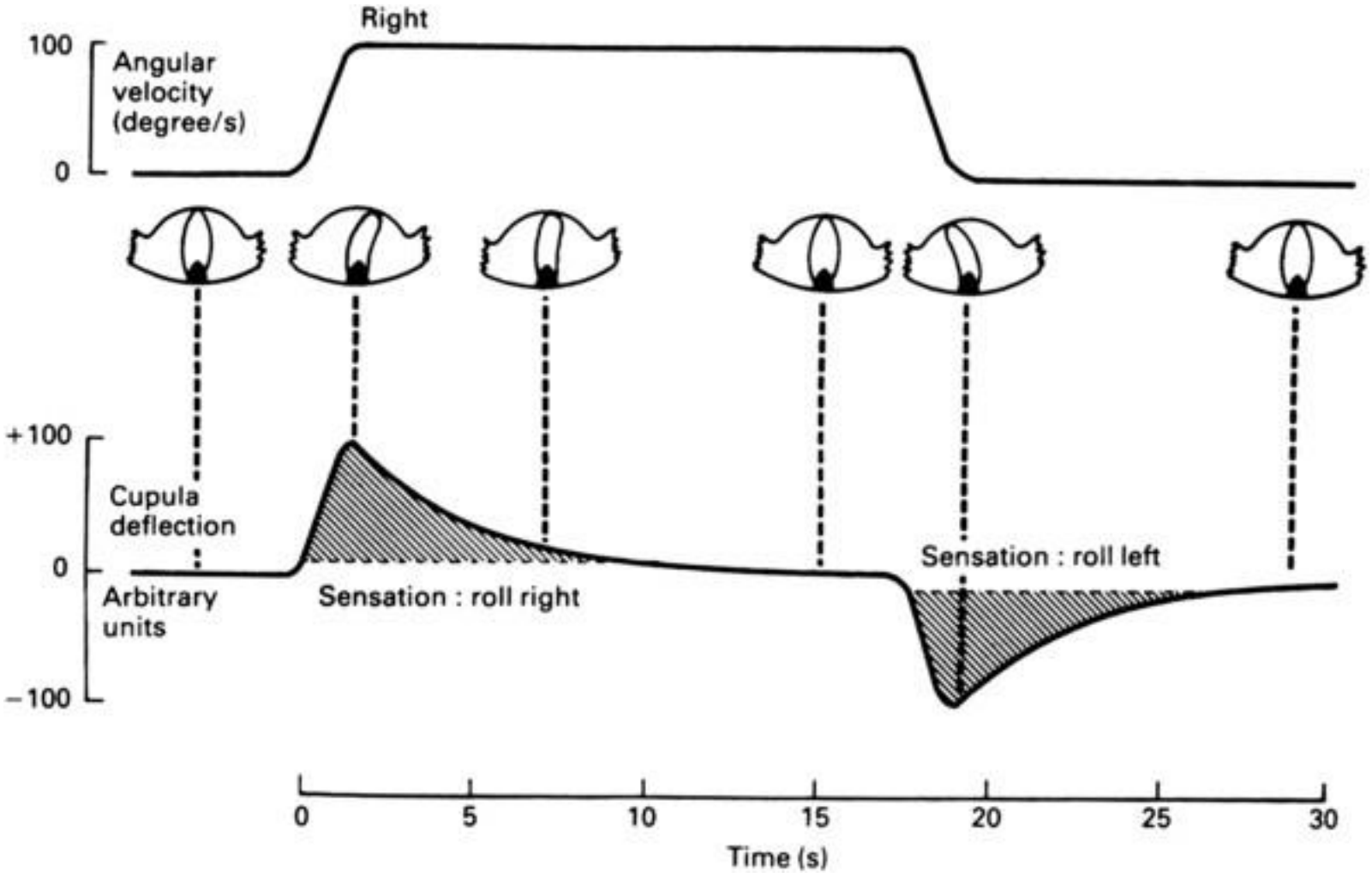
HUMANS ARE NOT MEANT TO FLY. Our senses are not made for it.

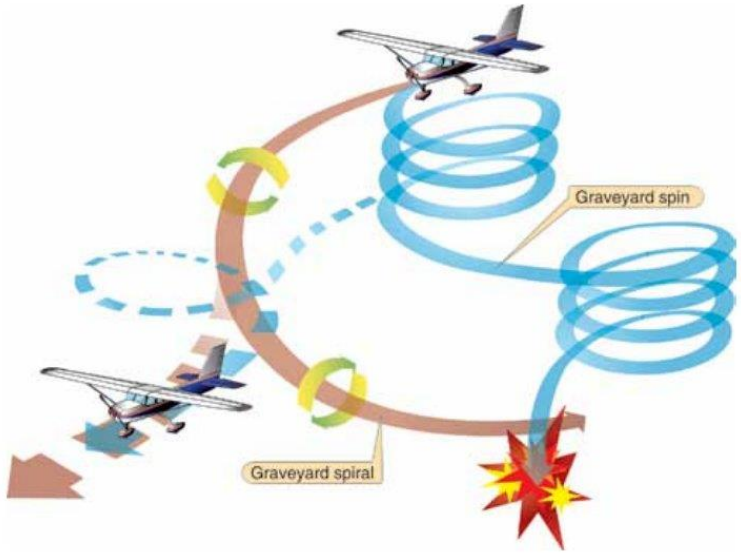
Rotational acceleration of >2 deg/sec is below the detection threshold of the semicircular canals.



After the pilot adapts to the sensation of a continued spin, any correction to the spin feels like a wild spin in the opposite direction

Sensory illusions in aviation: explained





The cupula return to initial positon as the lag of endolymph is reduced, which also reduces the sensation of the spin. A change in the stimulation (such as returning to baseline) deflects the cupula in the opposite direction, giving the sensation of an opposite spin.

Stott, John Richard Rollin. "Orientation and disorientation in aviation." *Extreme physiology & medicine* 2.1 (2013): 2.

In summary:

- The vestibular system is crucial for sensorimotor interface
  - As a sensory system, provides sense of direction/degree of acceleration, orientation of head, accurate self-representation of motion, and an internal map of “self” in space with respect to gravity (thalamic pathways)
  - Also provides postural and ocular motor reflexes, dynamic equilibrium relative to gravity, and visual acuity during movement (cerebellar pathways)
  - Compensation for your self-motions (wide spread cortical inputs)
  - Proper motor response is dependent on accurate sensory perception!!

- It’s cool