Lecture 5: Perception and Action

Part 2 of 4

The Vestibular System and Balance

Relevance

Al-dabbagh, A.H. and Ronsse, R., 2020. A review of terrain detection systems for applications in locomotion assistance. Robotics and Autonomous Systems, p.103628.

Sra, M., Jain, A. and Maes, P., 2019, May. Adding proprioceptive feedback to virtual reality experiences using galvanic vestibular stimulation. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (pp. 1-14).

Vailland, G., Gaffary, Y., Devigne, L., Gouranton, V., Arnaldi, B. and Babel, M., 2020, March. Vestibular feedback on a virtual reality wheelchair driving simulator: A pilot study. In Proceedings of the 2020 ACM/IEEE International Conference on Human-Robot Interaction (pp. 171-179).

Todd, C.J., Hübner, P.P., Hübner, P., Schubert, M.C. and Migliaccio, A.A., 2018. StableEyes—a portable vestibular rehabilitation device. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 26(6), pp.1223-1232.

Learning Objectives

To provide an introduction to the vestibular system

To provide a description of the main receptor cells involved in detection motion and involved in transduction of information into neural firing

To provide an understanding of the main role of the vestibular system in detection of rotation, linear acceleration, and static position

To develop an understanding of some of the limitations of the concept of optic flow

To provide an example of the role of vision in balance

Learning Outcomes

To be able to provide a description of the main components of the vestibular system

To be able to describe the main receptor cells involved in the detection of motion and neural transduction

To be able to provide a description of how the vestibular system detects rotation, linear acceleration, and static position

To be able to appreciate some of the limitations of the concept of optic flow

To be able to provide an example of how vision is important in balance

Do the senses work in isolation?

Is only optic flow sufficient?

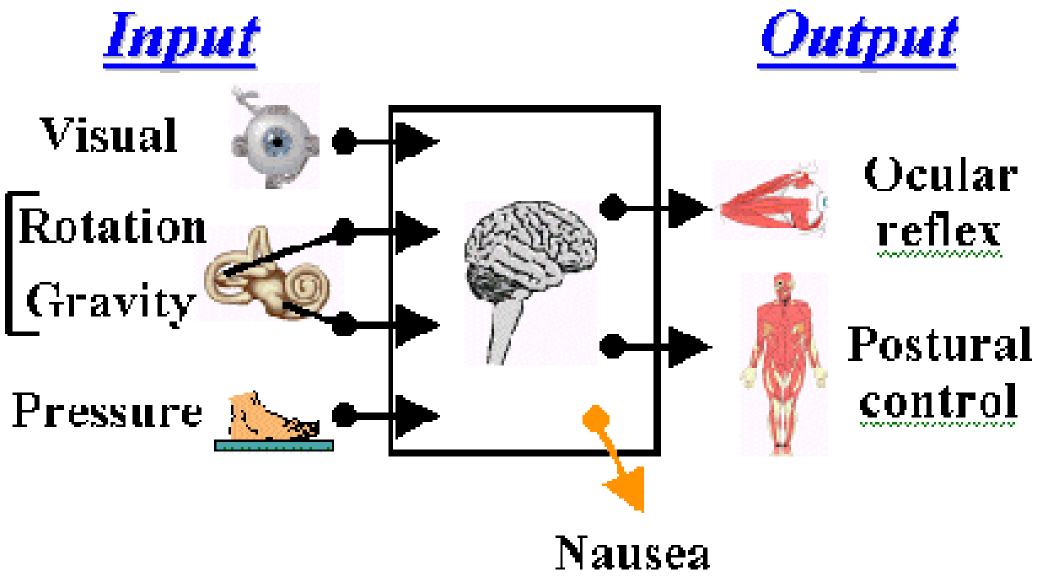
First let’s cover some basics about the balance system.

Sense of position and direction of movement in space is computed by the nervous system largely from 3 types of input

Visual

Proprioceptive

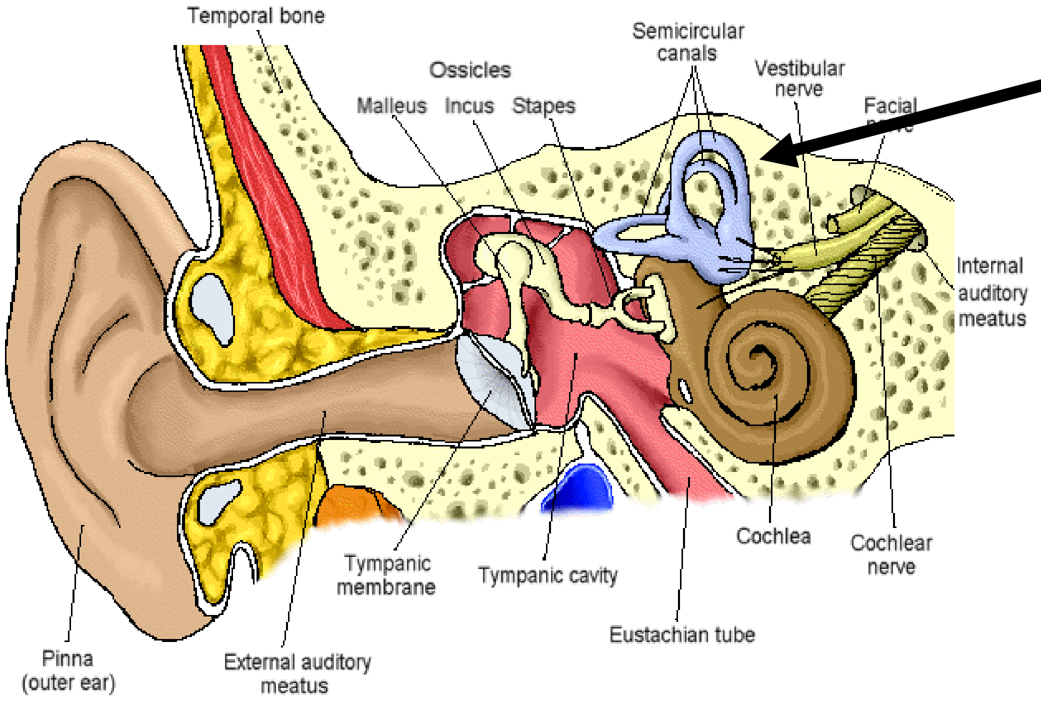
Vestibular



We need to maintain:

- Awareness of orientation and motion in space
- Equilibrium and posture-stable head position during body movement. Vestibular input to areas of the nervous system involved in motor control elicits adjustments of muscle activity and body position to allow for upright posture
- Control of extraocular muscles. Vestibular input to regions of the nervous system controlling eye movements helps stabilize the eyes in space during head movements. (constant eye repositioning). This reduces the movement of the image of a fixed object on the retina.

Audio-vestibular system



The vestibular apparatus or vestibular labyrinth.
The 3 semicircular canals (with utricle and saccule areas) are so arranged that they lie in planes orthogonal (90^0) to one another.

Senses the position and movements of the head and body.

Dizziness and Balance Disorders

May originate from vestibular dysfunction:

Dizziness

Postural instability

Lack of stability during locomotion

Purpose of the vestibular system is to process information on the position and motion of your head in space

Main components to monitoring motion- must be able to detect:

-Rotation (angular acceleration): e.g., shake your head.

-Motion along a line (linear acceleration): what happens when you move off in a straight line

-Static position: what happens when you lean to one side

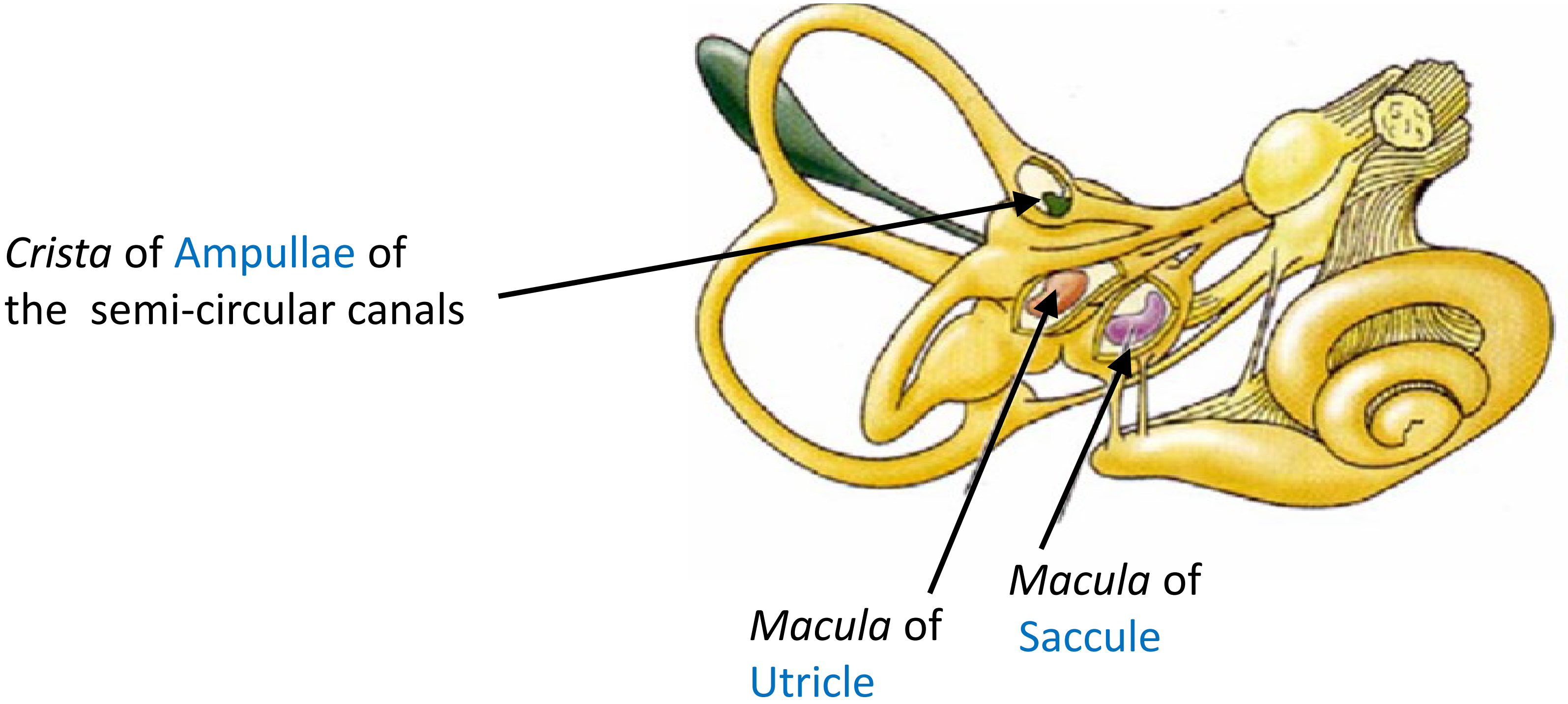
Vestibular system specialised to accomplish these tasks.

Mechanoreceptor Hair Cells:

Specialised <u>hair cells (receptor cells) </u>in:

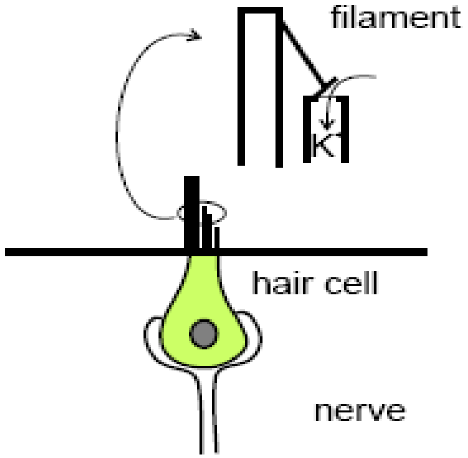
Area called the *macula* in the utricle and saccule

Crista of ampullae in the semi-circular canals.



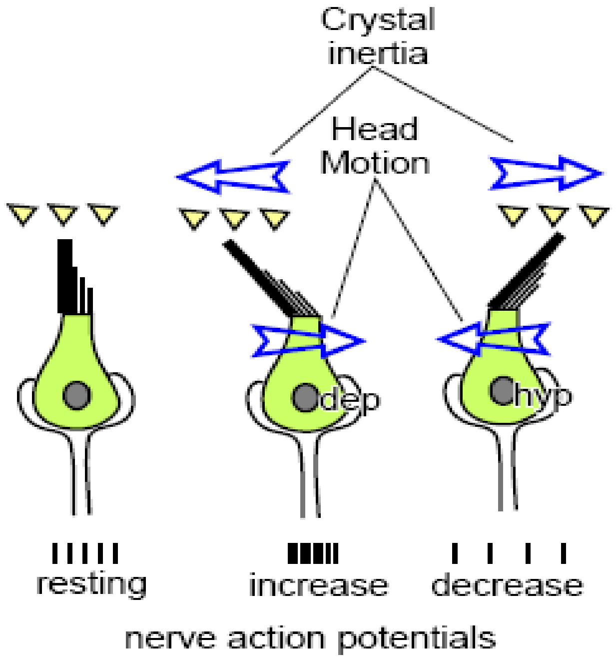
How is movement transduced into neural firing?

When the hairs are undisturbed there is a baseline potential (baseline nerve firing rate).

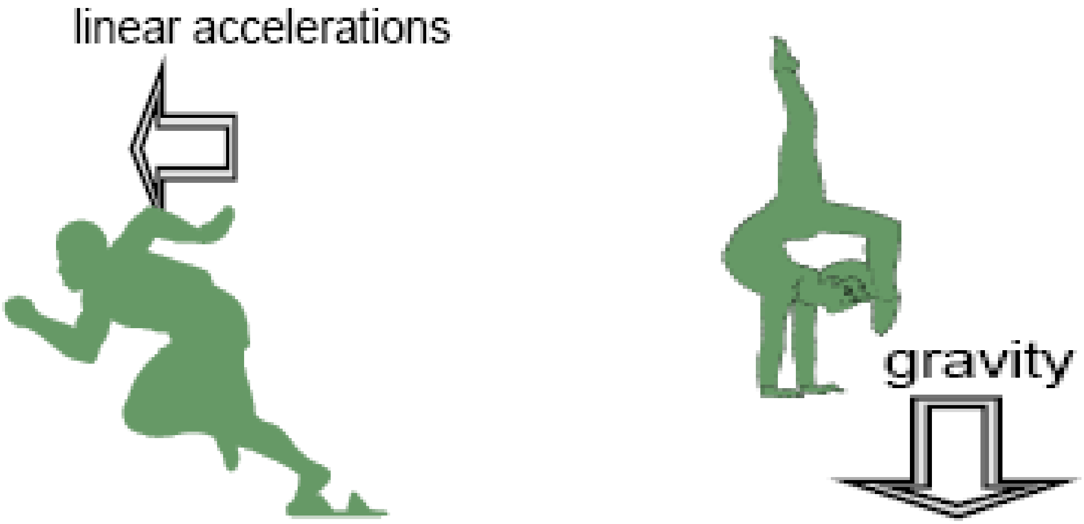


Head motion causes fluid motion and bends the hair cells in the opposite direction to the motion.

Deflection of the filaments (on top of the hair cells) sets up a receptor potential in the hair cell and neurotransmitter release at base of the hair cell.
Neurotransmitter release -> nerve action potential
This results in an increase or decrease in nerve action potential firing (depending on the direction of bending).



Detection of static head motion and linear acceleration

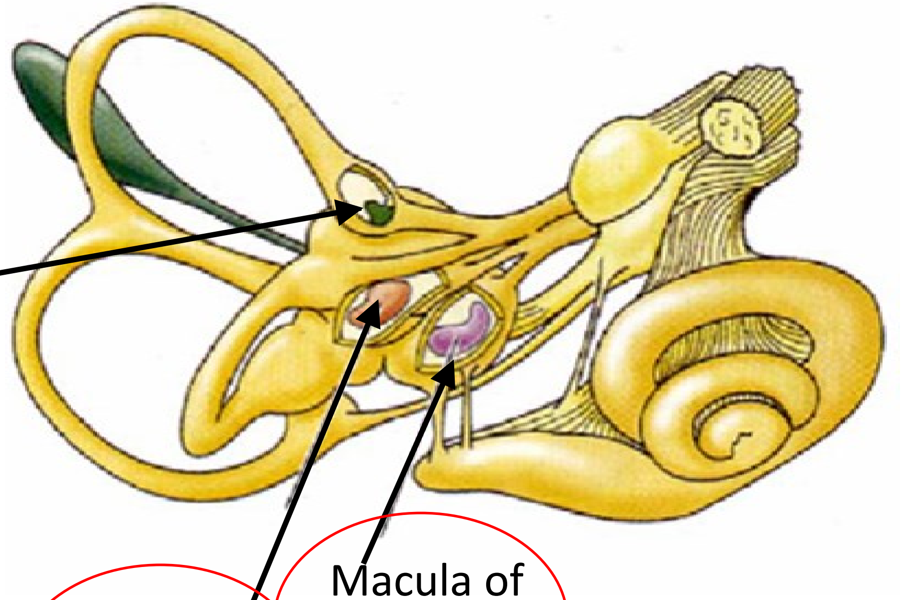


Mechanoreceptor hair cells:

Specialised hair cells (receptor cells) in:

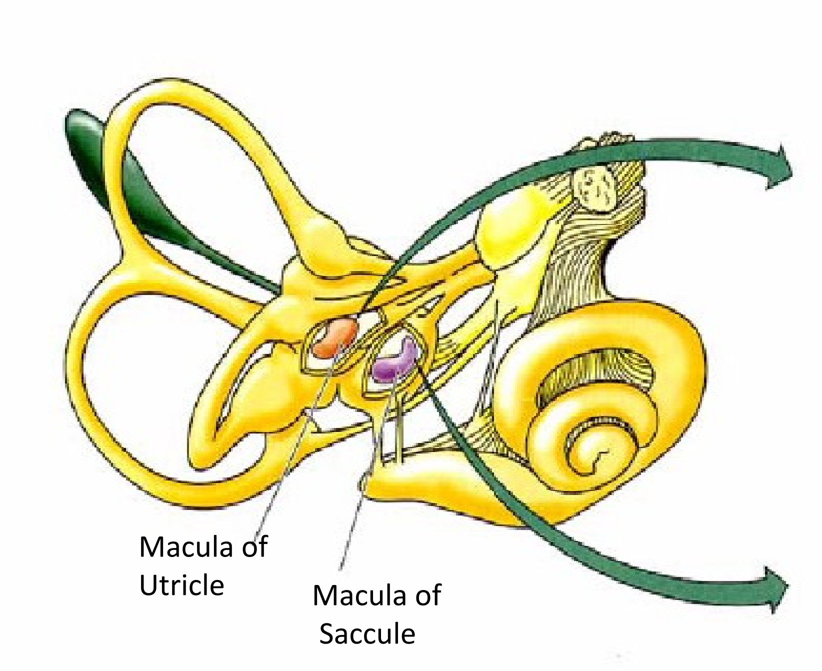
Area called the macula in the utricle and saccule

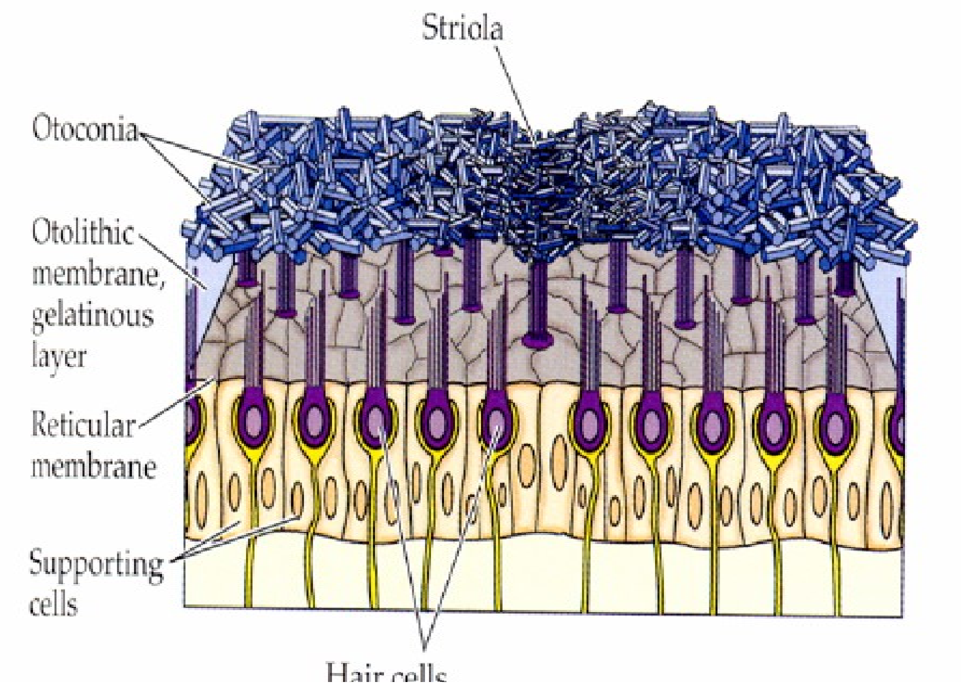
Crista of ampullae in the semi-circular canals.



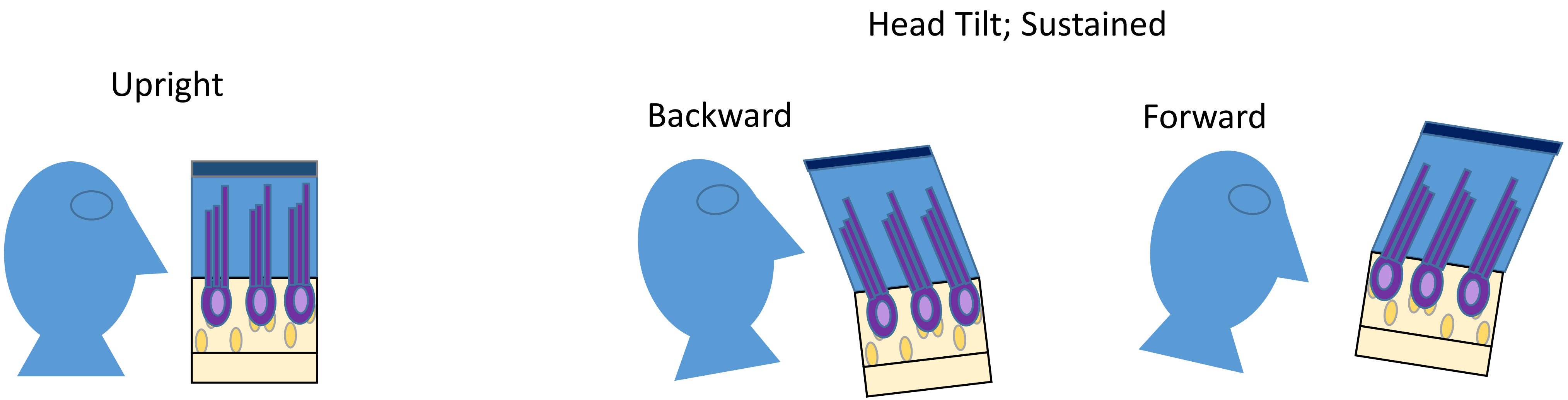
The Utricle and Saccule in Detail

Macula of the saccule and the macula of the utricle covered by a jelly-like mass (gelatinous layer) called the otolithic membrane containing concretions of calcium carbonate called otoliths.
Filaments of special hair cells (held in the gelatinous layer) are sensitive to linear acceleration and changes of position of the head in the gravitational field.





The utricle and saccule respond to static head position and detect head tilt

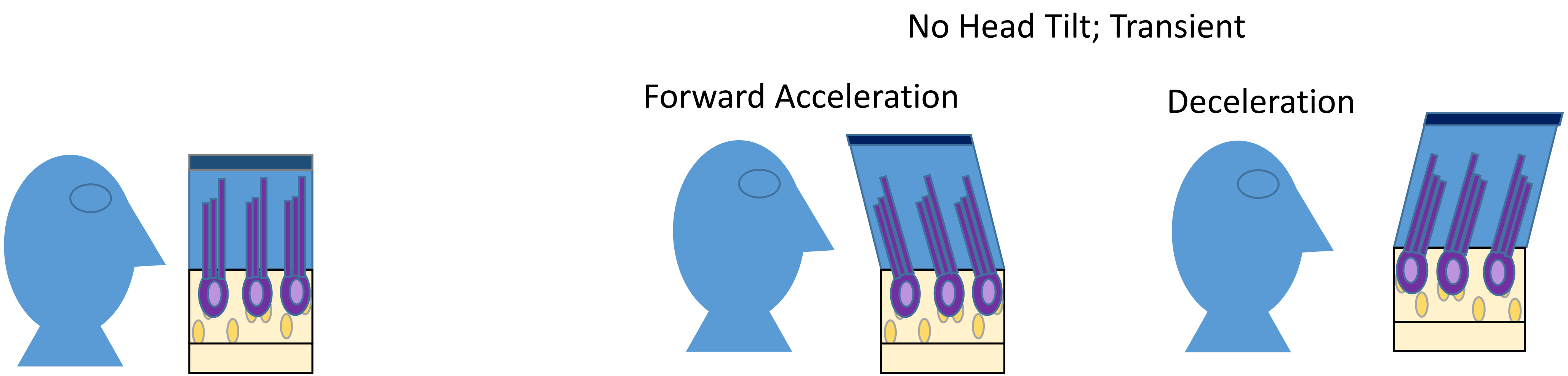


Main role of the saccule and utricle is to keep you vertically oriented with respect to gravity.

Static head position signalled by a baseline level of neural activity due to the effect of gravity on the otoliths.

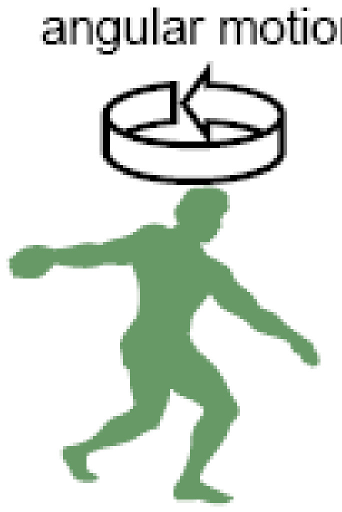
If your head and body start to tilt, the neural information from these hair cells will change accordingly and will be sent to the brain so that you can make the necessary adjustments to your posture to compensate.

The utricle and saccule respond to linear acceleration



Linear acceleration displaces the otoliths in the direction opposite to the direction of movement (fluid inertia), causing hair cells to bend and generating a receptor potential - - > neurotransmitter release - - > action potential - -> brain

Detection of angular acceleration

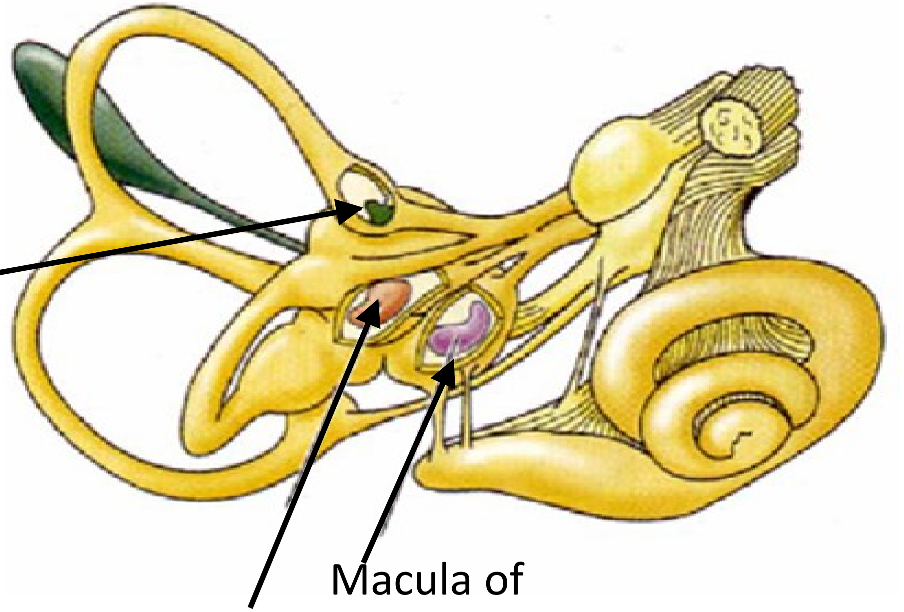


Mechanoreceptor hair cells:

Specialised hair cells (receptor cells) in:

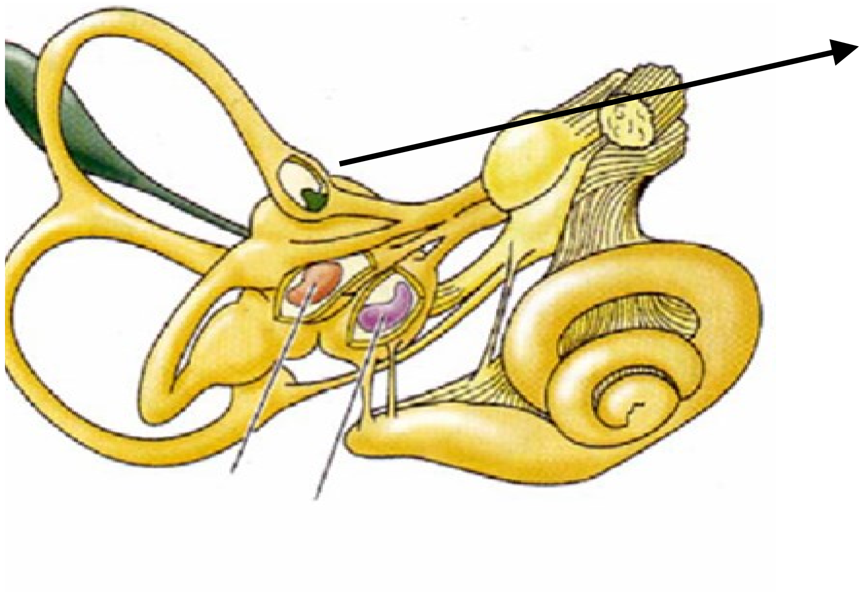
Area called the macula in the utricle and saccule

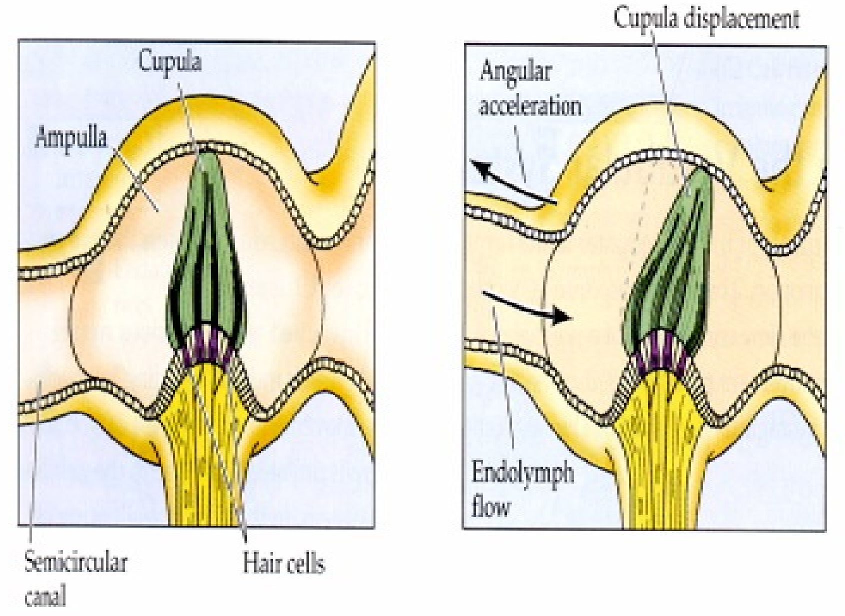
Crista of ampullae in the semi-circular canals.



Ampullae of the Semicircular Canals

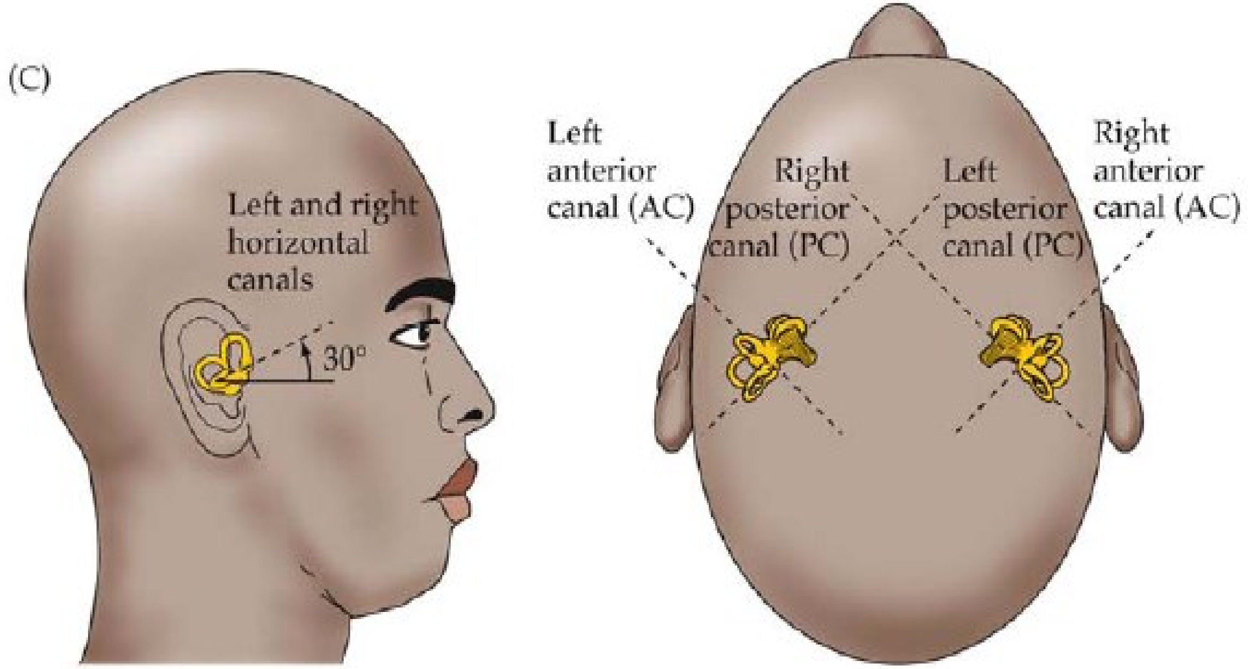
Ampullae of the semicircular canals: concerned with maintaining functional vision during movement (achieved by adjustment of eyeball position and movement). Detects angular acceleration of head in space by movement of the fluid around a mass called the Cupula.





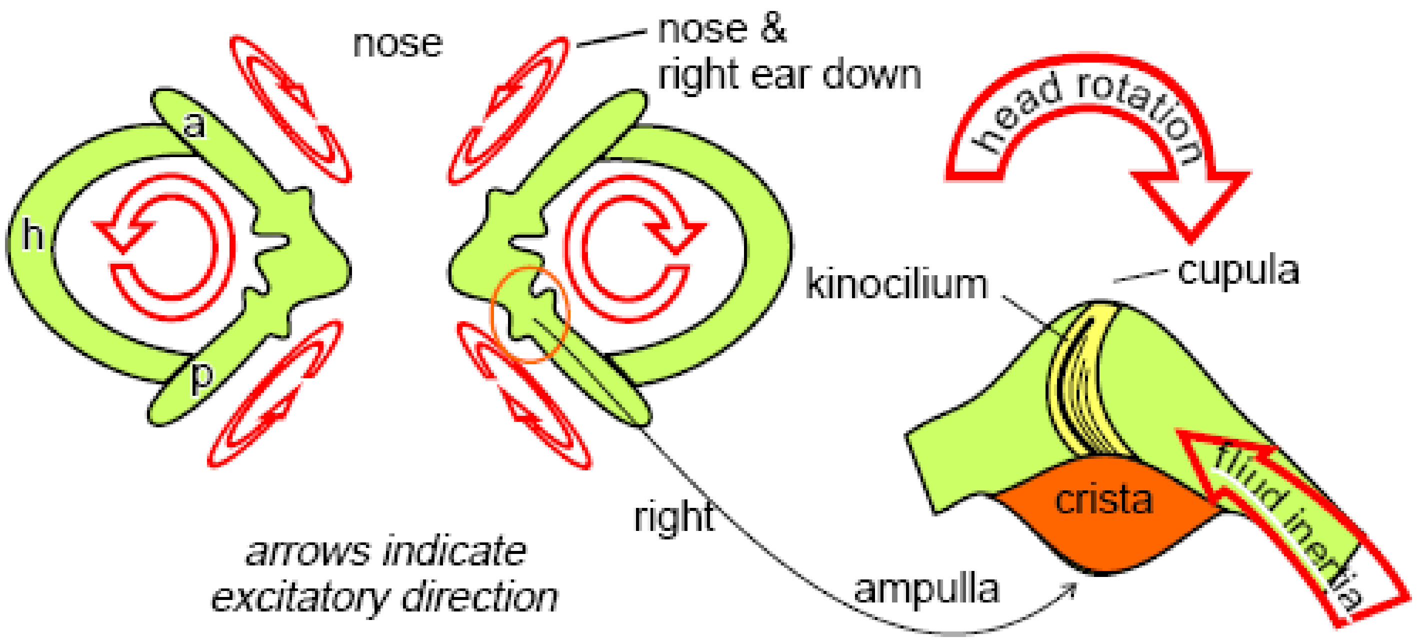
3 Semicircular Canals: Push-pull pairs

The three semicircular canals on each side of head are oriented in each of three orthogonal planes which are very nearly perpendicular (90^0) to each other. Define all possible planes of motion.
Same arrangement (mirrored) on both sides of the head. Hair cells excited if hair cell filaments pushed one way, inhibited if hair cell filaments pushed other way. This means that the canals on either side of the head will generally be operating in a **push-pull** rhythm; when one is excited, the other is inhibited,



3 canals – 3 dimensions

There are 3 canals, corresponding to the three dimensions in which you move, so



How does this structure detect angular acceleration of the head?

Head rotated to right– inertial fluid lags behind movement of head.

Right canal- cupula pushed to left-deflecting filaments in cupula in direction of relative fluid motion in canal (towards kinocilia) -> increase in nerve firing.

Sense rotation

When there is a change in speed of head rotation, the fluid inside the canals lags behind due to inertia, bending the cupula. Bending of the filaments in the cupula leads to decrease or increase in nerve firing depending on which way the cupula bends (towards kinocilium structure = increase in nerve firing; away from the knicilium structure = decrease in nerve firing). When no deformation of cupula and filaments = constant baseline nerve firing rate.

Returning to the Question-Do the senses work in isolation?

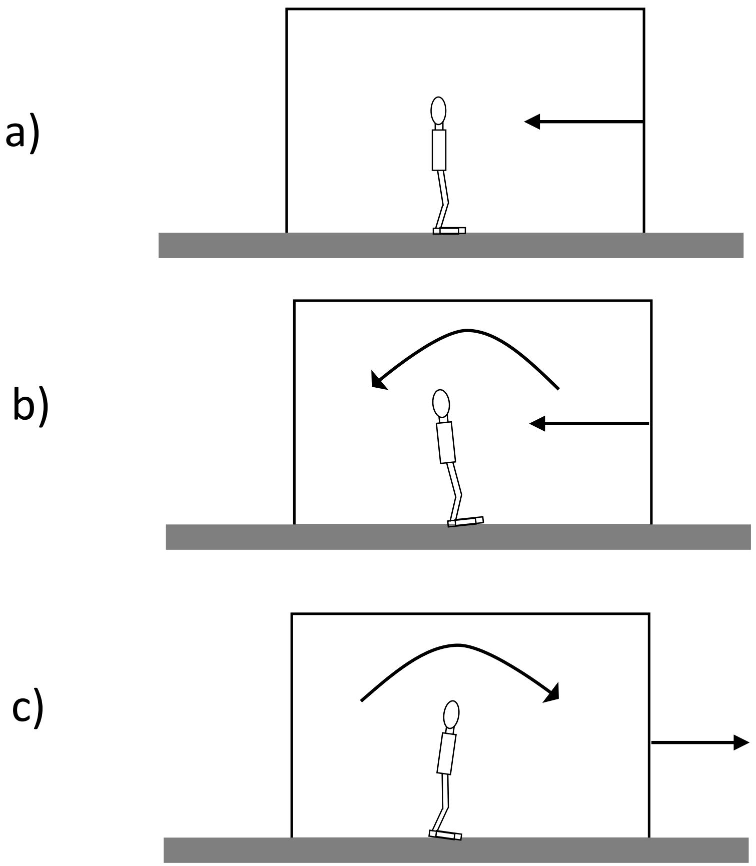
Is only optic flow sufficient?

Let's look at an example where both visual information and information from balance organs in the body are important.

Lee and Aronson classic experiment (1974;1980; and Fox, 1990)- swinging room.
Floor was stationary but walls and ceiling could swing towards and away from person.
Movement of the walls can create an optic flow.

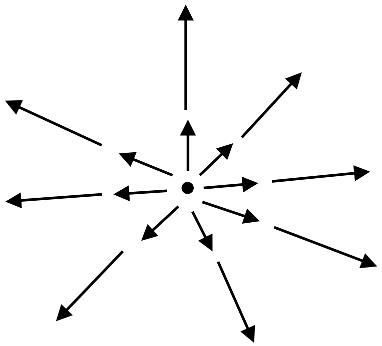
Floor was stationary but walls and ceiling could swing towards and away from person.
Movement of walls can create an optic flow.

Swinging room experiments

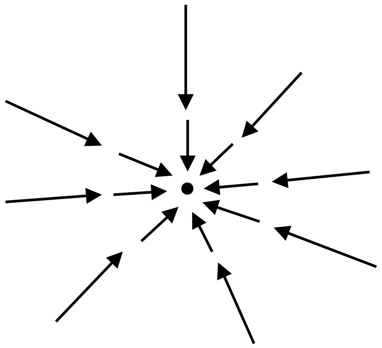


Lee and Aronson’s (1974) swinging room.
a) Moving room towards person creates a specific “moving forward” optic flow pattern. This is similar to an optic flow created if a person was moving/driving in a forwards direction.
b) This creates the impression that the person is swaying forward. To compensate for this apparent sway the person is observed to *physically sway back* to compensate.
c) When the room moves away, the flow pattern creates the impression of swaying backward, so the person *physically sways forward* to compensate.

Vision is an important contributor to balance and works in conjunction with other balance organ signals from the vestibular system and receptors in muscle and joints.



Flow when wall is moving towards person



Flow when wall is moving away from person

Applications of vestibular research

Assistive devices for applications in locomotion benefit from sensors that can include proprioceptive information (e.g., vestibular system)

Al-dabbagh, A.H. and Ronsse, R., 2020. A review of terrain detection systems for applications in locomotion assistance. Robotics and Autonomous Systems, p.103628.

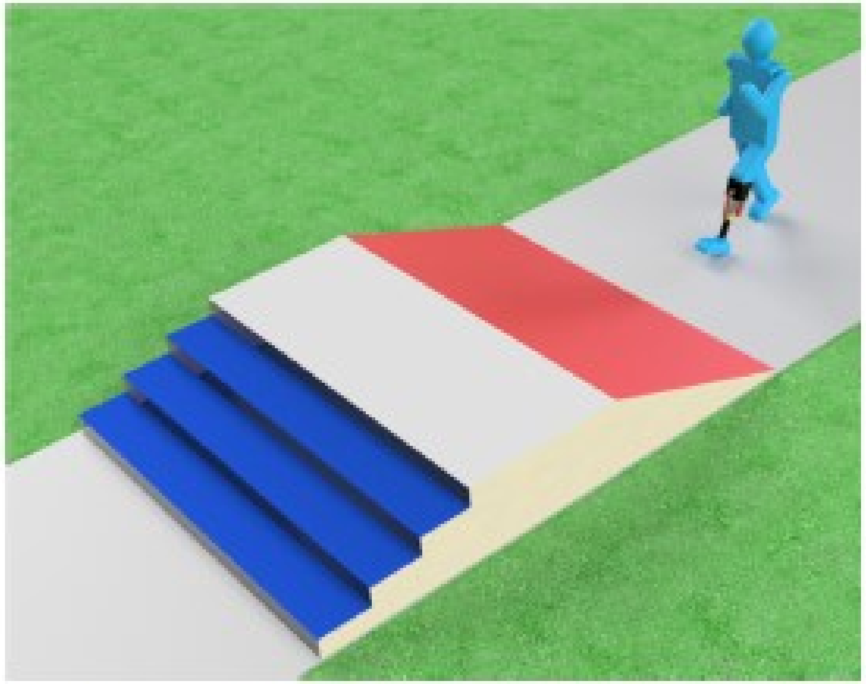


Fig. 1. Terrain detection is necessary to adapt the controller of a walking assistive device (here, a bionic lower-limb prosthesis) as a function of the task being performed. In this example, the amputee is going to transition between overground walking (gray), slope climbing (red), and stairs descending (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Importance of terrain detection systems

Considers sensory system information important to identify different locomotion terrains in indoor or urban environments.

Assistive devices for applications in locomotion benefit from sensors that can include proprioceptive information (e.g., vestibular system)

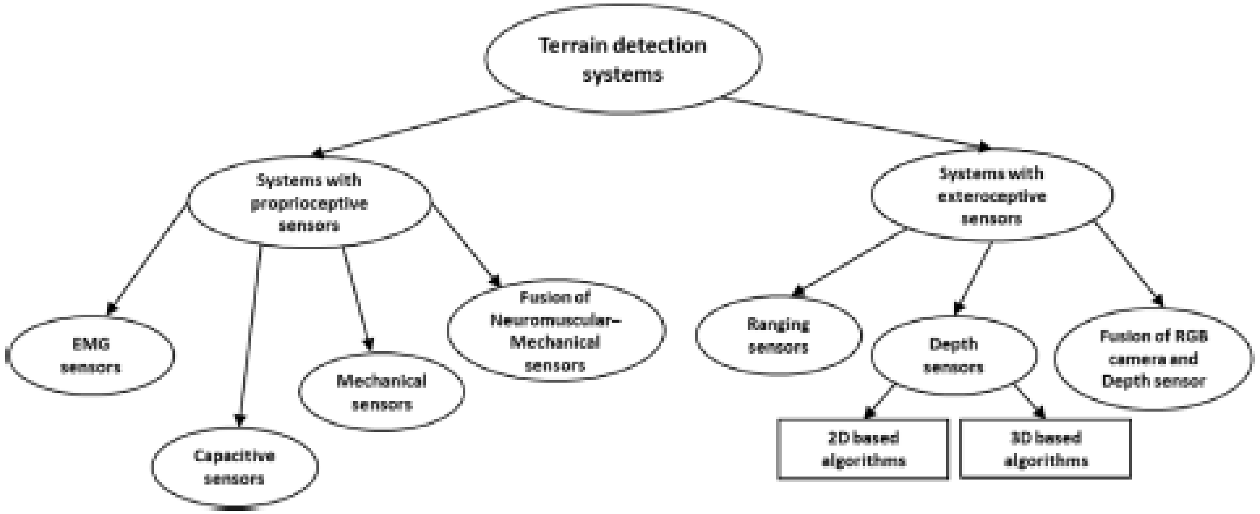


Fig. 3. This figure shows a classification of typical sensors that are used in terrain detection systems as a function of whether they use proprioceptive senso or also exteroceptive sensors.

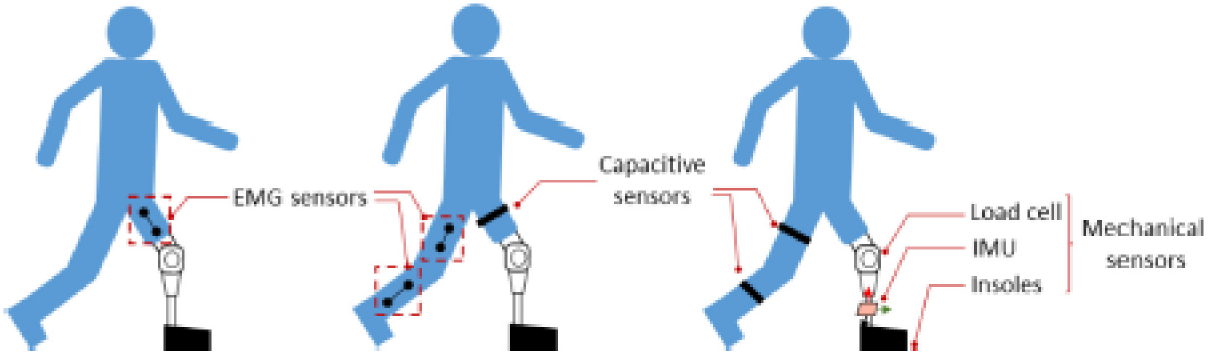
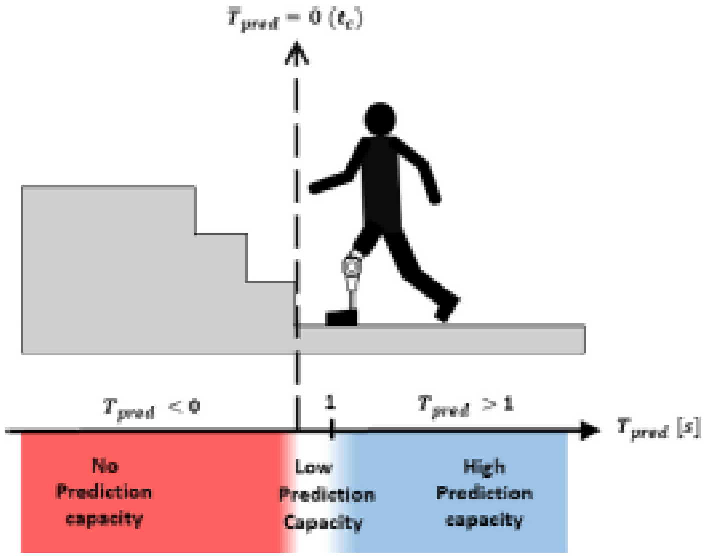


Fig. 4. Representative configurations of sensors for terrain and locomotion intention detection with a lower-limb amputee wearing a prosthesis. It shows th distribution of proprioceptive sensors measuring muscular activity (EMG), muscle contraction (capacitive), or the leg kinematics (Mechanical).

Ultimately want a system that can predict the users' future intention rather than just react to changes in behaviour.

So require a combination of proprioceptive sensors and exteroceptive sensors.



Activation of the vestibular system and its role in a virtual environment

Sra, M., Jain, A. and Maes, P., 2019, May. Adding proprioceptive feedback to virtual reality experiences using galvanic vestibular stimulation. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (pp. 1-14).

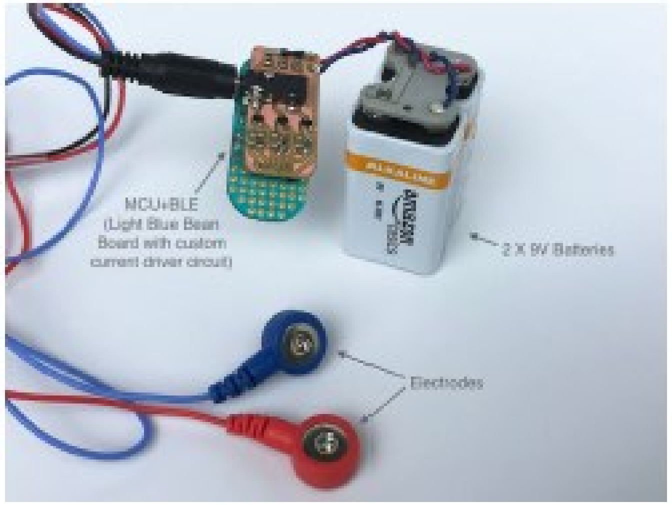


Figure 2: The first GVS prototype built using a Light Bl
Bean Board with a custom current driver circuit board.

Figure 1: Our GVS device induces proprioceptive feedback for VR motions: (a) riding a roller coaster, (b) driving a car, (c) leaping forward, and (d) navigating by flying.

Wearable device using galvanic vestibular stimulation – stimulates the vestibular system.

Found that this lowered cybersickness (visually induced motion sickness) when immersed in a VR environment

Vestibular Feedback on a Virtual Reality Wheelchair Driving Simulator

Vailland, G., Gaffary, Y., Devigne, L., Gouranton, V., Arnaldi, B. and Babel, M., 2020, March. Vestibular feedback on a virtual reality wheelchair driving simulator: A pilot study. In Proceedings of the 2020 ACM/IEEE International Conference on Human-Robot Interaction (pp. 171-179).

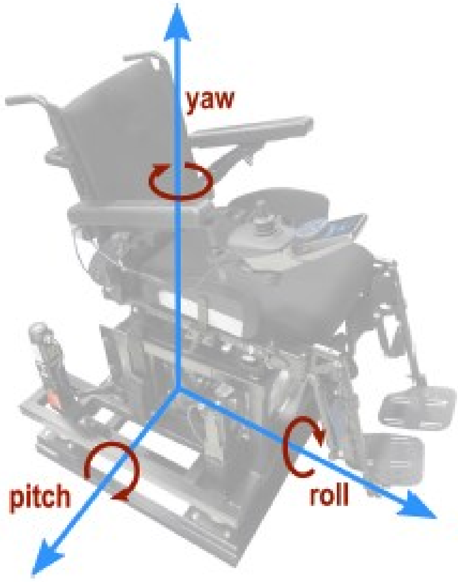


Figure 2: Illustration of feedback platform with rotatic axes illustration

Figure 3: Participant point-of-view during trials. The black part in the bottom-right corner corresponds to the arm of a virtual wheelchair, which is spatially colocated with the real joystick and vestibular feedback platform.

Training is often required for specialist wheelchairs.
Developed a VR driving simulator integrating vestibular feedback to simulate wheelchair motion sensations.
Vestibular feedback was found to increase a sense of presence and decrease cybersickness.

Overall Summary

Covered the basics of balance and posture- and the main organs involved in sensing and maintaining balance and posture.

Covered the role of the main receptor cells of the vestibular system and their role in detecting motion, especially with regards to rotation, linear acceleration, and static position.

Looked at studies that investigating optic flow contributions and show that multisensory inputs contribute to perceptual behaviour.

Applications and studies using vestibular input.

Resources

Essential: Fundamentals of Anatomy and Physiology, 9th Edition, by Frederic Martini. Chapter 17, pages 644-652.

Supplementary:

Al-dabbagh, A.H. and Ronsse, R., 2020. A review of terrain detection systems for applications in locomotion assistance. Robotics and Autonomous Systems, p.103628.

Sra, M., Jain, A. and Maes, P., 2019, May. Adding proprioceptive feedback to virtual reality experiences using galvanic vestibular stimulation. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (pp. 1-14).

Vailland, G., Gaffary, Y., Devigne, L., Gouranton, V., Arnaldi, B. and Babel, M., 2020, March. Vestibular feedback on a virtual reality wheelchair driving simulator: A pilot study. In Proceedings of the 2020 ACM/IEEE International Conference on Human-Robot Interaction (pp. 171-179).

Phillips, J.O., Bierer, S.M., Ling, L., Nie, K. and Rubinstein, J.T., 2011, August. Real-time communication of head velocity and acceleration for an externally mounted vestibular prosthesis. In 2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society (pp. 3537-3541). IEEE.

Todd, C.J., Hübner, P.P., Hübner, P., Schubert, M.C. and Migliaccio, A.A., 2018. StableEyes—a portable vestibular rehabilitation device. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 26(6), pp.1223-1232.