Primer

The vestibular system

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Small, beautifully formed and locked in the skull, the vestibular organs continuously bombard the brain with messages. The messages are quite unlike any others. They tell of accelerations, how the head is rotating and translating and its orientation in space. The messages never stop and cannot be turned off. Even when we are completely motionless, they signal the relentless pull of gravity. Perhaps because of their constant monologue, the vestibular sensation is different to the other senses. There is no overt, readily recognizable, localisable, conscious sensation from these organs. They provide a silent sense.

Known as balance organs of the inner ear, the vestibular organs serve this complex motor function at a largely subconscious level, but their role does not stop with balance. They contribute to a surprising range of brain functions, from the highest levels of consciousness to the most automatic reflexes. The value of the vestibular sensory system to brain functions such as perception of self and non-self motion, spatial orientation, navigation, voluntary movement, oculomotor control, and autonomic control, comes from their unique and complete description of head motion and orientation in three dimensions.

Two different vestibular organs, the otolith organs and semicircular canals, sense different types of acceleration. Two otolith sensors, the utricle and saccule, sense linear acceleration. Three semicircular canals, the anterior, posterior and horizontal canals, sense rotational movements. These two complimentary signals are necessary for the brain to understand the range of physical situations that we experience, probably the most fundamental of which is to work out which way is up.

Which way is up?

All terrestrial and aquatic animals need to know which way is up and, therefore, which way gravity acts, so it is not surprising that special graviceptive systems appear early in evolutionary history. A sense of the force of gravity and which way is up is with us at all times. This internal construction is based on multiple sensory sources, important among which are the vestibular organs. It provides our brains with a deep and special understanding of how the force of gravity moves things, from the fall of our body, as we lift a foot to take a step, to the fall of a ball during a game of cricket. In all of these situations, the brain predicts the trajectory of fall with startling accuracy.

The significance of this internal representation for predicting motion in gravity and its link to the vestibular system was recently shown by Indovina and colleagues. They displayed a ball moving in a visual scene that had strong cues to the up direction. Observers accurately predicted the flight and timing of the ball when the gravitational field was conventionally aligned with the visual scene. Yet when the gravitational field was reversed so that it acted upwards, observers made large prediction errors, even though the ball was subject to exactly the same acceleration. Furthermore, functional magnetic resonance imaging revealed that certain areas of the cerebral cortex were more active when the gravitational field was consistent with the visual scene than when it was reversed. These included areas that receive strong vestibular signals, pointing to a

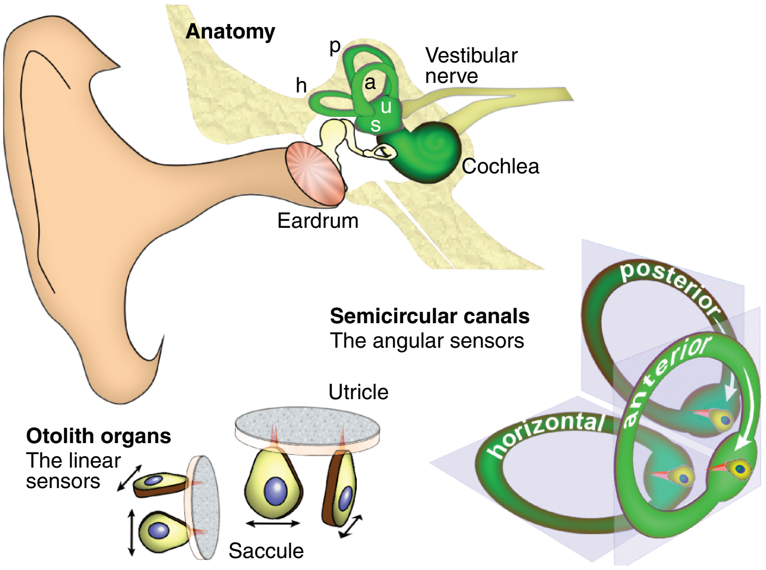

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Figure 1. The vestibular organs.

Locked in the bony structure of the inner ear in close association with the auditory organ, the cochlea, the vestibular organs form two functional units. The two otolith organs sense linear acceleration and its gravitational equivalent, and the three semicircular canals sense rotational movement in space. The hair cells of the utricle and saccule form a two-dimensional array with their cilia embedded in a membrane of dense calcium crystals known as otoliths ('ear stones'). Movement of the membrane by gravitational or inertial forces maximally activates those hair cells that are aligned with the movement. With the two organs oriented at right angles to each other, the direction of linear acceleration is spatially encoded in three dimensions and the magnitude of the acceleration is encoded by the firing rate. As the head rotates, the inertial force of the fluid in the semicircular canals deflects the cilia of hair cells aligned with the canals, modulating the firing of the afferent nerves. With the three semicircular canals aligned at right angles to each other, rotation in any direction can be resolved.

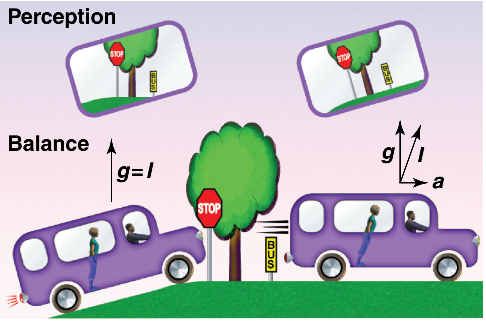

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Figure 2. The vestibular system in action.

Consider standing on a bus. The otolith organs contribute to a signal of the vertical that the brain's balance system uses to align the body with gravity (**g**). The signal of the direction of gravity is also used to align an internal representation of external space so that the world is perceived as upright. Our passenger perceives that she and the trees are upright, whereas the ground and bus is tilted. When the bus leaves the stop, the otolith organs no longer report just the gravitational vector (**g**) but the total gravito-inertial vector (**I**), which is now tilted because of a component (**a**) created by the acceleration. Her otolith signal remains correct for balance because she needs to align herself with the total vector rather than gravity. But with just the otolith signal to align the internal representation of external space, she would perceive a tilted world. We know that, somehow, the brain must solve this problem of the equivalence of acceleration and gravity because, in this situation, we perceive the world to be aligned with gravity rather than the gravito-inertial vector. Our passenger perceives that the ground and bus are level, the trees upright, the bus is accelerating and that she is tilted. The brain needs other sensory signals about rotation of the head and joints to extract the gravitational and acceleration components of the total vector.

vestibular contribution to our internal representation of gravity.

The equivalence problem

The otolith organs seem ideally suited to sense the direction of gravity and signal directly which way is up. The otoliths are essentially masses supported on hair cells. Tilting the head causes the cilia to bend under the sideways component of the gravitational force on the masses. This modulates the firing of the sensory nerves connected to the hair cells. Different hair cells respond to bending in different directions so that the total signal from all hair cells defines the direction of gravity with respect to the skull. There is, however, a serious problem that Einstein explained with his equivalence principle: the effect of a gravitational field on a mass is indistinguishable from the effect of linear acceleration.

For example, consider the otolith organs of a person sitting in a bus. When the head is accelerated forward as the bus pulls away from the bus stop, the inertia of the otolith masses causes them to be left behind and to bend the cilia of the hair cells backward. This is also exactly what happens when the front of the bus tilts upwards on starting to climb a hill. Thus, the otolith sensors send the same signal for two different physical situations; linear acceleration and tilt in the gravitational field. On their own, the otolith organs cannot signal unequivocally which way is up.

Why distinguish tilt and acceleration?

To operate beyond ourselves and navigate the environment, we need to create a stable internal representation of external, earth-referenced space in which the position and movement of objects is independent of our own. A navigation system needs to be able to distinguish the two physical situations of tilt and linear acceleration to build an accurate internal map of our movements. Evidence for this is seen at the processing level of place cells in the hippocampus. These neurons, which code for spatial location as part of a navigation system, depend on vestibular information for their function.

Control of eye movement is probably the most overt example of how the vestibular system creates a stable representation of external space, in this case visual space. The vestibular system profoundly influences eye movements via the vestibulo-ocular reflex to stabilize the visual image on the retina in the face of head motion. When we fix our gaze on an object and our head moves, the vestibular organs detect that movement and produce a counter movement of the eyes to maintain the retinal image. Clockwise head tilt requires the eyes to rotate anticlockwise. Leftward acceleration requires a rightward horizontal shift of the eyes. These two situations, which stimulate the otolith organs identically, must be distinguished to generate appropriate eye movements.

The angular trick

It appears that the brain goes some way toward solving the equivalence problem by simultaneously listening to the messages from the other vestibular organs, the semicircular canals. Like the otolith organs, the hair cells of the semicircular canals respond when their cilia are bent. The difference is that when the head rotates in the plane of a canal, the enclosed fluid is left behind and exerts a pressure that deflects the hair cells. Thus, they respond specifically to angular acceleration of the head and not to gravity or linear acceleration.

Now when the head tilts, say to the right, the brain receives two vestibular signals. The otolith organs signal the static head-tilt, which could equally represent leftward linear acceleration, but the semicircular canals report the transient head-rotation. If the otolith signal results from leftward linear acceleration, the semicircular canals report nothing. Angelaki and colleagues have shown recently, by recording from neurons in the cerebellum in the vestibular nuclei of the brainstem, that the brain can tell apart tilt and linear acceleration by combining the otolithic and semicircular canal signals.

Bipedal balance

The brain does not need to differentiate tilt in gravity from linear acceleration to control balance. Common experience tells us this is true. When we stand in a bus that is stationary or travelling at constant speed, we align our bodies with gravity. This means leaning with respect to the bus when it is on a slope. In exactly the same way, we lean with respect to the bus in the direction of its movement when it is on the flat but accelerating away from the bus stop. To direct the forces acting on the body so that they compress it into the ground rather than topple it, the body must be aligned to the net gravito-inertial acceleration vector, of which one component is gravity and the other the imposed linear acceleration. It does not matter whether it is tilt in gravity or linear acceleration, the brain must produce the same balance response.

The net gravito-inertial vector is precisely what the otolith organs sense. Therefore, simply to align the body in the gravito-inertial force field, the balance system need only consider the otolith vestibular signals and not those from the semicircular canals. But it turns out that the otolith organs provide a surprisingly crude sense of the direction of the gravito-inertial force. People find it difficult to detect a slow tilt of the body, usually only knowing about it when they are more than ten degrees from vertical. In contrast, we can keep the body aligned to within one degree when we stand. This incongruity points to a different solution to balancing the upright body, one that seems to rely upon information from the semicircular canals.

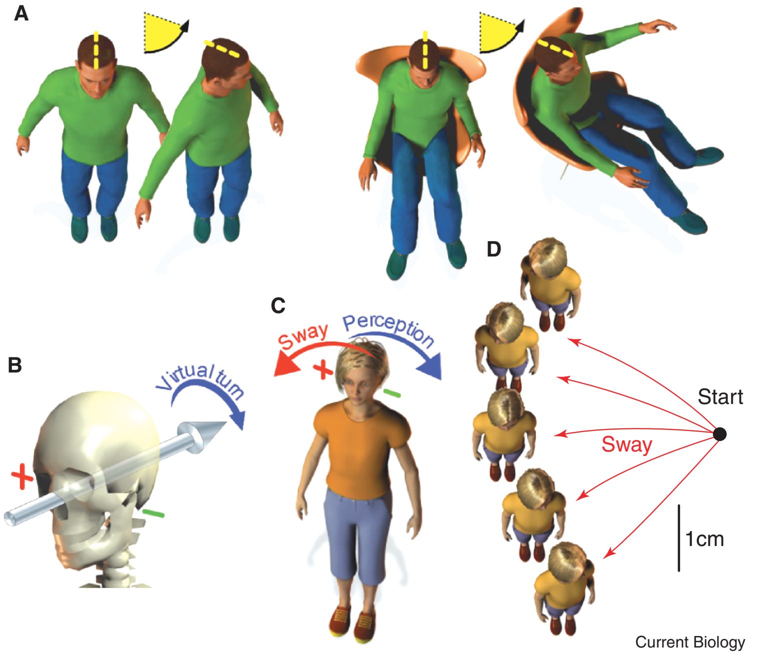

Figure 3. Interactions with other systems.

Identical rotations of the head (A) evoke identical vestibular signals but the brain interprets that signal according to what the other senses report and the current state of the body. If, when standing, the other senses simultaneously report that the neck, trunk and pelvis turn but the feet remain stationary, the vestibular signal contributes to an overall perception of turning to the side. When sitting in a swivel chair and no related signal arrives from the other senses, the vestibular signal alone will elicit a perception that the chair turned. Small electrical currents can be delivered to stimulate the vestibular nerves (B). Electrodes of opposite polarities on each side evoke a signal equivalent to lateral rotation of the head. This 'virtual rotation' (there is no real movement) evokes a perception of body sway in the same direction and a corrective sway response in the opposite direction (C). An experiment using this virtual stimulus (D) shows that, with different alignments of the head relative to the feet, the direction of the reflex sway response is always at the same angle as the head. Thus, the head-referenced vestibular signal is transformed into an earth-fixed reference frame to feed automatic balance reflexes and processes that provide for our perception of body orientation.

Evolution of the semicircular canals and bipedalism

Across different species, the radii of curvature of the semicircular canals are, in general, related to the size of the animal. More massive animals have larger canals. The functional significance is that large diameter canals are more sensitive than small canals because the longer tube of fluid exerts more pressure on the hair cells. Larger, more ponderous animals thereby preserve the rotational sensitivity of their semicircular canals despite their slower movements.

Fred Spoor and colleagues have provided fascinating evidence of an adaptation of the semicircular canals in the evolution of human bipedalism. A constant ratio of canal-radius to body-mass generally holds among land mammals, but within the primates, and even the family Hominidae, there is an interesting deviation. The anterior and posterior canals of the human vestibular organs are enlarged in size relative to the horizontal canal whereas the three canals are more equal in size in other species. The significance of this is that the anterior and posterior canals are orientated to sense rotation in the vertical planes, the movements that are important for controlling upright balance. Furthermore, fossil skulls of early primates believed to have been obligatory bipedal, such as *Homo erectus*, show the semicircular canal pattern of modern *Homo sapiens*, whereas those of non-obligatory bipedal species, such as *Australopithecus africanus*, show canals that resemble more those of extant non-human primates. Thus, the evolution of large vertical canals accompanied the evolution of bipedalism, suggesting that the anterior and posterior canals are important for bipedal balance.

The other senses

As the semicircular canals detect only angular movements and not the gravito-inertial force, we can conclude that human bipedalism relies on an enhanced ability to detect movement. But even using the semicircular canals as a movement detector and the otolith organs as an alignment detector, it appears that the vestibular system alone is still not enough for human bipedalism.

In *Pride and a Daily Marathon* (1995), neurologist Jonathon Cole tells the inspiring story of Ian Waterman who, at 19, suffered an extremely rare syndrome that destroyed the sensory nerves below his neck. With his eyes closed, he is unaware of the alignment or movement of his trunk and limbs. Despite his normally functioning vestibular system, loss of this proprioceptive sense makes standing and walking impossible without vision. Conversely, we know that people who lose their vestibular sense for various reasons can function almost normally in many situations. These observations tell us that the vestibular system does not operate in isolation, but in concert with all of the other available sensory information. The other senses provide additional and different views of the state of the body. Signals from muscles, joints, skin and eyes are all relevant and each may be especially important for resolving particular situations. How the brain integrates this total inflow of sensory information for its various functions remains very much a mystery.

One specific interaction between the vestibular and other sensory systems is worthy of mention here. The vestibular organs are fixed in the skull so that their signals are always referenced to the coordinate frame of the head. This is fine for controlling eye movements through the vestibulo-ocular reflex, because the eyes are also locked in the head. Because the head can adopt almost any position relative to the body or the world, however, there is a need to transform the signal into coordinate systems relevant to the behavior being controlled. Consider a human standing when the vestibular system sends a signal that the head is rotating sideways in a vertical plane. With the head facing forward, the balance system needs to interpret this as the body falling sideways. But with the head turned and facing over one shoulder, the same signal must be interpreted by the balance system as the body falling forward or backward. To transform vestibular signals from a head-fixed to an earth-fixed reference frame, the brain needs to know the relative orientation of all body segments between the feet and the head. This knowledge it gets from the non-vestibular senses.

Virtual head motion

A key question for neuroscience is to understand how the brain combines information from the different sensory systems to produce our complex behaviors and perceptions. Animal experimentalists have started to investigate the cellular and neuroanatomical bases for these sensory interactions. Complimentary human studies will also be important, but there is a major obstacle to isolating the vestibular contribution to brain functions that feed off multiple sensory channels. Any real movement or force that is applied to perturb the vestibular organs also evokes responses from many other sensory receptors, making it impossible to extract the vestibular response. A way around this is to bypass the process of mechanical activation of the vestibular organs and perturb the vestibular system by directly stimulating the vestibular nerves with small electrical currents.

An understanding of how this galvanic vestibular stimulation (GVS) technique works at the cellular level comes from extensive animal recordings of Jay Goldberg and colleagues. It turns out that external electrical stimulation has the same frequency-modulating effect on the vestibular neurons as natural movement. With anatomical knowledge of the hair cell alignment in the vestibular organs, we can calculate the direction of the natural movement that would produce the same signal that GVS evokes. Vectorially summing the responses to GVS from the entire semicircular canal neuron population reveals a virtual rotation about an antero-posterior axis. It is not as clear for the otolith organs, but the vectorial sum suggests a small lateral acceleration. It is simply the idiosyncrasies of the vestibular anatomy that define these virtual head movements evoked by GVS.

Non-invasive techniques like GVS for evoking virtual head motion allow us to probe the vestibular contributions to normal human behavior. We would like to think that future developments will allow us to dial up any desired virtual head motion trajectory. Then we will be well equipped to listen to this silent sense and understand its function in the normal state, as it ages, and in disease.

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Further reading

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