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Vestibular System

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The vestibular system is a key sensory system responsible for self-motion perception and spatial orientation, working in concert with visual, muscular, joint, and tactile receptors to maintain balance. It originates in the inner ear and comprises mechanoreceptors that transduce inertial forces related to motion and gravity into electrophysiological signals, which are transmitted via the vestibular nerve. Each ear contains five vestibular sensors: three *semicircular canals*, which detect angular accelerations generated by head rotations, and two *otolithic organs*, the saccule and the utricle, that encode vertical and horizontal linear accelerations, respectively. Although traditionally associated with reflexes supporting balance control and gaze stabilization, there is strong evidence for a contribution of the vestibular system to spatial navigation, memory, and cognition. Emerging evidence further suggests that the vestibular system may also contribute to the most fundamental sense of self, owing to its phylogenetically ancient role in encoding self-orientation and self-motion.

History

Unlike vision, hearing, touch, taste, and smell, the vestibular system does not belong to the five traditional senses from Aristotle [see [Hearing](#); [Touch](#); [Olfaction](#)]. Consequently, and because the vestibular system works most of the time pre-reflectively, it remains largely ignored by the general population. Like proprioception (the sense of the position and motion of one's own body parts based on mechanoreceptors located in muscles, joints, and tendons), the vestibular system is often referred to as a *sixth sense*. Although proprioception encodes the motion and position of body parts *relative* to one another, vestibular receptors encode the *absolute* motion of the head in space.

Although the vestibular system is phylogenetically very ancient, its functions remained unclear until the early 19th century ([Wade, 2003](#)). Anatomists such as Scarpa had described the inner ear but primarily in relation to hearing. In 1824, Flourens demonstrated its role by mechanically damaging the inner ear in animals, which altered head posture and balance. Volta and Purkinje applied galvanic stimulation to their ears and noted dizziness, vertigo, and nausea, further showing that the inner ear serves functions beyond hearing. Building on the work of Mach, Breuer, and Crum Brown, Bárány elucidated how fluid motion in the semicircular canals encodes self-motion, earning the 1914 Nobel Prize in Medicine ([Wade, 2003](#)).

By the 1950s, neurosurgeon Wilder Penfield was able to evoke conscious vestibular sensations (i.e., illusory self-motion perception) during direct electrical stimulation of the superior temporal gyrus ([Penfield, 1957](#)). The first noninvasive mapping of the human vestibular cortex occurred in the early 1980s using caloric vestibular stimulation, a technique in which warm or cold water is introduced into the external auditory canal to stimulate the semicircular canals and evoke vestibular sensations ([Friberg et al., 1985](#)).

Core concepts

A silent but crucial sense

The vestibular system functions mostly automatically and silently, becoming apparent only when it is impaired. Vestibular disorders can lead to vertigo (illusory motion), instability, and spatial disorientation. Such disorders are relatively common and can result from damage to the inner ear (e.g., Ménière's disease), the vestibular nerve (e.g., vestibular schwannoma), or brain regions involved in vestibular processing (e.g., stroke, epilepsy).

Multimodal sense

Under natural conditions, the peripheral vestibular system is often coactivated with neck muscles and visual receptors. As early as the first stage of vestibular processing in the brainstem (vestibular nuclei), vestibular signals are integrated with visual and somatosensory signals ([Cullen, 2012](#)). The vestibular cortex is also multisensory, containing neurons that respond to vestibular, visual, and proprioceptive signals related to self-motion. Evidence suggests that visual and vestibular signals combine in a statistically optimal way following Bayesian principles ([Angelaki et al., 2009](#)) [see [Bayesianism](#)].

Geocentric reference frame

Otolithic vestibular signals inform the central nervous system about body orientation relative to gravity, contributing to the perception of the visual vertical and the control of bipedal posture. These vestibular signals are also crucial for distinguishing up from down, providing a *geocentric* reference frame (i.e., a gravity-based coordinate system linked to the Earth) for interpreting visual scenes (e.g., face and body perception) and for perceiving object and body motion ([Jenkin et al., 2004](#)). Internal models of gravity, supported by multisensory vestibular areas, are thus essential for understanding the visual environment, for example, interpreting the motion of a ball falling under the influence of gravity ([Indovina et al., 2005](#)).

Spatial navigation and imagery

Research conducted in people with inner ear disorders indicates impaired performance in spatial navigation and memory, highlighting a crucial role of vestibular self-motion signals in path integration ([Glasauer et al., 2002](#)) [see [Spatial Cognition](#)]. Anatomical findings further corroborated this link, showing hippocampal atrophy in patients with bilateral vestibular dysfunction specifically related to spatial navigation deficits ([Brandt et al., 2005](#)). More recent investigations also indicate that the vestibular system is involved in spatial navigation within virtual environments based on optic flow ([Gammeri et al., 2022](#)) as well as in mental imagery of displacement (including visuospatial perspective changes) [see [Mental Imagery](#)].

Questions, controversies, and new developments

Vestibular contributions to self-consciousness and body representation

Recent research has explored the vestibular contribution to the multisensory foundations of the sense of self and body representations [see [Self-Consciousness](#); [Bodily Sensations](#)]. Although traditionally

associated with balance and spatial navigation, vestibular signals may also influence core aspects of the bodily self, including self-location, agency, first-person perspective, and body ownership ([Lenggenhager & Lopez, 2015](#)). Experiments in neurotypical individuals suggest that caloric or galvanic vestibular stimulation can modulate these various facets of the bodily self, potentially because of overlapping neural networks for vestibular processing and bodily self-consciousness ([Dary et al., 2023](#)). However, the precise nature of these interactions and their implications for self-perception remain open questions.

Neurodevelopment and affective disorders

As the vestibular system is functionally active early in development and contributes to the sense of self, it has been postulated that vestibular dysfunction may be linked to certain neurodevelopmental disorders and their comorbidities, such as anxiety and hyperactivity. Additionally, individuals experiencing vertigo, dizziness, or instability are also more likely to develop anxiety and depressive symptoms, and vestibular disorders have been linked to increased prevalence of depersonalization and derealization symptoms ([Tschan et al., 2013](#)).

Thus, vestibular stimulation has historically been explored as a potential therapeutic intervention for psychiatric disorders, including anxiety, mania, and depression ([Grabherr et al., 2015](#)).

While some epidemiological studies ([Bigelow et al., 2020](#)) and animal models with abnormal vestibular function ([Antoine et al., 2017](#)) support an association between vestibular dysfunction and psychiatric symptoms, the underlying mechanisms remain unclear. Considering the high prevalence of vertigo in the general population, further research is needed to understand vestibular contributions to mental health.

Broader connections

Vestibular sensors encode gravitational forces from embryonic development onward, calibrating sensorimotor reflexes for Earth's gravitational environment. Vestibular encoding of gravity also plays a crucial role in shaping visual motion perception. Accordingly, exposure to altered gravitational environments, such as during parabolic flights or during extended stays in the International Space Station, can disrupt sensorimotor reflexes, visuospatial perception, and bodily perceptions ([McIntyre et al., 2001](#)). Future long-term space missions should therefore consider the sensorimotor, cognitive, and affective consequences of partial vestibular deafferentation caused by the absence of Earth's gravity ([Arshad & Ferré, 2023](#)).

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