Correlates for Human Self-Rotation Estimators Are Found

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Published online: 25 February 2022

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A redundant multisensory signal is necessary for accurate motion perception and vestibulo-ocular reflex (VOR). A set of accelerometers (saccul and utricle) and gyroscopes (semicircular canals) from each inner ear provide acceleration and velocity signals, respectively. Despite the binaural redundancy and multiaxial precision, the vestibular system is neither precise nor persistent. For example, cupula, the elastic membrane with embedded hair cell sensors floating within the fluid-filled endolymphatic sac, provides an angular velocity signal [1, 2]. Encoded angular head velocity decays at the cupular elastic time constant it has to be mathematically integrated to estimate the head orientation in the space. This function is served by the neural integrators [3, 4]. Information regarding the head orientation in the space (i.e., tilt) is essential for accurate VOR and motion perception.

A fundamentally important function of the vestibular neural integrator is that it improves the fidelity of the short elastic time constant of the semicircular canals [5]. The integrator improves the accuracy and persistence of the VOR while moving in a curved path. The feedback mechanism, under cerebellar supervision, improves the accuracy of head velocity to position integration. Abnormal cerebellar or brainstem function can cause inaccurate integration of the head velocity signal. The consequence of such inaccuracy is an uncomfortable sense of spinning (vertigo) and postural or gait instability. Vertigo can be present in any posture or triggered by a particular head orientation with

respect to gravity (i.e., positional vertigo). It is fundamentally essential to understand, yet unclear, why only specific head orientation triggers positional vertigo. The perception of spinning is often correlated with the presence of nystagmus. It is also unclear why positional nystagmus is present only in the specific head orientations. The neural integrators are again critical. Head angular orientation encoded by the neural integrator is combined with the otolith derived gravito-inertial acceleration signal to internally estimate the gravity direction. The brain loses track of the head position in relation to gravity if the calibration of the internal estimate is disrupted. Consequently, the conversion of head velocity to position becomes inaccurate under specific angular head orientations, causing head position-dependent vertigo and nystagmus.

The fundamental question is where the vestibular neural integrator is located and what are the underlying physiological principles for its proper function. About half a century ago, Dr. David Robinson, in pioneering experiments, described nonlinear integration of velocity in the cat vestibular pathways [5]. Robinson described that the integrator has a peculiar property of extending the elastic time constant of the cupula, and suggested that such property is like a capacitor, hence called the “velocity storage.” The velocity storage function was hypothetically present in the vestibular brainstem or the deep nuclei, both under cerebellar supervision. A decade later, Raphan and Cohen lesioned the macaque cerebellar nodulus and ventral uvula, prolonging the velocity storage time constant [6, 7]. Subsequent experiments revealed the adaptable nature of the velocity storage time constant [8]. It was further shown that the abnormal adaptation process causes peculiar nystagmus whose direction changes in a cyclic fashion, i.e., periodic alternating nystagmus [8]. Subsequent studies showed that velocity storage is dependent on GABA-B receptor-induced neurotransmission. The treatment with GABA-B agonist, e.g., baclofen, reduced the velocity storage time constant. Baclofen then became a treatment of choice for nystagmus due to pathologies involving the cerebellar nodulus, such as periodic alternating nystagmus [9]. More recent literature

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revealed the velocity storage in all three canal planes. However, it is weaker in the vertical canal planes in humans [10]. Studies discovered a counterpart of VOR velocity storage in vestibular perceptual pathways [10]. Perceptual velocity storage is also dependent on GABA-B mediated neurotransmission. Despite the extensive literature on velocity storage and its critical significance in many brain diseases; its anatomical whereabouts are still unknown.

In the current volume of the cerebellum, Ruehl and colleagues revealed the anatomical correlates of the human velocity storage [11]. The experiments integrating galvanic vestibular stimulation with functional MRI revealed an essential role of vestibular nuclei in velocity storage. This function of the brainstem vestibular nuclei was not surprising. The activation of the feedback from the cerebellar nodulus and ventral uvula was also noted, as expected. In addition, the authors found the activation of cerebellar crus I, II, and lobule VII; the nonmotor structures. These structures are involved in navigational tasks, including spatial processing and prediction of orientation. These novel cerebellar areas underscored the cerebellar importance in perceptual velocity storage. These results offer to prove the principle why some patients with involvement of “non-vestibular” regions (such as areas outside of the posterior vermis) still present with chronic vestibular and navigational deficits. The work is an essential milestone in human vestibular physiology and its interaction with the cerebellum.

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