The neurological mechanisms underlying our sense of balance

We owe all of our innate physiological senses which enable us to fluidly carry out our daily lives, our sense of balance is perhaps the one that we are least consciously aware of. It prevents us from falling over when standing or moving and facilitates clear vision during movement, which enables us to read signs during driving or walking.

We owe all of this to the vestibular and organs in the inner ear which interact with neurons in the brainstem. The vestibular organs detect head movement and encode it into electrical signals that are sent to the brainstem and the neural structures that control eye muscles and muscles of the upper and lower limbs as well as higher brain centers that provide information about our posture and spatial orientation.

This all happens so automatically that we only become aware of it when something goes wrong.

EXCHANGING INFORMATION

Despite the importance of our sense of balance, scientists still know relatively little about the variety of ways through which the vestibular system and the brainstem exchange information.

It has been noticed that the vestibular system is damaged by diseases and the inner ear. The Sadeghi lab uses a variety of experimental approaches to investigate mechanisms of efferent-mediated afferent modulation.

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So far, they have found that these processes are mediated by two important types of nerve cells in a continuously adapting feedback loop. Vestibular afferent neurons (afferents) carry signals from vestibular hair cells in the inner ear to the vestibular nuclei in the brainstem and efferent neurons (afferents), also located in the brainstem, transport feedback to hair cells and the afferents.

There are two populations of hair cells in the inner ear, pear-shaped type I cells and cylindrical type II cells, which form synapses with different types of afferents. Type I hair cells form synapses with calyx-shaped afferent terminals, whereas type II hair cells form smaller bouton-shaped afferent terminals. Both type I and type II hair cells provide inputs to dimorphic afferent fibres.

The afferent nerve fibres have different electrophysiological properties. Calyx afferents fire electrical signals irregularly, boulon afferents have a more regular firing pattern, while dimorphic afferents’ firing pattern lies somewhere in between the two extremes. The overall pattern of afferent signalling sent to the brainstem depends on the type of afferents which are activated by the inner ear.

The irregular firing pattern of calyx afferents is thought to be a crucial mechanism which allows the vestibular system to deal with the rapid head movements that occur when running or playing sport, or to compensate when the vestibular system has been damaged through diseases that affect the inner ear such as labyrinthitis or Ménière’s disease.

The processes which induce this irregular firing have long remained a mystery.

EXISTING THEORIES

Over the past decade, scientists have hypothesised that certain biological adaptations following illness or natural ageing processes. Research suggests that various forms of vestibular dysfunction are present in at least 35% of Americans over the age of 40.

But how exactly does this happen?

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In addition to changes in chemical synaptic transmission, changes in intrinsic membrane properties of nerve cells through changes in the activity of different ion channels could also alter neural firing patterns. The vestibular system could use such modifications in membrane properties in order to adapt and try to maintain reasonably normal balance when vestibular damage occurs.

The peripheral vestibular organs (three semicircular canals and otolithic) are located near the organ of hearing (cochlea) in the inner ear. Information about head motion is carried through two afferent channels in the vestibular nerve (regular / tonic and irregular / phasic afferents) to the vestibular nuclei in the brainstem. These signals are then used to stabilise gaze and posture and provide information to higher brain centers.
Recent studies conducted in a variety of species ranging from macaque monkeys to toadfish have appeared to confirm the neurotransmitter-based nature of vestibular compensation signalling from vestibular brainstem neurons to vestibular afferents. Most notably they have shown that cholinergic efferents exert powerful effects on afferent firing and sensitivity, i.e., the release of acetylcholine from vestibular efferent fibres has a significant effect on the activity of afferent fibres and vestibular hair cells.

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**NEW STUDIES**

The potential consequences of both cholinergic and GABAergic efferent stimulation on afferents are being investigated by Sadeghi’s research group. Sadeghi’s lab uses a variety of experimental approaches to investigate changes in afferent firing by these two efferent pathways, as well as the underlying cellular mechanisms by using immunohistochemistry and electrophysiology approaches in vivo and in vitro.

Previous studies suggest that the activity of neurons in the vestibular nuclei and the vestibular nerve change from tonic (i.e., responding to slow movements) to a more phasic pattern (i.e., responding to fast movements). This functional shift is probably mediated by changes in calyx membrane potassium channels through cholinergic inputs. However, Sadeghi’s group believes that this is only part of the story and that GABAergic efferents also play a role in this tonic-to-phasic shift in neural firing through modulating calcium and potassium channels.

Future studies by Sadeghi’s lab aim to further elucidate this tonic-to-phasic shift in firing and to explore the effect of the two efferent pathways on firing properties of afferents in response to rotational movements.

**IMPACT**

It is hoped that gaining a better understanding of the functioning of the vestibular system and, in particular, the ability of the system to modulate itself through information feedback transmitted between afferents and efferents, could provide the basis for new drug discovery approaches for patients with vertigo and other symptoms of vestibular dysfunction.