VEMP and OVEMP for air-conducted sound lies between 400 and 800 Hz.[84] Whereas with bone-conducted sound (vibration), the best frequency response for both VEMP and OVEMP is at 100 Hz. Modeling of the frequency tuning and other aspects of the response, such as laterality, phase differences, and gain, suggests that the air-conducted peak comes from the rigidly attached saccule, whereas the bone-conducted or vibratory peak derives from the more mobile utricle.[85] A particular type of vestibular hair cell, Type I cells, is thought to be involved in the utricular response and accounts for the marked sensitivity of the OVEMP response to vibration, since these cells typically produce a strong neural vestibular signal in response to a low degree of mechanical disturbance.[86,87]

Most exciting, Todd et al. provide direct experimental evidence that at the 100 Hz tuning peak, the vestibular organs (probably utricle, as above) of normal humans are *much more sensitive than the cochlea* to low frequency bone-conducted sound/vibration.[88] The researchers applied vibration directly to the skin over the bony mastoid prominence behind the subjects' ears, adjusting the power by measuring the tiny whole-head acceleration produced by each vibration force and frequency. They were able to elicit and measure neural signals of the vestibulo-ocular reflex (OVEMP, as above) at vibration intensities 15 dB below the subjects' hearing thresholds. In other words, the amount of vibration/bone-conducted sound was so small that the subjects could not hear it, yet the vestibular parts of their inner ears still responded to the vibration and

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[84] Todd et al. 2009.

[85] Todd et al. 2009.

[86] Todd et al. 2009.

[87] Curthoys IS, Kim J, McPhedran SK, Camp AJ. 2006. Bone conducted vibration selectively activates irregular primary otolithic vestibular neurons in the guinea pig. Exp Brain Res 175(2): 256–67.

[88] Todd et al. 2008.

transmitted signals into the balance and motion networks in the brain, resulting in specific types of eye muscle activation. Since dB is a base 10 logarithmic measure, *15 dB below* means a signal 0.0316 ($10^{-1.5}$), or about 3%, of the power or amplitude of the signal these normal subjects could hear.

The researchers note that "the very low thresholds we found are remarkable as they suggest that humans possess a frog- or fish-like sensory mechanism which appears to exceed the cochlea for detection of substrate-borne low-frequency vibration and which until now has not been properly recognized."[89] Thus the potential exists, in normal humans, for stimulation of balance signals from the inner ear by low frequency noise and vibration, even when the noise or vibration does not seem especially loud, or even cannot be heard. In the presence of pre-existing inner-ear pathology, thresholds for vestibular stimulation by noise or vibration are even lower than in normal subjects.[90]

Central balance processing

When there is conflict in neurologically normal people among the signals coming from the different balance channels, the brain areas that integrate the information quickly compensate by suppressing or down-weighting information from the anomalous channel[91]—information that does not match what is coming from the other channels. On functional brain scans, vestibular and visual cortical areas show a pattern of inverse activation and deactivation, such

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[89] Todd et al. 2008, p. 41.

[90] Colebatch et al. 1998. See footnote 73.

[91] Jacob RG, Redfern MS, Furman JM. 2009. Space and motion discomfort and abnormal balance control in patients with anxiety disorders. J Neurol Neurosurg Psychiatry 80(1): 74–78. E-pub 2008 July 24.