



Central Representation of Cervical Vestibular Evoked Myogenic Potentials

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Received: 18 April 2023 / Accepted: 20 April 2023 / Published online: 6 May 2023
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Abstract Sensitivity of vestibular system to sounds (SVSS) can be measurable by cervical vestibular evoked myogenic potentials (cVEMPs). The aim of this study is to investigate central representation of vestibular system sensitivity to sound. The research was conducted in 2022–2023 by searching English language databases. The criterion for selecting documents was their overlap with the aim of this work. The animals studies were not included. The sacculle is stimulated by sounds, that are transmitted through air and bone conduction. Utricle and semicircular canals are activated only by the vibrations. The afferent nerve fibers of the vestibular system project to the temporal, frontal, parietal, primary visual cortex, insula and the cingulate cortex. There is a relationship between normal results of the cVEMPs and these parameters. Improved phonemes recognition scores and word recognition scores in white noise, the efficiency of auditory training, increased amplitude of the auditory brainstem responses to 500 HZ tone burst. Learning the first words is not only based on the hearing and other senses participate. The auditory object is a three-dimensional imaging in people's minds, when they hear a word. The words expressed by a speaker create different auditory objects in people's minds. Each of these auditory objects has its own color, shape, aroma and characteristics. For the formation of the auditory objects, all senses and whole areas of the brain contribute. Like other senses, central representation of vestibular system sensitivity to sound are also involved in the formation of auditory objects.

Keywords Vestibular evoked myogenic potentials · Sensitivity to sound · Vestibular system

Abbreviations

cVEMPs Vestibular evoked myogenic potentials
SVSS Sensitivity of vestibular system to sounds

Introduction

The human inner ear is consisted of two separate organs; the cochlea and vestibule. The cochlea is an organ of hearing, the vestibule is responsible for maintaining the body's balance in linear and angular accelerations [1, 2]. The SVSS in human has been confirmed by invention of the cVEMPs [3–9]. It is generated during the stimulation of the sternocleidomastoid muscle with intense low frequency sounds [3, 10, 11]. The sacculle has highest sound sensitivity between vestibular organs [12–14].

Pathologies that involve the inner ear cochlea, also cause damage to the sacculle. Then, the most susceptibility of the vestibular organs to impairment is related to the sacculle, in cases of sensorineural hearing loss [15, 16], Meniere's disease [17], sudden sensorineural hearing loss [18, 19], auditory-neuropathy [20], noise induced hearing loss [21], destructive effects of musical sounds [22], aging [23], ototoxic drugs [24], and covid-19 [25]. Also, continuous loudly singing, which lasts longer than duration time of the stapedius reflex of the middle ear can cause saccular damage [26]. In addition, the recovery of the patients with acute low-frequency sensorineural hearing loss and saccular damage is weaker than similar cases with normal saccular function [27].

The most important reason for saccular susceptibility to impairment is the proximity of the sacculle to the cochlea

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through the Reunion duct [2], which connects the lower part of the saccule to the cochlear duct near its vestibular extremity [1].

The aim of this study is to investigate central representation of vestibular system sensitivity to sound. In order to retrieve original documents that were published between 2000 and 2022, information sources about SVSS in human were studied, such as Science Citation Index, Web of Science, PubMed, PubMed/Medline, Scopus, Springer, Pearson, Google Scholar. First, 89 documents were found, and finally 58 papers that were related to the title of this study were considered. The criterion for selecting articles was their overlap with the purpose of this work and gain access to the full text of the sources. The SVSS in animal literatures was not included.

Results

A summary of the conclusion section of the published articles on sensitivity of vestibular system to sounds in the years 2000 to 2023 is presented in Table 1.

Discussion

Based on the findings reported in the results section of this research, the human vestibular system is sound sensitive and sends signals to the neural centers of the brainstem and the brain. Now, this question is raised: Are the neural information from the vestibular system useful in the neural processing? To answer this question, it is necessary to take a brief look at how to learn new words.

Learning the first language for every native listener is a natural part of that person's daily life, which is formed based on the relationship he/she has with the world around him. The first language of a child is part of that child's personal, social and cultural identity, it brings about the reflection and learning of effective social patterns of acting and speaking [48]. To perception the world, contribution of all senses is necessary. Learning the first words is not only based on the hearing and other senses participate. The auditory object is a three-dimensional imaging in people's minds, when they hear a word. The words expressed by a speaker create different auditory Objects in people's minds. For example, upon hearing the word "flower", different auditory objects of flower may be represented for people; a flower in a glass, a flower in a garden, a faded flower, a flower in a bride's hand or a flower on a tombstone. Each of these auditory objects

has its own color, shape, aroma and characteristics. Then for a native listener, each spoken word is equivalent to an auditory object. For the formation of the auditory objects, all senses and whole areas of the brain contribute [49].

Speech-in-noise perception is also done with the participation of all areas of the brain. The neural centers for speech perception are various and temporal lobe is influenced by several sensory processings and mechanisms, the auditory brain is not actually monosensory and had multi-modal processing [38, 50, 51].

The vision also plays a guiding role in the formation and maturation of auditory responses. If the visual signals are damaged during childhood, the auditory representation in the superior colliculus is impaired due to the disturbance in the normal development. Vision problems due to surgery or head trauma can disturb the auditory spatial balance in the nucleus of the superior colliculus [52].

The inferior frontal gyrus improves people's accuracy in repeating unfamiliar foreign speech sounds, and matches perceived speech to produced speech [49]. Mirror-neuron brain areas, which have no role in interpretation of high-level activities and are involved in low-level processing have a precise and essential role in speech-in-noise perception [53].

The insula in the left cortex is exactly motivated when main frequency of human voices transport lexical information to a native listener, whereas the insula of the right cortex is activated once main frequency of human voices do not provide lexical information [48]. The cingulo-opercular system is involved in central-peripheral processing of attention and control [49]. Therefore, the neural signals from the vestibular system project to various areas of the brain and participate to other senses for formation the auditory Objects.

The SVSS is in the range of the fundamental frequency of the human voice [36], which differs between men = 100_{HZ}, women = 200_{HZ}, and infants = up to 400_{HZ} [54]. Considering that the saccule is close to the larynx and is also connected to the cochlea [2], the afferent nerve fibers of the saccule are stimulated during self-voice production [34, 38], and the person ossifies his own voice through feedback control or bone-conducted pathway [38].

Saccular nerve fibers spirit to the brainstem. The brainstem is also sensitive to low-frequency sounds and participates in detection the pitch of speech and the melody of music. The brainstem encodes the first formant of speech (the lowest frequency or the strongest harmonic of the speaker's voice), which is necessary for the perception of vowels [51, 54]. Therefore, the acoustical information of the vestibular system that goes to the brainstem may be effective in detection beats and pitch [30, 33].

Table 1 A summary of the conclusion section of the published articles on sensitivity of vestibular system to sounds

1	Todd et al. [28]: Saccular sensitivity to intense sound in human has maximum response at frequencies between 300 and 350 HZ [28]
2	Todd [8]: Upper limit of human saccular sensitivity to sound is around 600 HZ. Unlike other frequency sounds, the sense of pleasure at 200 HZ rises with increasing intensity, which is in the range of SVSS [8]
3	Lenhardt [4]: Best human saccular sensitivity to sound is around 350 HZ [4]
4	Todd et al. [29]: The human vestibular system displays a remarkable sensitivity to low-frequencies. Most human utricular sensitivity to vibration had largest response at 100 HZ [29]
5	Sheykholeslami et al. [6]: Biggest bone-conducted cVEMPs amplitude is related to frequency range 200–400 _{Hz} , which can participate to the perception of loud sounds [6]
6	Welgampola et al. [11]: Bone-conducted sounds evoke cVEMPs, which is an additional evaluation of vestibular function and is not confused by conductive hearing loss [11]
7	Sheykholeslami et al. [5]: SVSS with Tullio phenomenon is a sign of superior semicircular canal dehiscence, which causes more sensitivity to changing pressure and confirming the theory of Third Window [5]
8	Fröhlich et al. [14]: Due to the presence of false air-bone gaps in patients with profound sensorineural hearing loss, the use of air conducted stimulus for cVEMPs measurement is an ineffective diagnostic method to evaluate otolith function in patients with profound sensorineural hearing loss and should be avoided. Then, bone conducted stimulus should be used instead. Because, it gives more accurate results. While, the use of air conducted stimulus bears the risk of false negative results, bone conducted stimulus is an effective stimulus enabling the assessment of utricular and saccular function in cochlear implant patients [14]
9	Sheykholeslami and Kaga [7]: The human inner ear vestibule has retained its sensitivity to acoustic stimulation. The cVEMPs remains intact in humans who have discrete genetic pathologies of the cochlea and semicircular canals but have normal otolithic organs [7]
10	Emami and Daneshi [30]: The amplitude of an auditory brainstem response (ABR) component depends on the amount of synchronized neural activity, and the auditory nerve fibers' responses have the best synchronization with the low frequency. There is a significant relationship between abnormal findings of cVEMPs and abnormal findings of slow wave ABR component (decreased neural synchronization) [30]
11	Butler and Trainor [31]: There is the strong cooperation between the auditory and vestibulo-motor systems for rhythm perception and neural synchronization [31]
12	Kassow et al. [32]: The SVSS contribute in acoustico-motor synchronization. The P300 wave of the evoked electrophysiological responses amplifies during non-self-voice practice and synchronised motion [32]
13	Emami and Gohary [33]: The saccular nerves fibers can be projective to auditory bundles and interact with auditory brainstem response to 500 HZ tone. There is a relationship between normal results of the cVEMPs and the amplitude wave-V ABR 500 HZ. It is also obvious that the word of ABR 500 HZ is not suitable and the novel term or vestibular-auditory brainstem response to 500 HZ tone burst is more possible [33]
14	Trivelli et al. [34]: The cVEMPs is obtainable in deaf people and the saccule has sound sensitivity for intense low frequencies [34]
15	Emami [35]: Auditory training and more experience of self-voice production improved neural synchronization in auditory nerve fibers, and also can increased cVEMPs amplitude in deaf people [35]
16	Emami [36]: In high-level of noisy competing situations, healthy human saccular sensation can mediate the detection of low frequencies [36]
17	Emami et al. [37]: The score of phonemes recognition in white noise is higher in persons with normal cVEMPs [37]
18	Iannotti et al. [38]: The highest score of speech discrimination at most comfortable level of hearing is related to the bone-conducted human voice, and causes better neural processing in the insula, cingulate cortex, and medial temporal lobe. Indeed, human hearing is multi modal [38]
19	Emami et al. [39]: The people with normal cVEMPs had better word recognition scores in white noise [39]
20	Longridge et al. [13]: Internal sounds are decreased by stapedius reflex, when they reach to the ear through the air and bone-conducted pathway. These brief tones can not stimulate vestibular system [13]
21	Emami and Nikoo [40]: Vestibular afferent fibers project to the stapedius muscle and decrease stimulation threshold of this muscle. The cVEMPs can predict the probability of the occurrence the ipsilateral stapedial muscle reflex to 500 HZ [40]
22	Phillips-Silver and Trainor [41]: In all group ages, the musical programming of rhythm on pitch perception of tonality and sound quality can be biased by reflexive motion of the body. The cortical and subcortical area cooperate to integration of auditory and vestibular inputs that may cause the cooperation among motion and auditory pitch perception [41]
23	Oh et al. [12]: Auditory and vestibular junctions are contained in overlapping areas of the caudal part of the superior temporal gyrus and the posterior insula. There are segments that are reactive only to suprathreshold signals, suggesting vestibular sound processing in these regions [12]
24	Todd et al. [42]: The SVSS stimulates the bilateral upper temporal lobes and the cingulate cortex. The result of this auditory-vestibular interaction is a new wave. It is one of the late auditory evoked potentials of cortical origin, and the presence of vestibular-dependent contributions to auditory evoked potentials (AEPs) when passing through the vestibular threshold as determined by cVEMPs, including a particular deflection labeled as an N42 / P52 prior to the long-latency AEPs N1 and P2 [42]

Table 1 (continued)

25	Miyamoto et al. [43]: High-intensity clicks activated wide areas of the cortex, namely, the frontal lobe (prefrontal cortex, premotor cortex, and frontal eye fields), parietal lobe (the region around the intraparietal sulcus, temporo-parietal junction, and paracentral lobule), and cingulate cortex. Semicircular canals and saccular signals may be processed in similar regions of the human cortex [43]
26	Sch lindwein et al. [44]: Major motivations of the vestibular cortical areas are located in the multisensory cortical vestibular network within both hemispheres, comprising the posterior insular cortex, the middle and superior temporal gyri, and the inferior parietal cortex. The activation pattern is bilaterally with a majority of the right hemisphere in right-handers. Saccular vestibular projections is mainly ipsilateral, while processing of auditory signals is contralateral and mainly in the left hemisphere. The stimulation design is like to the horizontal semicircular canal [44]
27	McNerney et al. [45]: Several regions of brain are motivated by otolith stimulation, which include the primary visual cortex, the precuneus, the precentral gyrus, the medial temporal gyrus, and the superior temporal gyrus [45]
28	Todd et al. [46]: The SVSS contributes to formation the auditory T-complex of the auditory evoked potentials (AEP) in posterior lateral surface of the temporal lobe [46]
29	Emami [47]: There is false air bone gaps in pure tone audiograms of people with profound sensorineural hearing loss and normal cVEMPs. The false air bone gaps are better bone-conducted hearing thresholds in compared to air, in frequency range of 250–750 HZ. False air bone gaps does not exist in people with profound sensorineural hearing loss and abnormal cVEMPs (Figs. 1 and 2) [47]

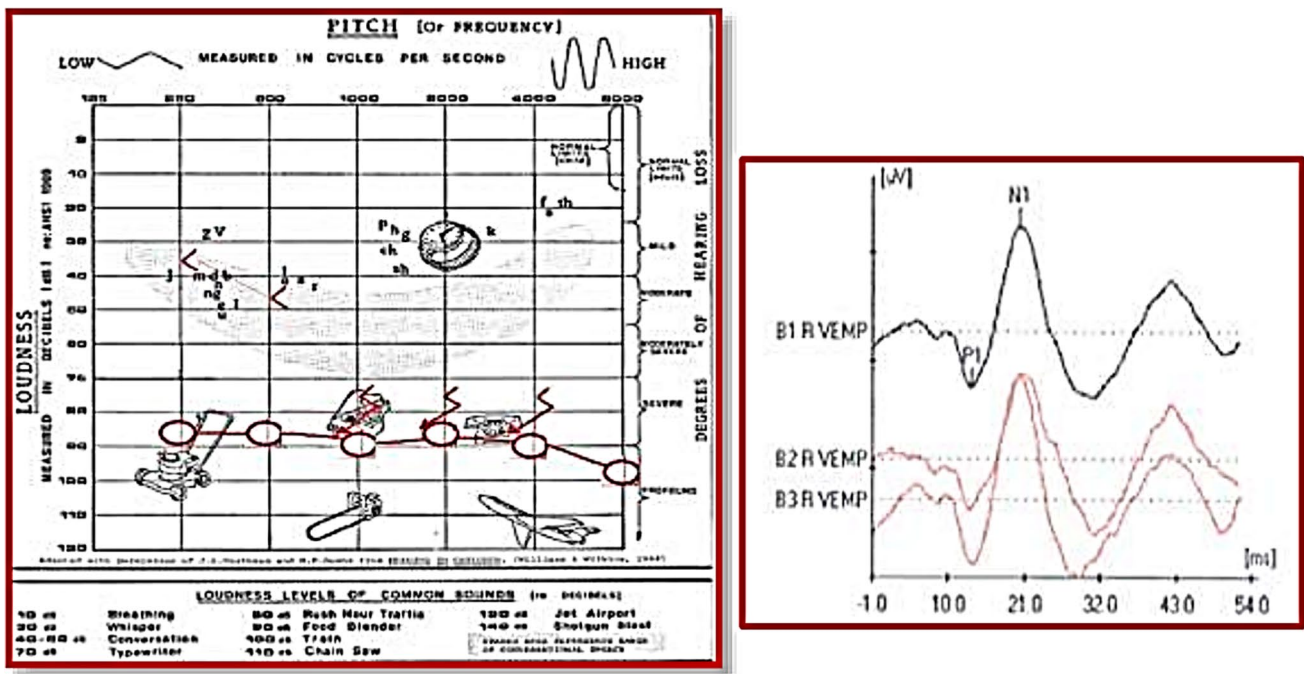


Fig. 1 Pure tone audiogram of the right ear a person with profound sensorineural hearing loss and false air-bone gaps (ABG) in 250-500 Hz, and normal cVEMPs [47]

The SVSS can be motivated when people participate in group activities in noisy competing situations, e.g. singing poetry together, chanting in the crowd, shouting in the group, cheering on their favorite team in sports activities, performing military parades, and similar cases [7, 9, 38, 39, 55–58].

The limbic receives inputs from vestibular afferent nerve fibers and regulates emotions, such as anger, joy, hate,

sadness [28]. The limbic is also connected to musculo-skeletal systems [8, 9]. Then, intense low-frequency sounds stimulate the saccule, the limbic, the musculo-skeletal systems [9] and generate the desire to perform the harmonic movements, in the form of pacing, marching, clapping or chest beating [28, 31, 41].

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