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Frequency analyses of postural sway demonstrate the use of sounds for balance given vestibular loss[☆]

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ABSTRACT

Purpose: To investigate how adults with unilateral vestibular hypofunction and healthy controls incorporate visual and auditory cues for postural control in an abstract visual environment.
Methods: Participants stood on foam wearing the HTC Vive, observing an immersive 3-wall display of 'stars' that were either static or dynamic (moving front to back at 32 mm, 0.2 Hz) with no sound, static white noise, or moving white noise played via headphones. Each 60-second condition repeated twice. We recorded the center-of-pressure variance, and its power spectral density [PSD, cm^2] components in low [0, 0.25 Hz], mid [0.25, 0.5 Hz] and high [0.5, 1 Hz] frequencies in the anterior-posterior direction. We used linear mixed-effects models to compares healthy controls (n = 41, mean age 52 years, range 22–78) to participants with unilateral peripheral vestibular hypofunction (n = 28, 61.5, 27–82), adjusting for age.
Results: Variance and low PSD: we observed a significant vestibular by visual load interaction in the presence of sounds, such that the vestibular group had significantly higher sway than controls only on dynamic visuals in the presence of sounds. Mid PSD: the vestibular group had significantly higher sway than controls regardless of condition. High PSD: the vestibular group had significantly higher sway than controls, except for the presence of sounds on static visuals.
Conclusions: Patients with vestibular hypofunction used sounds to reduce sway in a static abstract environment and were somewhat destabilized by it in a dynamic environment. This suggests that sounds, when played from headphones, may function as an auditory anchor under certain level of challenge and specific tasks regardless of whether it's stationary or moving. Our results support that increased sway in middle frequencies reflects vestibular dysfunction.

1. Introduction

Postural control is often quantified by traditional measures of standing steadiness, such as variance, path, and velocity. For these metrics, higher values mean reduced postural stability. In addition to these metrics, power spectral density (PSD) analysis may reveal more specific strategies and subtle changes in sway. PSD analysis looks at the time series across frequencies and quantifies sway at different frequency segments. The sum of the area under the curve forms the total variance. While the literature varies in internal cutoffs, it is well known that the largest contributor to the variance in quiet standing is low frequency sway (sway at 0.01–0.25 Hz) [1]. Accordingly, low frequency sway is dependent on slow cortical loops [2] and overall feedforward/ anticipatory postural control [3]. High frequency sway (defined as above 0.5 Hz [4] or 1 Hz [5] or 2 Hz [6]) is considered to reflect the fast corrective movements done by somatosensory system (proprio-spinal reflex), i.e., reactive / feedback postural control [3]. The mid-range (0.25–0.5 Hz) has been suggested to reflect vestibular in-flow via the

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vestibulo-spinal reflex [7], and excessive activation in this range is considered to reflect vestibular dysfunction [5,8,9].

There is a clear, well established, visual effect on balance. Indeed, even healthy young adults will significantly increase their postural sway when closing their eyes or reduce their sway with a fixed visual reference [10]. The inclusion of sound, specifically fixed, non-moving broadband noise (white or pink) has been shown to reduce postural sway, suggesting that sounds may serve as "auditory anchor" perhaps similar to visual cues for balance. However, the "auditory anchor effect is less clear than that of a visual reference. For example, sounds appear to influence postural control only when the task is challenging enough [11] and mostly in those who have balance problems [12]. In addition, some discrepancies between studies with significant and null results, particularly in healthy adults, call for further investigation of the nature of involvement of sounds in normal and impaired postural control as well as if and how sounds may be implemented in balance rehabilitation. Finally, most studies showing a significant effect of varying types of sound on postural control used stationary loudspeakers [13], whereas the results when using headphones were more variable [14–16].

In this study, we aimed to test the "auditory anchor" theory in an abstract immersive environment using a well-established visual protocol [8,17]. We tested the role of stationary vs. moving generated white noise in static and dynamic visual environments. Because the influence of sounds on postural control has been shown to depend on the circumstance [14], we chose a standing balance task that was challenging enough to produce sensory reweighting and potentially over-reliance on vision and sounds (standing on foam). To balance the need for challenge with creating a task that is feasible for people with vestibular hypofunction, we had participants stand hips-width apart. The purpose of this study was to investigate the role of stationary and moving white noise in postural control. By adding sounds to a well-established visual protocol [8,9,17,18] and incorporating frequency analysis of postural sway, we hoped to gain a deeper understanding of how sounds influence sensory integration for postural control.

2. Materials and methods

The full study was registered on clinicaltrials.org (NCT04479761) and approved by the Biomedical Research Alliance Of New York LLC Institutional Review Board (BRANY IRB, study #20–02–278–05) and

2.1. Sample

We recruited participants with unilateral peripheral vestibular hypofunction and normal hearing (i.e., vestibular neuritis) from the vestibular rehabilitation department at the New York Eye and Ear Infirmary of Mount Sinai. We identified potentially eligible participants with a complaint of head motion provoked instability or dizziness affecting their functional mobility and quality of life during their standard clinical evaluation. To participate in the study, participants were required to present with at least 1 positive finding indicating unilateral peripheral vestibular hypofunction on the following clinical tests: bedside head impulse test, head shaking nystagmus, spontaneous and gaze holding nystagmus [19], in addition to a score of at least 16 (mild handicap) on the Dizziness Handicap Inventory (DHI)[20]. We excluded diagnoses associated with an unstable peripheral lesion or retrocochlear pathology, specifically: Benign Paroxysmal Positional Vertigo, Meniere's Disease, Perilymphatic Fistula, Superior Canal Dehiscence, or Acoustic Neuroma. We recruited healthy controls from the university community. Normal hearing for both groups was defined as an unaided PTA < 26 dB HL (0.5–4 kHz) bilaterally, or for those above 65 years of age, we included symmetric high frequency loss leading to an unaided PTA < 40 dB (0.5–4KHz) [21]. Exclusion criteria for both groups also included a medical diagnosis of peripheral neuropathy; lack of protective sensation based on the Semmes-Weinstein 5.07 Monofilament Test [22]; visual impairment above 20/63 (NYS Department of Motor Vehicle cutoff for driving) on the Early Treatment Diabetic Retinopathy Study (ETDRS) Acuity Test that cannot be corrected with lenses; conductive hearing loss; pregnancy; any neurological condition interfering with balance or walking (e.g. multiple sclerosis, Parkinson's disease, stroke); acute musculoskeletal pain at time of testing; currently seeking medical care for another orthopaedic condition; and inability to read an informed consent in English or Spanish. We excluded any healthy controls who had vestibular symptoms (DHI≥ 16) or any hearing loss that did not meet the criteria specified above. Healthy controls were required to have no history of participating in vestibular rehabilitation.

2.2. System

We developed the system in C# with Unity 2019.4.16f1(64-bit) (©Unity Technologies, San Francisco, CA, USA). The scenes were displayed via an HTC Vive Pro Eye head-mounted display (HMD, HTC Corporation, Taoyuan City, Taiwan). The sounds were played via Bose QuietComfort® 35 II around-ear headphones (Bose Corporation, Framingham, MA, USA). The system ran on an Alienware® m15 R4 laptop running Windows®10 with 32 GB RAM, Intel i9–10980HK CPU, Nvidia®GTX 3080 GPU (Dell Technologies, Round Rock, TX, USA).

The stars scene is an abstract scene with a display of randomly distributed white spheres as stars on a 3-sided wall (front and two sides) with a black background around participants to cover their field of view [17]. A 0.46 m radius circular area of occlusion is created in front of the participants at their eye level height to suppress the "sampling artifacts" aliasing effects [23]. The stars had either no movement (static) or an anterior-posterior movement at 0.2 Hz frequency and 0.032 m amplitude (dynamic) [8]. See Supplementary Videos 1 and 2.

Supplementary material related to this article can be found online at doi:10.1016/j.gaitpost.2024.12.013.

White noise was generated at 44.1 kHz sampling rate by independent and identically distributed random variables. The low auditory level of the star scene is a quiet scene with no audio (No Sound). The middle auditory level plays the white noise constantly over the entire 60 s trial with the white noise audio source spatialized at the eye level height and 1.63 m away in front of the participant (stationary). At the high auditory level, the white noise audio sources make a circular movement at constant speed and at the participant's eye level around the participant from each starting point in a quarter circle of 2 m radius in 2 seconds. There are 24 starting points, 12 on the left side and 12 on the right side of the participant's lateral plane. The 12 starting points are evenly distributed on each side with 10-degree intervals from 20 to 70 and from 110 to 160 degrees on the horizontal plane at the participant's eye level height. All the 24 white noise players run consecutively with 0.5-second intervals in a random order in the high auditory level[24].

2.3. Procedure

Participants signed an informed consent and underwent a screening session to confirm visual and tactile eligibility criteria, comprehensive behavioral audiometry, the caloric portion of the Videonystagmography (VNG) test and the Video Head Impulse Test (vHIT). Caloric weakness was defined as asymmetry > 25 % between ears[25] and vHIT was considered abnormal < .79 [26,27].

During the postural control testing session, the participants wore the HTC Vive Pro HMD and a cable-connected noise-cancelling headphones. They stood on a foam surface (AIREX, Sins, Switzerland) placed on a force platform (Kistler, Winterthur, Switzerland) with their feet hips-width apart (See Fig. 1). Feet position was marked on the foam to maintain consistency of base of support between conditions. We introduced the sounds at 80 % of the computer's intensity (which corresponds to 72 dB SPL for the stationary white noise and 79–83 dB SPL for the moving white noise). We then adjusted the loudness to the highest level that was comfortable to the participant. Scenes were 60 seconds

Fig. 1. Experimental Setup.

long. There was a total of 6 combinations: 2 visuals (static, dynamic) for each of 3 sounds (none, stationary white noise, moving white noise) and each combination was repeated twice in a random order. Participants completed the Simulator Sickness Questionnaire (SSQ), a 15-items questionnaire, before, mid and at the end of postural control testing. They rated their symptoms per item as none, slight, moderate or severe and the total sum was recorded [28].

2.4. Data processing and outcome measures

We recorded center-of-pressure (COP) data from a Kistler force plate. Data processing was performed in Matlab R2024a (Mathworks, Natick, MA). We removed the first 5 sec of each 60 sec trial and used the remaining 55 seconds to quantify Power Spectral Density (PSD, decomposing the signal into its frequency components) in the anterior-posterior direction in 3 segments: PSD 1 (0–0.25 Hz), PSD 2 (0.25–0.5 Hz) and PSD 3 (0.5–1 Hz). The variance of the signal was calculated as the sum of all discrete PSD values.

2.5. Data analysis

First, to evaluate the main effect of group, we fit a linear mixed effects model for each outcome measure (Variance, PSD 1, PSD 2, PSD 3) using a log transformation of the outcomes. We used a log transformation because preliminary analysis showed that the residuals from a model without the log transformation were heteroscedastic. The models were fit separately for each auditory condition (none, stationary, moving). Each model included the main effect of group (control, vestibular) and visual condition (static, dynamic) as well as their two-way interaction. Next, to evaluate the main effect of sound, we fit the same models, now including the 3 auditory levels per group and visual condition. All models adjusted for age. While these models are equivalent to a 3-way interaction of group by visual by auditory condition, we chose this modeling approach to simplify interpretation.

These models maximize the information we can obtain from the data by accounting for the inherent multi-level study design (person, conditions, repetitions). Since each person completes various trials for each condition, the linear mixed effects model accounts for these sources of variability [29]. *P*-values for the fixed effects were calculated using the Satterthwaite approximation for the degrees of freedom for the T-distribution [30]. The Model Estimated difference (MED) is reported as an indication of effect size for the difference between groups.

3. Results

3.1. Sample

The mean age of the control group (N = 41) was 52 years (SD=17.9) and that of the vestibular group was 61.5 years (SD=14.6). Females comprised 49 % of the control group (N = 20) and 54 % of the vestibular group (N = 15). The vestibular group had an average DHI of 35.6 (SD=18.1) whereas the controls all had a score of 0 on the DHI. The average chronicity of vestibular symptoms was 2.46 years (SD=2.82). The results of the comprehensive behavioral audiometry can be seen in Table 1. All participants completed caloric testing. Unilateral caloric weakness was recorded in 89 % of the vestibular group (N = 25) and 12 % of the control group (N = 5). Three controls and 5 participants in the vestibular group did not complete the vHIT. Lateral vHIT gain < 0.79 [26,27] was recorded in 61 % of the tested vestibular group

Table 1
Results of comprehensive behavioral audiometry.

	Control Group (N = 41, mean age 52)	Vestibular (N = 28, mean age 61.5)
PTA RT ear (dB) Mean (SD)	12.93 (8.35)	20.55 (9.84)
PTA LT ear (dB) Mean (SD)	13.35 (8.33)	20.94 (10.54)
Word Discrimination Score RT ear (%) Mean (SD)	99.12 (2.42)	98.59 (2.39)
Word Discrimination Score LT ear (%) Mean (SD)	99.02 (2.62)	97.57 (3.09)

(N = 14) and none of the controls. The majority of participants chose to keep the sound loudness as presented. Six participants in the control group (15 %) and 2 in the vestibular group (7 %) opted to increase volume to 90 % (73.5 dB SPL for stationary, 80–86 dB SPL for moving). Ten participants in the control group (24 %) and 6 in the vestibular group (21 %) opted to reduce volume with the lowest being 60 dB SPL for stationary and 69–74 dB SPL for moving (1 participant per group).

Across all outcome measures, no main effect of auditory condition was observed.

Variance: The vestibular group was significantly higher than controls only on dynamic visuals with either sound (stationary: MED=0.41, $p = 0.014$; moving: MED=0.38, $p = 0.008$). A significant main effect of visual was observed for both groups across sound conditions ($p < 0.001$). A significant group by visual interaction was observed such that the effect of changes in visual load was greater for the vestibular group only in the presence of sounds (stationary $p = 0.004$, moving $p = 0.04$). See Fig. 2.

PSD 1: The vestibular group was significantly higher than controls only on dynamic visuals with either sound (stationary: MED=0.2, $p = 0.022$; moving: MED=0.17, $p = 0.04$). A significant main effect of visual was observed for both groups across sound conditions ($p < 0.001$). A significant group by visual interaction was observed, such that the effect of changes with visual load was greater for the vestibular group only in the presence of sounds (stationary $p = 0.001$, moving $p = 0.04$). See Fig. 3.

PSD 2: The vestibular group was significantly higher than controls on all 6 conditions (static visual: none: MED=0.05, $p = 0.006$; stationary: MED=0.04, $p = 0.025$; moving: MED=0.05, $P = 0.006$; dynamic visual: none: MED=0.09, $p = 0.002$; stationary: MED=0.1, $p = 0.001$; moving MED=0.1, $p < 0.001$). A significant main effect of visual was observed for both groups across sound conditions ($p < 0.001$) with no interactions. See Fig. 4.

PSD 3: The vestibular group was significantly higher than controls on all conditions except for static visual in the presence of either sound (static visual: none: MED=0.02, $p = 0.04$; dynamic visual: none MED=0.04, $p = 0.024$; stationary: MED=0.05, $p = 0.005$; moving: MED=0.036, $p = 0.029$). A significant main effect of visual was observed for both groups across sound conditions ($p < 0.001$) with no interactions. See Fig. 5.

4. Discussion

This study investigated how adults with vestibular loss and healthy controls incorporate visual and auditory cues for postural control in an abstract visual environment via frequency analysis of postural sway. Changes in visual load from static to dynamic influenced both groups across frequency segments, which was likely because participants were standing on foam, known to induce somatosensory reweighting and visual reliance. Because PSD 1 is the primary component of the variance, the results were similar for these two outcomes. Both groups similarly relied on slow anticipatory loops to maintain stability in standing but the combination of sounds and increased visual load challenged the vestibular group more than it did the control group, i.e., the effect of changes in visual load was greater for the vestibular group only in the presence of sounds. PSD 2 is known to reflect vestibulo-spinal loops [5,8,9], and remained consistently higher in the vestibular group across all conditions. PSD 3 is known to reflect reactive, short loops – it appears that this is where the vestibular group used sounds to reduce separation from the control group but were able to do so only when the visual environment was static.

The theory of auditory anchor suggests that stationary white noise may reduce postural sway [31–34], similar to fixating gaze on a stationary visual target, and moving white noise will lead to increased sway [15,35], similar to looking at moving visuals [36,37]. Our findings provide some contextualization for the auditory anchor theory. In prior studies of young and older adults with normal hearing, fixed, static broadband noise has been suggested to provide a stabilizing spatial anchor for postural control and has been associated with reduced body sway when standing or walking [31,32]. Moving sounds (i.e., broadband noise that ‘jumps’ from one ear to the other or between speakers) have been associated with an increase in postural sway when standing or walking, if people can hear them [15,35]. Because most other studies used an eyes open / closed paradigms, our study offers a unique insight on how sounds are integrated with dynamic visual load. First, in standing with continuous visual flow, healthy participants, including older adults, were not perturbed by white noise played via headphones and did not use it for stabilizations. Second, in this specific setup, stationary and moving white noise both functioned as perturbation to the vestibular group when combined with dynamic visual load but assisted in reduction of high frequency sway when combined with static visual load.

A key strength on this study is the inclusion of people with known balance problems related to sensory integration in a challenging balance task. Another unique contribution of HMDs to the study of sounds in balance is the ability for the researcher to combine different visual and auditory cues. However, given the highly contextualized nature of sounds involvement in balance, the results of this study can only be generalized to a standing task when individuals are standing on foam and white noise is played via headphones. Another limitation is the cross-sectional design which does not allow for evaluation of changes in

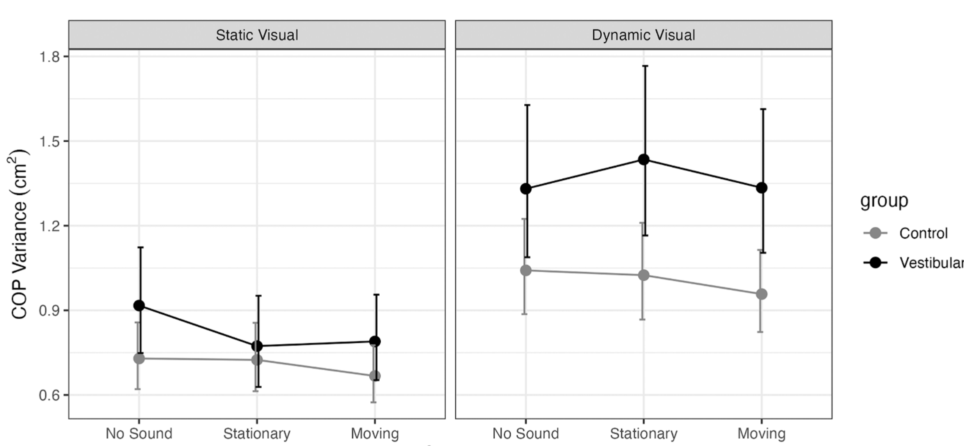

Fig. 2. Anterior-posterior *variance* (cm^2) derived from center of pressure (COP) data for participants with unilateral peripheral vestibular hypofunction (Vestibular) and healthy controls (Control). The left-hand side reflects the static visual condition, and the right-hand side reflects the dynamic visual condition. The X axis has the 3 sound conditions: none, stationary white noise or moving white noise.

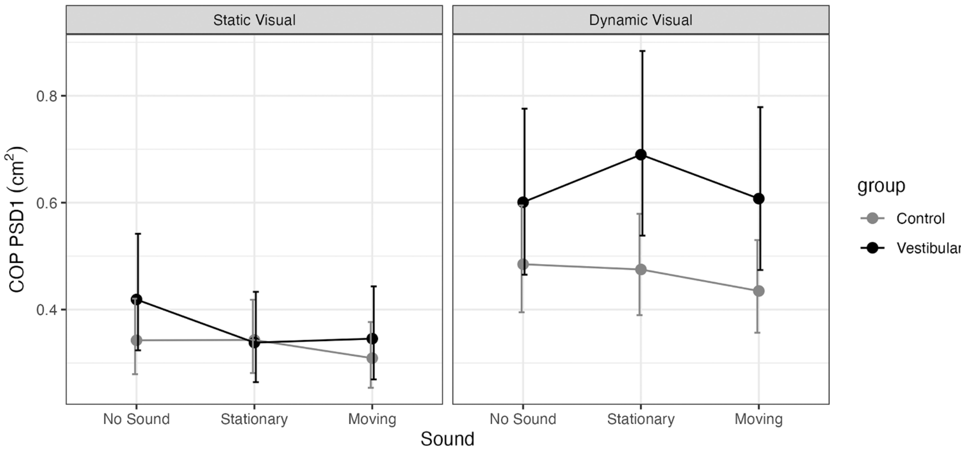

Fig. 3. Anterior-posterior *power spectral density in low frequencies* (PSD 1, cm^2) derived from center of pressure (COP) data for participants with unilateral peripheral vestibular hypofunction (Vestibular) and healthy controls (Control). The left-hand side reflects the static visual condition, and the right-hand side reflects the dynamic visual condition. The X axis has the 3 sound conditions: none, stationary white noise or moving white noise.

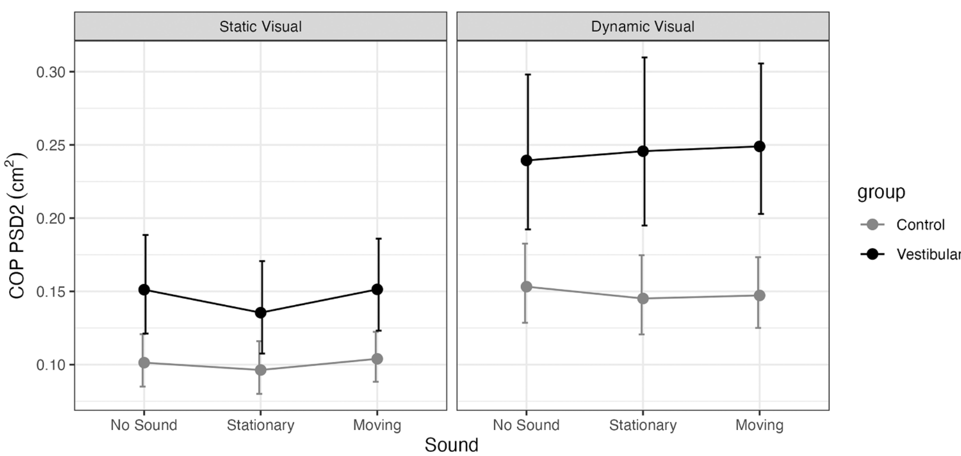

Fig. 4. Anterior-posterior *power spectral density in mid frequencies* (PSD 2, cm^2) derived from center of pressure (COP) data for participants with unilateral peripheral vestibular hypofunction (Vestibular) and healthy controls (Control). The left-hand side reflects the static visual condition, and the right-hand side reflects the dynamic visual condition. The X axis has the 3 sound conditions: none, stationary white noise or moving white noise.

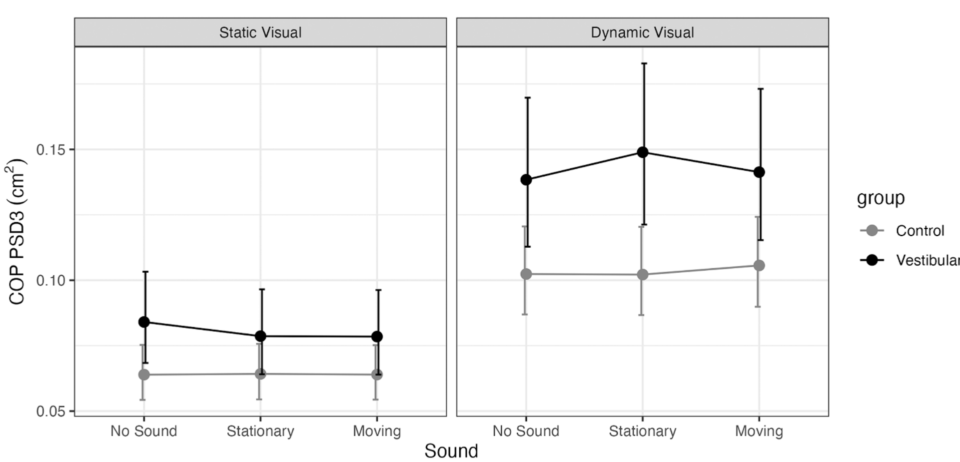

Fig. 5. Anterior-posterior *power spectral density in high frequencies* (PSD 3, cm^2) derived from center of pressure (COP) data for participants with unilateral peripheral vestibular hypofunction (Vestibular) and healthy controls (Control). The left-hand side reflects the static visual condition, and the right-hand side reflects the dynamic visual condition. The X axis has the 3 sound conditions: none, stationary white noise or moving white noise.

response to sounds over time. Five people in the control group (12 %) presented with unilateral caloric weakness. This is slightly higher than Campbell et al. who found 8 % (4 out of 49) caloric weakness in healthy younger adults (average age 37 years, range 18–60) [38]. These participants were included in the analysis because they had no vestibular complaints. In addition, we tested all 6 canals but defined vHIT weakness based on lateral canals only due to concerns about machine mal-function and goggle slippage in the vertical directions. Concerns about high variability of gains in the vertical canals have been expressed in the literature[39]. Finally, while some participants chose to increase or reduce the loudness of the sounds, we did not adjust for loudness in our models both because several studies found no effect of sound loudness on balance[40–42] and because the proportion of participants who chose to lower the loudness was similar between groups.

5. Conclusion

Sound influences postural control in individuals with vestibular hypofunction but the magnitude of response is subtle in comparison to that of visual load[33]. In this study, no differences were observed across varying types of sounds by themselves, but rather as an interaction with visual load. Patients with vestibular hypofunction used white noise to reduce sway in a static abstract environment and were somewhat destabilized by it in a dynamic environment. This suggests that white noise, when played from headphones, may function as an auditory anchor under certain level of challenge and specific tasks regardless of whether it's stationary or moving. Our results support that increased sway in middle frequencies reflects vestibular dysfunction.

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CRediT authorship contribution statement

Maura Cosetti: Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Daphna Harel:** Writing – review & editing, Visualization, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Anat Vilnai Lubetzky:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Jennifer Kelly:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Zhu Wang:** Writing – review & editing, Supervision, Software, Resources, Methodology, Investigation, Conceptualization. **Agnieszka Roginska:** Writing – review & editing, Validation, Supervision, Software, Resources, Methodology, Conceptualization. **Katherine Scigliano:** Writing – review & editing, Resources, Project administration, Investigation. **Marlee Sherrod:** Writing – review & editing, Visualization, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare no conflict of interest. MC reported unpaid participation in research on cochlear implants and other implantable devices manufactured by Cochlear Americas, MED-El, and Oticon Medical. Neither is related to the submitted work.

Data Availability

The dataset used in this manuscript can be found at: Lubetzky, Anat (2024), "Frequency Analyses of Postural Sway Demonstrate the Use of Sounds for Balance Given Vestibular Loss", Mendeley Data, V2, doi: 10.17632/89vb5s4vxr.2

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