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ORIGINAL ARTICLE

Comparative effects of visual and auditory stimuli on the sensory components of postural control: A study in individuals with sensorineural hearing loss

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ABSTRACT

Objectives: This study examined whether sensorineural hearing loss (SNHL) severity affects the sensory components of postural control in asymptomatic young to middle-aged adults under increasing multisensory load using a virtual reality (VR)-based Clinical Test of Sensory Interaction on Balance (CTSIB).

Patients and Methods: Between October 2025 and February 2026, a prospective cross-sectional study was performed on 53 participants (23 males, 30 females; mean age: 26.51±4.27 years; range: 18 to 57 years). Participants were categorized into three groups according to their hearing status: the healthy control group (n = 24), the mild SNHL group (n = 21), and the moderate SNHL group (n = 8). Postural control was assessed under four conditions: C1 (silent-standard vision), C2 (music-standard vision), C3 (silent-optokinetic vision), and C4 (music-optokinetic vision). Composite balance scores and VR-CTSIB sensory subcomponents were analyzed using condition-wise nonparametric tests. Subjective workload was evaluated using the mental demand and effort subscales of the National Aeronautics and Space Administration Task Load Index.

Results: Composite balance performance differed between groups in a condition-dependent manner, with greater separation under higher multisensory load. Somatosensory and visual components showed increasing group differences, whereas vestibular-based strategies diverged only under multisensory conflict. Visual preference differed only in the music-standard vision condition, indicating a context-dependent shift in sensory weighting. Subjective workload increased with sensory conflict, while between-group differences diminished under the highest load.

Conclusion: In asymptomatic adults, hearing loss is associated with condition-specific postural control vulnerability that emerges under auditory-visual sensory conflict, supporting impaired sensory reweighting rather than a global balance deficit. Virtual reality-based CTSIB protocols provide a sensitive framework for detecting these effects.

Keywords: Auditory perception, postural balance, sensorineural hearing loss, sensory integration, virtual reality, visual perception.

Postural orientation and balance control are achieved through complex multisensory integration processes within the central nervous system, combining inputs from the vestibular apparatus, the visual system, and somatosensory receptors.[1,2] Although balance regulation has traditionally been conceptualized as relying on these three primary sensory modalities, increasing evidence indicates that the auditory system

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also contributes to postural control and may support spatial orientation and balance regulation.[3,4]

The functional link between hearing and balance is supported by close anatomical and physiological connections between the auditory and vestibular systems, as well as by the role of auditory input in environmental monitoring, spatial localization, and perception of self-motion, functions directly relevant to postural stability and mobility.[5]

A growing body of epidemiological research has demonstrated robust associations between hearing loss and impaired balance, mobility limitations, and increased fall risk, particularly in older adults.[6-9] Population-based studies show that postural instability and fall risk increase with the severity of hearing loss, with even mild impairment associated with elevated risk.[9,10] However, the predominance of observational designs in aging populations limits causal inference and mechanistic interpretation.[11]

Several non-mutually exclusive mechanisms have been proposed to explain the association between hearing loss and impaired balance. These include reduced access to auditory spatial cues, increased cognitive load due to effortful listening, and shared or parallel pathophysiological changes within the auditory and vestibular systems.[11-13] Disentangling these mechanisms requires controlled experimental approaches that systematically manipulate sensory and task-related demands.

Laboratory-based studies provide a framework for examining hearing-balance interactions by selectively manipulating sensory conditions.[5,14-16] Experimental findings suggest that auditory input can support postural stability, particularly under challenging sensory conditions, consistent with sensory reweighting models.[17] However, sensory reweighting may not be uniformly adaptive, especially in individuals with hearing loss, where compensatory reliance on somatosensory input may be insufficient under increased sensory or cognitive demand.[18]

Methodologically, a substantial proportion of the balance literature continues to rely on static postural assessments performed under restricted sensory conditions, which may fail to reflect balance behavior in ecologically valid, multisensory environments. While recent advances in dynamic and mobile posturography have enabled selective manipulation of visual and proprioceptive inputs, auditory stimulation is still infrequently treated as a systematically controlled experimental variable.[18,19] Experimental evidence indicates that auditory, visual, and proprioceptive cues jointly contribute to balance regulation, yet their relative weighting is highly context dependent.[20] Consequently, the condition-specific effects of combined auditory and visual perturbations on modality-specific balance components, particularly across different degrees of sensorineural hearing loss (SNHL), remain insufficiently characterized in existing research.[21]

Accordingly, the present study aimed to evaluate postural control performance under four experimental conditions with systematically varying levels of auditory and visual stimulation in healthy adults and in individuals with mild and moderate SNHL. Using a Clinical Test of Sensory Interaction on Balance (CTSIB) framework, the study examined both the composite balance score and modality-specific postural control components in order to determine how increasing sensory load influences multisensory integration as a function of hearing loss severity. It was hypothesized that (H1) postural control scores, including the composite measure and modality-specific CTSIB components, would differ significantly between groups across conditions involving different levels of auditory and visual stimulation and that (H2) deterioration in postural control would become more pronounced with increasing hearing loss severity, particularly under conditions of elevated multisensory demand.

PATIENTS AND METHODS

Study design and participants

This prospective cross-sectional study was conducted at Malatya Turgut Özal Üniversitesi, Malatya Eğitim ve Araştırma Hastanesi, Department of Otorhinolaryngology between October 2025 and February 2026. A total of 53 participants (23 males, 30 females; mean age: 26.51±4.27 years; range: 18 to 57 years) were included and divided into three groups based on their hearing status: the healthy control group (n = 24), the mild SNHL group (n = 21), and the moderate SNHL group (n = 8). Inclusion criteria for all participants were being aged 18 years and older and the ability to stand independently without assistive devices. Specifically, inclusion criteria for the healthy control group were normal pure-tone audiometric thresholds and the absence of hearing loss, dizziness, vertigo, or balance complaints. For the hearing loss groups, inclusion criteria were a clinical diagnosis of mild or moderate SNHL based on pure-tone audiometry and the absence of any subjective balance-related symptoms. Exclusion criteria across all groups were known vestibular disorders, neurological diseases affecting balance or motor control, orthopedic conditions limiting upright stance, uncorrected visual impairment, and any acute or chronic medical condition that could interfere with postural assessment. Written informed consent was obtained from all participants prior to inclusion. Ethical approval was obtained from the Health Sciences Scientific Research Ethics Committee (Date: 05.10.2025; Approval number: 2025/391). This study was conducted in accordance with the principles of the Declaration of Helsinki.

The study sample was recruited from individuals presenting to the otorhinolaryngology clinic and from hospital staff who met the inclusion criteria. Age distributions were comparable across groups, and age was therefore not used as a stratification variable.

Participants in the hearing loss groups were identified through routine otorhinolaryngological evaluation and classified as having mild or moderate SNHL based on pure-tone audiometric assessment. To isolate the effects of hearing loss on sensory integration mechanisms, only individuals without subjective complaints of dizziness, vertigo, or balance disturbance were included. The healthy control group consisted of hospital staff and healthcare personnel with normal hearing thresholds and no history of hearing or balance-related complaints.

The smaller size of the moderate SNHL group reflects the clinic-based recruitment of individuals without dizziness or overt balance complaints; findings related to this group should therefore be interpreted with caution. Based on prior experimental studies examining hearing loss and balance using comparable sample sizes and effect estimates, an a priori power analysis indicated that the sample size was sufficient to detect between-group differences in postural control measures under varying sensory conditions.[22,23]

Test protocols

All participants underwent a comprehensive otorhinolaryngological examination conducted by an experienced otolaryngologist. Following the clinical evaluation, individuals were referred for standardized audiological assessment, including pure-tone air- and bone-conduction threshold audiometry performed using an Interacoustics AC40 (Interacoustics, Middelfart, Denmark) in accordance with established clinical procedures.[24,25] Audiometric findings were used to classify participants into healthy hearing, mild SNHL, or moderate SNHL groups based on better-ear pure-tone average thresholds. To exclude vestibular disorders and central nervous system pathology, all participants additionally underwent bedside vestibular examination prior to inclusion in the study. This assessment included evaluation of spontaneous and gaze-evoked nystagmus, the bedside head impulse test, and positional maneuvers such as the Dix-Hallpike test and supine roll test, following standard clinical guidelines.[26] Individuals presenting with clinical signs suggestive of peripheral vestibular pathology, central vestibular involvement, or active vertigo were excluded from the study.

Clinical test of sensory interaction and test conditions

Postural control was assessed using a virtual reality-based Clinical Test of Sensory Interaction on Balance (VR-CTSIB) protocol (BalanceVR Virtualis, Montpellier, France) under four experimental conditions specifically designed for this study. These conditions systematically manipulated auditory and visual inputs while maintaining a static stance task: C1 (silent condition with standard vision), C2 (music condition with standard vision), C3 (silent condition with optokinetic visual stimulation), and C4 (music condition with optokinetic visual stimulation). Each condition was performed for a fixed duration, and balance performance was automatically quantified by the system's embedded algorithm.[27]

Music was delivered as auditory stimulation via the integrated headphones of the head-mounted display during C2 and C4. The same musical stimulus was presented to all participants to ensure standardization, while sound intensity was individually adjusted according to audiometric thresholds. Presentation levels were calibrated relative to the better-ear pure-tone average in accordance with recommended clinical audiology procedures to ensure audibility without discomfort.[28] This approach allowed auditory stimuli to be clearly perceivable in participants with mild and moderate SNHL while avoiding excessive loudness in normal-hearing individuals, thereby minimizing the confounding effects of unequal audibility across groups.

Optokinetic visual stimulation was applied during C3 and C4 using the head-mounted display. Participants were exposed to a moving visual field consisting of white dots drifting across a uniform blue background, generating global visual motion. This stimulus was designed to induce sensory conflict by providing dynamic visual input incongruent with actual body motion and was presented continuously throughout each balance task to ensure consistent visual perturbation. Such optokinetic stimulation is commonly used to challenge visual-vestibular integration and increase sensory load during postural control tasks.

For each condition, composite, somatosensory, visual, vestibular, and visual preference CTSIB scores were calculated to characterize condition-specific sensory integration strategies. Composite scores were interpreted as indicators of overall postural stability, whereas sensory subscores provided insight into modality-specific contributions under each experimental condition.

Virtual reality-based CTSIB allows controlled manipulation of sensory environments while preserving ecological relevance through immersive visual stimulation.[29] Previous studies have demonstrated acceptable within-session reliability of CTSIB-derived center-of-pressure metrics, particularly for sway magnitude and velocity.[30-32] However, different CTSIB outcome measures capture distinct aspects of postural control, and sensory subscores may show condition-dependent sensitivity to altered sensory demands.[2]

Accordingly, VR-CTSIB subscores were analyzed separately for each condition to determine how auditory stimulation, optokinetic visual input, and their combination modulate postural control as a function of hearing loss severity, enabling a condition-specific evaluation of sensory reweighting mechanisms rather than a single aggregated balance outcome.

NASA task load index

Subjective workload associated with the experimental procedures was assessed using selected subscales of the National Aeronautics and Space Administration Task Load Index (NASA-TLX), a validated multidimensional self-report measure of perceived workload during task performance.[33] Although the original NASA-TLX includes six dimensions (mental demand, physical demand, temporal demand, performance, effort, and frustration), only the mental demand and effort subscales were administered in the present study, as these dimensions most directly reflect cognitive workload and attentional investment during sensory integration tasks.

Mental demand captured the perceived cognitive processing requirements imposed by the balance task under varying auditory and visual conditions, whereas effort reflected the amount of mental and physical resources allocated to maintain postural stability. The remaining subscales were not included as the task involved static stance with fixed duration and no explicit time pressure, physical exertion, or performance feedback, rendering these dimensions less relevant to the study aims.

Participants rated mental demand and effort on a 21-point scale ranging from 0 (very low) to 100 (very high) immediately after each experimental condition to minimize recall bias. This focused use of NASA-TLX allowed assessment of condition-specific changes in subjective cognitive workload associated with increasing auditory and visual sensory load.

Statistical analysis

Statistical analyses were performed using IBM SPSS version 22.0 software (IBM Corp., Armonk, NY, USA). Distributional properties of continuous variables were evaluated using visual inspection (histograms and Q-Q plots), indicating that VR-CTSIB scores and NASA-TLX subscale scores did not meet the assumption of normality. Accordingly, nonparametric statistical tests were used for between-group comparisons.

Participants were classified into three groups based on hearing status: healthy control (HL-Degree = 0), mild SNHL (HL-Degree = 1), and moderate SNHL (HL-Degree = 2). Postural control was assessed under four experimental conditions (C1-C4), and CTSIB composite, somatosensory, visual, vestibular, and visual preference scores were analyzed separately for each condition.

Since the CTSIB conditions represented repeated measurements within individuals, analyses focused on condition-specific between-group differences rather than modeling within-subject covariance. Accordingly, between-group differences for each condition were examined using the Kruskal-Wallis H test. The same approach was applied to the mental demand and effort subscales of the NASATLX. For Kruskal-Wallis analyses, chi-square statistics (χ^2), degrees of freedom (df = 2), and corresponding p values were reported.

When a significant Kruskal-Wallis effect was detected, Bonferroni-corrected post hoc pairwise comparisons were conducted. To control for type 1 error due to multiple testing across conditions and outcome measures, the Bonferroni correction was applied to post hoc analyses.

Descriptive statistics for non-normally distributed variables were reported as mean ranks, while categorical variables were summarized as frequencies and percentages. All tests were two-tailed, and statistical significance was set at $p < 0.05$.

RESULTS

The descriptive statistics of the demographic and audiological characteristics of the participants included in the study are presented in Table 1. The sample consisted of adults with a balanced distribution of females and males. Pure-tone average values indicate that the study population encompassed a broad auditory profile, ranging from normal hearing to moderate hearing loss. The relatively low interaural threshold differences suggest that symmetric hearing characteristics were predominant in the majority of participants.

Significant between-group differences in composite CTSIB scores were observed across all experimental conditions, as shown in Table 2. Even under the lowest sensory load condition (C1), a statistically significant group effect was detected (χ^2 = 6.268, p = 0.044). As overall sensory demands increased across conditions (C2 and C3), group differences became more pronounced, reaching their maximum under the highest multisensory load condition (C4) ($p \leq 0.001$). Overall, these findings indicate a graded deterioration in global postural stability with increasing hearing loss severity, particularly under conditions involving combined sensory challenges.

Somatosensory CTSIB scores differed significantly between groups starting from condition C1, as shown in Table 3 (χ^2 = 6.530, p = 0.038). These between-group differences became more pronounced in conditions C2, C3, and C4, in which auditory stimulation and/or optokinetic visual input increased sensory load and conflict (all $p < 0.001$). Notably, under conditions where visual reliability was reduced and sensory conflict was heightened, individuals with hearing loss exhibited greater deterioration in

Table 1. Descriptive statistics of demographic and audiological characteristics of the study sample

Variables	n	%	Mean±SD	Min-Max
Age (year)			26.51±4.27	18-57
Sex				
Female	30	56.6		
Male	23	43.4		
BMI			23.95±3.19	18.0-32.6
PTA-BE (dB HL)			24.11±12.37	7-41
PTA-difference (dB)			4.72±3.92	0-16

SD, standard deviation; BMI, body mass index; PTA, pure-tone average; PTA-BE, pure-tone average of the better ear.

Table 2. Between-group comparison of composite CTSIB scores across conditions

Condition	Group (HL degree)	n	Mean rank	df	χ^2	p
C1	Healthy	24	32.75	2	6.268	0.044
	Mild HL	21	22.93			
	Moderate HL	8	20.44			
C2	Healthy	24	35.67	2	14.034	0.001
	Mild HL	21	20.55			
	Moderate HL	8	17.94			
C3	Healthy	24	38.10	2	22.782	< 0.001
	Mild HL	21	17.64			
	Moderate HL	8	18.25			
C4	Healthy	24	39.85	2	30.777	< 0.001
	Mild HL	21	15.48			
	Moderate HL	8	18.69			

CTSIB, Clinical Test of Sensory Interaction on Balance; HL, hearing loss; df, degrees of freedom; χ^2, Kruskal-Wallis test statistic; p: asymptotic significance value; C1, silent condition with standard vision; C2, music condition with standard vision; C3, silent condition with optokinetic vision; C4, music condition with optokinetic vision.

somatosensory-based balance performance. These findings indicate that hearing loss may affect not only auditory processing but also multisensory integration mechanisms and somatosensory balance strategies.

Visual CTSIB scores did not differ significantly between groups under condition C1, as shown in Table 4 (p = 0.299). In contrast, significant between-group differences emerged in conditions C2, C3, and C4, which involved auditory stimulation and/or optokinetic visual input (all $p \leq 0.005$). These findings suggest that visual balance performance is not solely determined by visual input per se, but becomes increasingly sensitive to the degree of hearing loss under conditions of elevated cognitive demand and sensory load.

Regarding vestibular scores, no significant between-group difference was observed under the baseline condition (C1) (p = 0.108). In contrast, statistically significant group differences emerged in conditions involving added auditory and visual perturbations (C2, C3, and C4), as shown in Table 5 (all $p \leq 0.001$). These findings suggest that

Table 3. Between-group comparison of somatosensory CTSIB scores across conditions

Condition	Group (HL degree)	n	Mean rank	df	χ^2	p
C1	Healthy	24	32.67	2	6.530	0.038
	Mild HL	21	23.55			
	Moderate HL	8	19.06			
C2	Healthy	24	37.02	2	18.917	< 0.001
	Mild HL	21	19.81			
	Moderate HL	8	15.81			
C3	Healthy	24	39.13	2	27.140	< 0.001
	Mild HL	21	16.74			
	Moderate HL	8	17.56			
C4	Healthy	24	38.75	2	29.925	< 0.001
	Mild HL	21	15.14			
	Moderate HL	8	22.88			

CTSIB, Clinical Test of Sensory Interaction on Balance; HL, hearing loss; df, degrees of freedom; χ^2, Kruskal-Wallis test statistic; p: asymptotic significance value; C1, silent condition with standard vision; C2, music condition with standard vision; C3, silent condition with optokinetic vision; C4, music condition with optokinetic vision.

Table 4. Between-group comparison of visual CTSIB scores across conditions

Condition	Group (HL degree)	n	Mean rank	df	χ^2	p
C1	Healthy	24	29.94	2	2.412	0.299
	Mild HL	21	26.17			
	Moderate HL	8	20.38			
C2	Healthy	24	34.50	2	10.513	< 0.005
	Mild HL	21	20.21			
	Moderate HL	8	22.31			
C3	Healthy	24	38.10	2	22.788	< 0.001
	Mild HL	21	17.67			
	Moderate HL	8	18.19			
C4	Healthy	24	38.27	2	26.818	< 0.001
	Mild HL	21	14.43			
	Moderate HL	8	26.19			

CTSIB, Clinical Test of Sensory Interaction on Balance; HL, hearing loss; df, degrees of freedom; χ^2, Kruskal-Wallis test statistic; p: asymptotic significance value; C1, silent condition with standard vision; C2, music condition with standard vision; C3, silent condition with optokinetic vision; C4, music condition with optokinetic vision.

vestibular-weighted postural control strategies become increasingly vulnerable in individuals with hearing loss under conditions of heightened multisensory stimulation.

In terms of visual preference scores, a statistically significant between-group difference was observed only under the C2 condition, as shown in Table 6 (χ^2 = 9.196, p = 0.010). The lack of significant differences across the other conditions indicates that visual dependence does not represent a stable, trait-like characteristic but instead emerges in a condition-specific manner. The fact that this effect appears exclusively when an auditory stimulus is present suggests that visual preference becomes accentuated under increased multisensory load, particularly in the context of concurrent auditory input.

NASA-TLX mental workload subscale scores differed significantly between groups across most experimental conditions, as shown in Table 7. Significant between-group differences were observed under C1 (χ^2 = 18.150, p < 0.001), C2 (χ^2 = 18.663, p < 0.001), and C3 (χ^2 = 8.652, p = 0.013), indicating

Table 5. Between-group comparison of Vestibular CTSIB scores across conditions

Condition	Group (HL degree)	n	Mean rank	df	χ^2	p
C1	Healthy	24	30.56	2	4.459	0.108
	Mild HL	21	26.62			
	Moderate HL	8	17.31			
C2	Healthy	24	35.96	2	14.847	< 0.001
	Mild HL	21	19.29			
	Moderate HL	8	20.38			
C3	Healthy	24	37.04	2	18.602	< 0.001
	Mild HL	21	18.55			
	Moderate HL	8	19.06			
C4	Healthy	24	39.17	2	27.291	< 0.001
	Mild HL	21	16.98			
	Moderate HL	8	16.81			

CTSIB, Clinical Test of Sensory Interaction on Balance; HL, hearing loss; df, degrees of freedom; χ^2, Kruskal-Wallis test statistic; p: asymptotic significance value; C1, silent condition with standard vision; C2, music condition with standard vision; C3, silent condition with optokinetic vision; C4, music condition with optokinetic vision.

Table 6. Between-group comparison of visual preference CTSIB scores across conditions

Condition	Group (HL degree)	n	Mean rank	df	χ^2	p
C1	Healthy	24	27.88	2	1.672	0.433
	Mild HL	21	24.14			
	Moderate HL	8	31.88			
C2	Healthy	24	20.52	2	9.196	0.010
	Mild HL	21	34.29			
	Moderate HL	8	27.31			
C3	Healthy	24	30.48	2	2.448	0.294
	Mild HL	21	23.45			
	Moderate HL	8	25.88			
C4	Healthy	24	31.69	2	4.360	0.113
	Mild HL	21	23.83			
	Moderate HL	8	21.25			

CTSIB, Clinical Test of Sensory Interaction on Balance; HL, hearing loss; df, degrees of freedom; χ^2, Kruskal-Wallis test statistic; p: asymptotic significance value; C1, silent condition with standard vision; C2, music condition with standard vision; C3, silent condition with optokinetic vision; C4, music condition with optokinetic vision.

Table 7. Between-group comparison of NASA-TLX effort workload subscale scores across experimental conditions

Condition	Group (HL degree)	n	Mean rank	df	χ^2	p
C1	Healthy	24	17.16	2	18.150	< 0.001
	Mild HL	21	35.88			
	Moderate HL	8	33.29			
C2	Healthy	24	16.96	2	18.663	< 0.001
	Mild HL	21	35.24			
	Moderate HL	8	35.50			
C3	Healthy	24	22.63	2	8.652	0.013
	Mild HL	21	26.64			
	Moderate HL	8	41.06			
C4	Healthy	24	22.31	2	5.437	0.066
	Mild HL	21	32.95			
	Moderate HL	8	25.44			

NASA-TLX, NASA Task Load Index, mental workload subscale; HL, hearing loss; df, degrees of freedom; χ^2, Kruskal-Wallis test statistic; p: asymptotic significance value; C1, silent condition with standard vision; C2, music condition with standard vision; C3, silent condition with optokinetic vision; C4, music condition with optokinetic vision.

Table 8. Between-group comparison of NASA-TLX effort workload subscale scores across experimental conditions

Condition	Group (HL degree)	n	Mean rank	df	χ^2	p
C1	Healthy	24	17.13	2	18.150	< 0.001
	Mild HL	21	35.90			
	Moderate HL	8	33.31			
C2	Healthy	24	16.99	2	18.661	< 0.001
	Mild HL	21	35.24			
	Moderate HL	8	35.47			
C3	Healthy	24	22.65	2	8.635	0.013
	Mild HL	21	26.62			
	Moderate HL	8	41.09			
C4	Healthy	24	22.31	2	5.438	0.066
	Mild HL	21	32.95			
	Moderate HL	8	25.44			

NASA-TLX, NASA Task Load Index, mental workload subscale; HL, hearing loss; df, degrees of freedom; χ^2, Kruskal-Wallis test statistic; p: asymptotic significance value; C1, silent condition with standard vision; C2, music condition with standard vision; C3, silent condition with optokinetic vision; C4, music condition with optokinetic vision.

that mental workload varied as a function of hearing loss severity under silent, music, and optokinetic visual conditions. In contrast, no statistically significant group difference was detected under the C4 condition (χ^2 = 5.437, p = 0.066), suggesting a relative convergence of perceived mental workload when auditory and optokinetic visual stimuli were presented concurrently.

NASA-TLX effort workload subscale scores showed significant between-group differences across most experimental conditions, as shown in Table 8. Statistically significant group effects were observed under C1 (χ^2 = 18.150, p < 0.001), C2 (χ^2 = 18.661, p < 0.001), and C3 (χ^2 = 8.635, p = 0.013), indicating that perceived effort increased with hearing loss severity under silent, music,

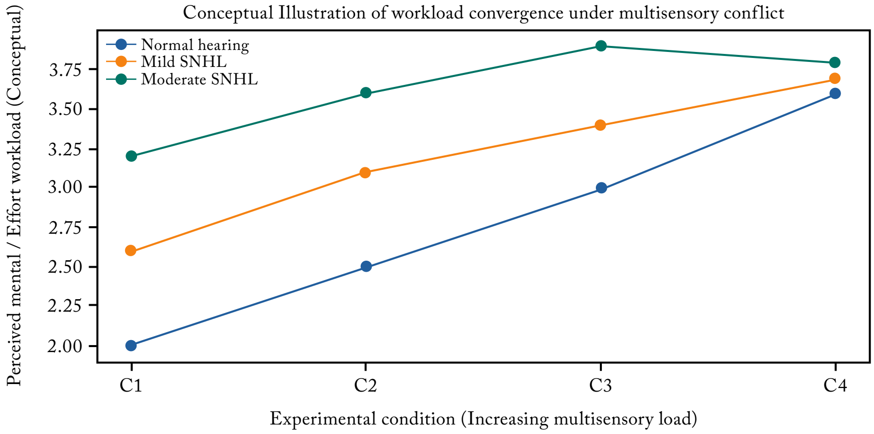

Figure 1. This figure provides a schematic illustration of the observed pattern and does not represent individual-level data or exact numerical values.

and optokinetic visual conditions. In contrast, no significant between-group difference was detected under the C4 condition (χ^2 = 5.438, p = 0.066), suggesting a convergence of perceived effort levels when auditory and optokinetic visual stimuli were simultaneously present.

As schematically illustrated in Figure 1, both mental demand and effort subscales show increasing between-group separation across C1-C3, followed by convergence under the highest multisensory load condition (C4).

DISCUSSION

The present study examined the effect of hearing loss severity (normal hearing, mild SNHL, moderate SNHL) on the sensory components of postural control in young to middle-aged adults without dizziness or vertigo, using a CTSIB framework with systematically increasing sensory load. Across four experimental conditions (C1 silent-standard vision; C2 music-standard vision; C3 silent-optokinetic; C4 music-optokinetic), auditory and visual inputs were independently and jointly manipulated to progressively increase sensory conflict.

The primary finding was that composite balance performance differed across conditions as a function of hearing loss degree, with group separation becoming more pronounced under higher multisensory load. Overall, these findings support H1, indicating condition-specific sensitivity of postural control to hearing loss severity. While the marked separation observed in C4, the condition with the highest sensory conflict, is consistent with H2, the absence of a fully linear pattern across all subcomponents warrants cautious interpretation.

The emergence of group differences in composite scores already in C1, with amplification in C2-C4, suggests that the effect of hearing loss on postural control is not merely a secondary consequence that appears only when other sensory inputs are degraded. Rather, hearing loss may introduce a measurable vulnerability in sensory integration even in asymptomatic individuals. By employing a CTSIB-based approach with systematically increased sensory demands, the present study mitigates the low task-demand limitations of traditional laboratory stance protocols and approaches conditions under which hearing-balance interactions are more likely to emerge.

Group differences in the somatosensory component beginning in C1 and strengthening across C2-C4 underscore postural control as a process governed by sensory reweighting rather than reliance on a single modality. Under increasing sensory and cognitive load, individuals with hearing loss appear to rely more heavily on somatosensory input; however, as load increases, this strategy becomes insufficient to stabilize balance. In line with the meta-analysis by Foster et al.,[10] which reported worsening postural and mobility outcomes with increasing hearing loss severity, particularly in moderate-to-severe loss, our findings extend this severity-related pattern to a young/middle-aged asymptomatic population at the subcomponent level, reducing confounding by aging and comorbidity.

The visual component conveys one of the study's most distinctive messages. While groups did not separate in C1, significant differences emerged in C2-C4, which included music and/or optokinetic stimulation. This pattern suggests that visual contributions to postural control become sensitive to hearing loss degree under multisensory load rather than in isolation. Consistent with findings from VR-based listening-while-balancing paradigms, multisensory stimulation does not uniformly enhance performance; instead, the utility of visual information depends on task relevance and resource competition.[34] Although no explicit listening task was included here, the combination of visual flow and auditory stimulation appears to tax resource management within the postural system, producing condition-specific vulnerability in the visual component.

In the vestibular component, the absence of differences in C1 and their emergence in C2-C4 indicate that vestibular-input-based postural strategies become more fragile under increased sensory load, without implying vestibular pathology. This pattern aligns with the framework proposed by Carpenter and Campos,[21] who argued that hearing-related balance effects may be weak when other sensory inputs are reliable but become more apparent as task demands increase or sensory reliability decreases. The finding that visual preference differed between groups only in C2 suggests that visual dependence reflects a condition-sensitive strategic shift rather than a stable trait. The absence of differences under optokinetic conditions may reflect either a compression effect due to uniformly high visual conflict or a distinct mechanism through which music alters sensory weighting, such as attentional capture or affective arousal. In this context, the distinction articulated by Carpenter and Campos, whereby sound may act either as an orienting cue or as a balance-irrelevant stimulus increasing attentional competition, is particularly informative. The C2 pattern in our data is more consistent with music functioning as a load-increasing stimulus rather than as an informative spatial cue.

The selective use of the mental demand and effort subscales of the NASA-TLX is justified by the paradigm's emphasis on cognitive and perceptual resources consumption rather than physical or temporal pressure.[33] Between-group differences observed in C1-C3 and their attenuation to a borderline level in C4 ($p = 0.066$) suggest convergence of subjective workload under the highest multisensory conflict. At very high load, participants may experience similar levels of perceived demand and effort, or adopt strategy shifts (e.g., posture-first or protective stiffening) that homogenize subjective workload, consistent with non-linear dynamics described in prior multisensory balance research.[34]

Relative to the literature, this study addresses a critical gap in three ways. First, it demonstrates degree-dependent, condition-specific postural vulnerability in a young/middle-aged sample without dizziness. Second, it provides experimental support for the notion that hearing-related balance effects become apparent primarily as sensory load increases.[21] Third, by systematically increasing sensory conflict through auditory and visual stimulation rather than a listening task, it shows that postural outcomes are shaped by the interaction of conditions rather than by a single main effect, with differences emerging at the sensory subcomponent level.[34] The severity-related pattern identified in prior meta-analytic work thus gains a more mechanistic expression under controlled conditions.[10]

Clinically, these findings suggest that the absence of balance complaints does not preclude multisensory postural vulnerability in individuals with SNHL. In real-life environments involving intense visual flow and concurrent auditory stimulation, postural strategies may become more fragile in a hearing-loss-degree-dependent manner. From a research perspective, CTSIB-based protocols offer a structured framework to map sensory load profiles by hearing status and to inform personalized assessment and targeted rehabilitation strategies.

Among the limitations, the small size of the moderate SNHL group constrains power and may reduce the stability of dose-response patterns. In addition, the condition-wise nonparametric approach does not explicitly model repeated-measures structure, and the use of a single music stimulus limits mechanistic dissociation of sound effects. Vestibular subcomponent differences should be interpreted as reflecting increased fragility of vestibular-input-based strategies under multisensory load rather than evidence of vestibular pathology.

In conclusion, under systematically increased auditory and optokinetic visual load, composite postural stability and sensory components differed in a condition-specific manner among asymptomatic individuals with mild and moderate SNHL. These findings support the interpretation that hearing loss affects postural control through vulnerability in sensory reweighting that becomes evident as multisensory context and sensory conflict increase.

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