Horizontal vHIT Gain is Unaffected by Moderate Cognitive Load: Evidence from a Single-Distance Dual-Task Paradigm

Abstract

Purpose: To determine whether moderate cognitive load alters horizontal vestibulo-ocular reflex (VOR) gain during the video head impulse test (vHIT) and to evaluate the reliability of vHIT under dual-task conditions.

Methods: Thirty-three healthy young adults (mean age 21.3 ± 2.1 years) completed two vHIT conditions: (1) a baseline single-task condition and (2) a dual-task cognitive load condition involving serial subtraction aloud while fixating a constant target at a single distance. Horizontal VOR gains were measured bilaterally. Mental effort and dizziness were rated on 0 to 10 numerical rating scales.

Results: Baseline VOR gains were 0.925 ± 0.063 (left) and 0.924 ± 0.074 (right). Under cognitive load, gains were 0.938 ± 0.084 and 0.938 ± 0.074, small increases of 1.4 to 1.5% that were non-significant ($p > 0.40$) and met equivalence criteria within ±0.05 gain units. Reliability across conditions was excellent (ICC [3,1] = 0.90 left; 0.89 right). Cognitive engagement increased significantly (2.1 ± 1.1 to 7.3 ± 1.4; $p < 0.001$), while dizziness remained minimal. No meaningful correlation was observed between gain change and perceived effort or dizziness (Spearman's $\rho < 0.05$, $p > 0.05$).

Conclusion: Horizontal vHIT gain remained stable, statistically equivalent, and highly reliable under cognitive load, despite marked increases in perceived effort. These findings highlight the attentional resilience of the horizontal VOR, consistent with its brainstem-mediated circuitry. Consequently, horizontal vHIT appears robust for use in routine clinical settings where divided attention may be present.

Keywords: vestibulo-ocular reflex, video head impulse test, cognitive load, dual-task paradigm, vestibular function, semicircular canals.

Introduction

The vestibulo-ocular reflex (VOR) is a rapid, compensatory reflex that stabilises vision during head movement by generating eye movements opposite to the direction of head rotation [1]. With latencies of only a few milliseconds, the reflex enables clear vision during everyday activities such as walking or turning the head [2]. Traditionally regarded as an automatic, brainstem-mediated response, the VOR has been assumed to operate independently of higher cognitive influences. However, modern neurophysiological research demonstrates that vestibular pathways interact with cortical networks involved in attention, multisensory integration, and spatial orientation [3,4], raising the possibility that cognitive load may influence reflexive vestibular behaviour, even in healthy individuals.

The video head impulse test (vHIT) is now an established clinical tool for assessing high-frequency semicircular canal function [5]. By quantifying the ratio of eye velocity to head velocity (VOR gain), vHIT provides a rapid and objective measure of semicircular canal integrity. Its strong test-retest reliability and diagnostic sensitivity have been demonstrated across both healthy and vestibular-impaired populations [6-8]. Nevertheless, vHIT performance can be influenced by non-reflex factors such as goggle slippage, target distance, fixation stability, and blink or saccade artefacts [7]. Age-related variability in VOR gain and compensatory saccades has also been reported in older adults with vestibular symptoms [9], highlighting that non-reflex factors can influence vHIT metrics. Anxiety and heightened arousal have likewise been shown to modulate VOR responses [10]. One factor that has not been systematically examined is attentional state. In clinical practice, patients may be anxious, distracted, or cognitively engaged in other tasks during assessment, raising the question of whether cognitive load can influence VOR gain. Despite the widespread clinical use of vHIT, no study to date has isolated cognitive load effects using a fixed-distance, single-task horizontal paradigm, leaving uncertainty about how attentional engagement influences high-frequency VOR gain.

Dual-task research consistently shows that cognitive load disrupts balance and gait control. Performing mental arithmetic while standing or walking increases postural sway and modifies gait patterns, indicating shared attentional resources between cognitive and motor control systems [11,12]. Whether these attentional effects extend to the VOR remains unclear. Unlike posture and gait, which involve significant cortical contribution, the VOR is predominantly mediated at the brainstem level [2]. Prior studies of cognitive vestibular interaction have largely examined

perceptual outcomes such as motion perception or spatial orientation rather than the reflexive eye movements measured through vHIT [13,14]. However, whether such dual-task interference extends to rapid, brainstem-mediated VOR pathways remains largely unexplored.

Limited evidence specifically addresses whether cognitive load influences vHIT performance. The most notable study is by Rozendorn et al., who reported unchanged horizontal VOR gain during concurrent cognitive and visual tasks [15]. However, their protocol employed multiple fixation distances, a methodological factor known to introduce gain variability related to vergence adjustments and target-distance effects [7]. As a result, the stability of the reflex under isolated cognitive load and fixed-distance conditions remains uncertain. Moreover, cognitive load in dual-task paradigms primarily increases working-memory demand and attentional engagement, but its impact on rapid, reflexive vestibular pathways has not been clearly delineated.

This study therefore aimed to determine whether moderate cognitive load alters horizontal VOR gain in healthy young adults using a controlled dual-task vHIT paradigm with a single fixed target distance. To our knowledge, this is the first study to isolate attentional effects on horizontal vHIT gain using a remote-camera system under single-distance conditions. By integrating equivalence testing, reliability analysis, and subjective effort ratings, the study provides new evidence on the attentional resilience of the horizontal VOR and the clinical robustness of vHIT under conditions of divided attention. Given the reflexive nature of the VOR, we hypothesised that cognitive load would not significantly alter horizontal VOR gain. Demonstrating stability under distraction would support the reliability of vHIT in routine clinical practice and help to understand the extent to which attentional modulation influences high-frequency VOR pathways.

Materials and Methods

This was a controlled within-subject experimental study designed to compare horizontal VOR gain across two vHIT conditions; a baseline single-task condition and a dual-task cognitive load condition. The order of testing was fixed (baseline first) to prevent carryover of cognitive task strategies into the baseline condition, acknowledging the potential for minor practice effects. All assessments were performed using a remote camera vHIT system by the same experienced examiner to ensure measurement consistency. Thirty-three healthy young adults (18-26 years) were recruited. This age range was selected to minimise age-related VOR variability. Sample size was determined *a priori* using G*Power (v3.1.9.7) based on a paired-sample design with an

expected true difference of 0.05 gain units, $\alpha = 0.05$ and power > 0.80. Inclusion criteria were: (i) normal hearing thresholds $\leq$ 25 dB HL at 0.5 - 8 kHz in both ears (measured using a calibrated AC audiometer meeting ISO 389-1 standards), (ii) normal otoscopic findings, (iii) normal vision sufficient for target fixation, and (iv) no history of vestibular, neurological, or musculoskeletal disorders. Exclusion criteria included previous otologic surgery, vestibulotoxic medication, migraine, visual impairment affecting fixation, or upper respiratory infection within the preceding two weeks. Eligibility was additionally verified using a brief health-screening questionnaire covering vestibular, neurological, auditory, visual, and neck-mobility history to ensure all inclusion criteria were met. All participants provided written informed consent. The study protocol was reviewed and endorsed by the ethics committee of the university (Decision No. REC-25-03-25-02-F) and adhered to the Declaration of Helsinki.

Horizontal VOR gain was measured using the Inventis remote camera vHIT system (Inventis, Padova, Italy; v2.0). The system records monocular pupil movements at 220 Hz using a fixed infrared camera positioned approximately 1 metre in front of the participant. Calibration was performed using the manufacturer's standard five-point on-screen procedure, with the participant maintaining fixation on each target. Participants were seated upright, 1.2 metres from a high-contrast wall-mounted fixation dot (2 cm diameter) at eye level. Horizontal head impulses were delivered manually by the same audiologist from behind the participant. Impulses consisted of small amplitude, high-acceleration rotations (15-20°, 150-250°/s) delivered unpredictably to minimise anticipation. At least 10 valid impulses were collected per direction, with left and right impulses interleaved. Impulses were inspected in real time. Traces showing blink artefacts or inconsistent acceleration profiles were excluded. The software automatically calculated mean left and right horizontal VOR gains based on the ratio of eye velocity to head velocity.

During the cognitive load condition, participants performed a validated mental arithmetic task (serial subtraction by sevens) aloud while maintaining fixation on the target [16]. A random three-digit starting number was assigned for each participant to prevent memorisation. The task was continuous throughout the sequence of impulses. Task accuracy was not formally recorded, as the arithmetic task served to impose sustained cognitive load; participant engagement was assessed using post-condition mental-effort ratings. Immediately after each condition, participants rated mental effort [17] and dizziness [18] using separate 0 to 10 numerical rating scales.

Statistical analysis

Normality of paired gain differences was assessed using the Shapiro-Wilk test. Left and right horizontal VOR gains were compared between conditions using paired t-tests ($\alpha = 0.05$), with effect sizes expressed as Cohen's *dz*. Clinical equivalence was evaluated using the Two One-Sided Tests (TOST) procedure with an equivalence margin of ± 0.05 gain units. This margin was selected based on commonly reported test–retest variability of horizontal vHIT gain in healthy individuals [6,7]. Intraclass correlation coefficients (ICC [3,1]; two-way mixed effects, single measures, consistency) quantified reliability between baseline and cognitive load conditions. Associations between gain change and subjective ratings (mental effort and dizziness) were assessed using Spearman's ρ. All results are reported as mean ± standard deviation (SD) with 95% confidence intervals (CI). No data were missing and no vHIT gains exceeded the physiological range (0.6-1.3).

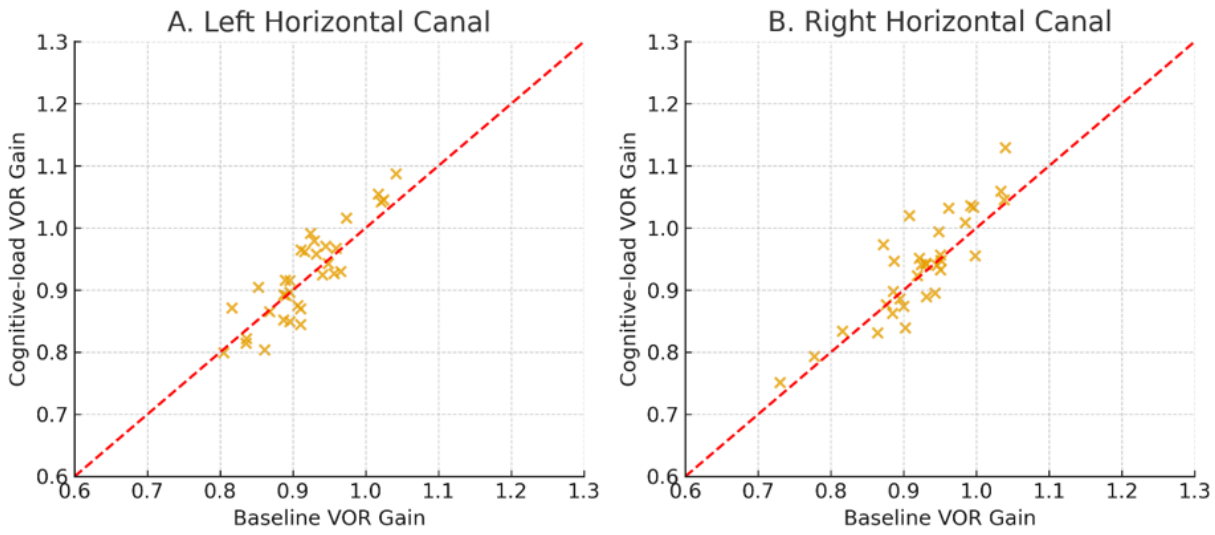
Results

Thirty-three participants (23 males, 10 females; mean age ± SD = 21.3 ± 2.1 years; range 18-26) completed both test conditions without discomfort or adverse events. Head velocity profiles were smooth and comparable across trials, with no evidence of artefact contamination or velocity drift. All VOR gains were within the physiological range for healthy adults (typically 0.7–1.3), with no values approaching the abnormal threshold (< 0.70). Shapiro–Wilk tests confirmed that left and right paired gain differences were normally distributed ($p > 0.20$).

Horizontal canal VOR gains remained stable across both conditions (Table 1). Baseline mean gains were 0.925 ± 0.063 (left) and 0.924 ± 0.074 (right), compared with 0.938 ± 0.084 and 0.938 ± 0.074 under cognitive load. Although mean gains increased slightly by approximately 1.4 to 1.5%, these differences were not statistically significant (left: $t(32) = 0.64$, $p = 0.53$; right: $t(32) = 0.85$, $p = 0.40$). Effect sizes were negligible ($dz = 0.11$ left: 0.15 right). TOST analyses confirmed statistical equivalence of gains within the predefined ± 0.05 margin (left: $p1 = 0.0017$, $p2 = 0.0348$; right: $p1 = 0.0003$, $p2 = 0.0201$). Fig.1 shows the close agreement between baseline and cognitive load gains.

Fig. 1 Horizontal vHIT gain at baseline and under cognitive load. Scatterplots show individual VOR gain values for (a) left and (b) right horizontal canals (n = 33). Each point represents one

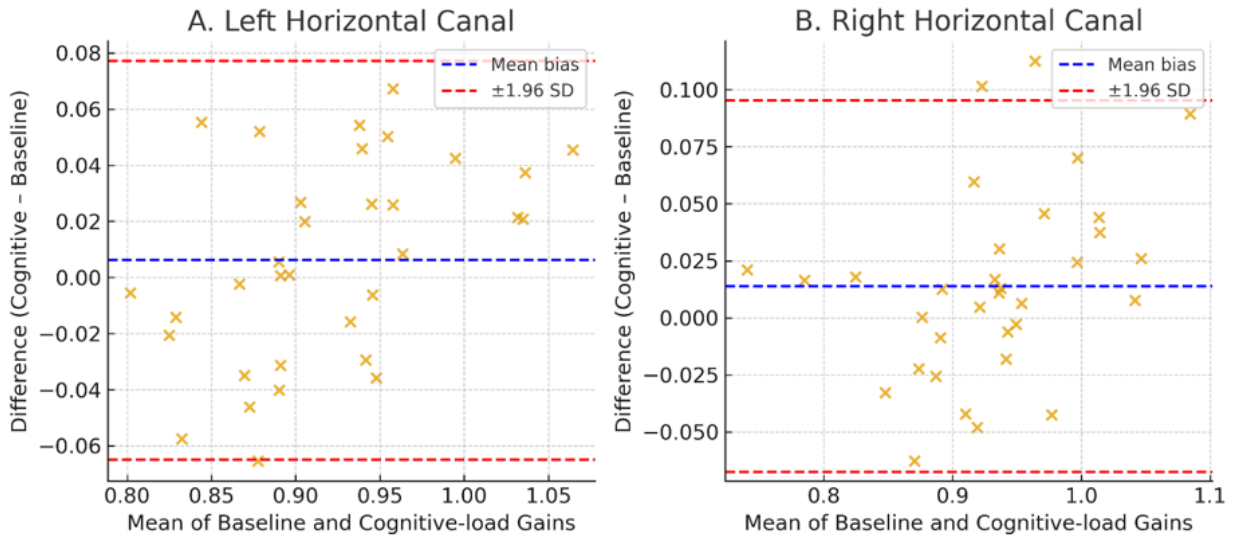
participant. The diagonal line indicates the line of identity (y = x), illustrating close agreement between baseline and cognitive load measurements. Individual data points are shown without confidence interval (CI) bars.



ICC [3,1] values indicated excellent reliability between conditions (left = 0.90, 95% CI 0.81-0.95; right = 0.89, 95% CI 0.79-0.94). No significant associations were observed between gain changes and subjective mental effort (left: $\rho = -0.04$, $p = 0.78$; right: $\rho = 0.02$, $p = 0.88$) or dizziness ($|\rho| < 0.05$, $p > 0.50$).These findings are summarised in Table 2.

The cognitive task elicited a significant increase in perceived mental effort, rising from 2.1 ± 1.1 at baseline to 7.3 ± 1.4 during the dual-task condition ($t(32) = 14.8$, $p < 0.001$). Dizziness ratings remained low and did not differ significantly between conditions (0.4 ± 0.7 vs 0.8 ± 0.9; $p = 0.10$). Agreement analyses supported the statistical findings: scatterplots showed strong alignment along the line of identity and Bland-Altman plots (Fig. 2) demonstrated narrow limits of agreement, ranging from − 0.06 to + 0.08 for the left canal and − 0.05 to + 0.10 for the right canal, with minimal mean bias.

Fig. 2 Bland–Altman plots of agreement between baseline and cognitive load horizontal vHIT gain. Panels show (a) left and (b) right canals. The solid line indicates the mean difference (cognitive load - baseline), and dashed lines represent the 95% limits of agreement (mean ± 1.96 SD). The narrow limits (approximately ±0.10 gain units) and minimal bias indicate high agreement between conditions. Individual data points are shown without confidence interval (CI) bars.



Discussion

The present study demonstrates that horizontal VOR gain remains stable under moderate cognitive load in healthy young adults. Despite a substantial increase in perceived mental effort, VOR gains were statistically unchanged between baseline and dual-task conditions and equivalence analysis confirmed that both measurements fell within a clinically accepted ±0.05 gain-unit margin. Excellent reliability scores further indicated that introducing a concurrent cognitive task did not introduce meaningful variability into the vHIT response. These findings support the position that the horizontal VOR is resistant to transient attentional interference, consistent with its short-latency, predominantly brainstem-mediated architecture [1,19,20], and reinforce the robustness of horizontal vHIT in routine clinical environments.

These results align with emerging evidence that short-latency vestibular reflexes exhibit limited susceptibility to cognitive modulation. Rozendorn et al. reported preserved VOR gain during dual-task paradigms combining cognitive and motor tasks, although their multi-distance protocol introduced potential vergence related variability [15]. By employing a fixed-distance, cognitively isolated design, the present study provides a more controlled evaluation of attentional effects and demonstrates that cognitive load alone does not alter horizontal canal performance.

The contrast between the present findings and the well documented dual-task interference observed in postural control and gait is noteworthy. Concurrent mental tasks consistently impair standing balance and gait dynamics, as these behaviours rely heavily on multisensory integration

within cerebellar and cortical networks [21,22]. In contrast, the horizontal VOR is a rapid, low-level, brainstem reflex optimised for maintaining gaze stability during high-velocity head rotations. The dissociation supports the view that VOR pathways are relatively less influenced by attentional demands that readily influence higher order vestibular behaviours such as navigation, visual vestibular integration, or spatial orientation.

Previous studies showing cognitive effects on vestibular perception or visually induced motion intolerance such as changes in self-motion awareness or susceptibility to vertigo, likely reflect modulation at perceptual or cortical processing levels rather than at the reflex arc itself [14,24]. The dissociation between stable VOR gain and marked increases in effort ratings in the present study further supports this interpretation and suggests that divided attention influences subjective cognitive experience more strongly than reflexive physiological output.

The underlying neurophysiology of the horizontal VOR provides a strong explanatory basis for its stability under cognitive load. The canonical three-neuron arc linking semicircular canal afferents to vestibular nuclei and ocular motor neurons operates with latencies less than 10 ms and shows limited dependence on cortical modulation [20]. In addition, an indirect cerebellar pathway contributes to adaptive calibration and motor learning within the vestibulo-ocular system but operates over longer timescales and is unlikely to influence rapid, high-frequency VOR responses during brief head impulses [25]. Functional imaging studies similarly show limited cortical activation during high-frequency vestibular stimulation [26,27], suggesting limited influence of attentional networks on rapid VOR responses.

Importantly, the absence of any dizziness increase despite elevated mental effort indicates that participants' perceptual experience was not confounded by discomfort or behavioural distraction. The reflex therefore appears to remain largely governed by subcortical mechanisms even under divided attention. Whether this resilience extends to more complex vestibular behaviours such as vertical canal responses, visuo-vestibular integration, or otolithic reflexes remains unknown.

These findings have direct relevance for clinical practice. The equivalence margin used in this study should be interpreted as a literature-based estimate of typical vHIT variability rather than a device-specific universal threshold. Although vHIT requires stable visual fixation, it does not rely on sustained executive attention and particularly children, older adults, or individuals with cognitive vulnerabilities may not always maintain optimal attentional engagement during testing.

This study has demonstrated that moderate cognitive load does not alter horizontal VOR gain, providing reassurance that fluctuations in attention are unlikely to compromise the accuracy of horizontal vHIT assessments in healthy young adults, although caution is warranted when generalising these findings to older or clinical populations. Methodologically, the study supports the use of a simplified single distance vHIT protocol for dual-task paradigms and offers a framework for future work examining vestibulo-cognitive interactions in clinical groups such as those with mild cognitive impairment, vestibular migraine, concussion, or central vestibular disorders.

Several limitations must be acknowledged. The fixed order of testing (baseline followed by cognitive load) may have introduced potential learning or adaptation effects, including improved head-impulse compliance or fixation strategy. The small increase in gain observed under cognitive load may therefore partially reflect order effects rather than cognitive resilience alone. Second, although mental effort ratings confirmed that participants experienced increased cognitive demand, objective performance metrics for the serial-subtraction task were not recorded. As a result, inter-individual variability in cognitive load intensity could not be quantified, and sustained task engagement could not be objectively verified. In addition, it was not possible to examine whether gain stability varied with task performance or difficulty. Although subjective effort ratings increased significantly, they remain susceptible to reporting bias, and the absence of objective cognitive measures may limit interpretation of the findings. The study sample consisted of young healthy adults, restricting generalisability to older or clinical populations in whom attentional capacity, vestibular compensation and dual-task vulnerability may differ. Furthermore, the study measured only horizontal canals; results may not fully generalise to vertical canal and otolithic pathways, which may exhibit different susceptibility to cognitive interference. Finally, no objective cognitive load measures were included, which would have supported more comprehensive validation of cognitive state changes.

Future research should examine whether cognitive load affects vertical canal function (RALP and LARP planes), VEMPs, or visuo-vestibular integration tasks. Dose-response paradigms changing cognitive load intensity may clarify threshold effects. Studies should include older adults and clinical populations to determine whether reduced attentional capacity or impaired central compensation modulates susceptibility to dual-task interference. Finally, longitudinal work

could assess whether cognitive training, fatigue, or vestibular rehabilitation influence the relationship between attention and reflexive gaze stability.

Conclusions

Horizontal VOR gain measured using vHIT remained statistically equivalent and highly reliable under moderate cognitive load, despite substantial increases in perceived mental effort. These findings confirm the attentional resilience of the horizontal VOR and reinforce the robustness of vHIT in routine clinical practice. The present framework offers a foundation for future investigations across vertical canals, otolithic reflexes, ageing cohorts, and clinical populations where vestibulo-cognitive interactions may differ.

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Table 1 Mean horizontal VOR gains under baseline and cognitive-load conditions (n = 33)

Condition	Left gain (mean ± SD)	Right gain (mean ± SD)	Mean difference (Cognitive – Baseline)	95% CI	% change	t (df = 32)	p	Cohen's dz
Baseline	0.925 ± 0.063	0.924 ± 0.074	—	—	—	—	—	—
Cognitive load	0.938 ± 0.084	0.938 ± 0.074	+0.0127 (Left) / +0.0142 (Right)	−0.028 to +0.053 (Left) / −0.020 to +0.048 (Right)	+1.4% / +1.5%	0.64 (Left) / 0.85 (Right)	0.53 (Left) / 0.40 (Right)	0.11 (Left) / 0.15 (Right)

No significant differences were observed between conditions ($p > 0.40$). Both left and right canal gains were statistically equivalent within ±0.05 gain units (TOST, $p_1 < 0.002$, $p_2 < 0.04$).

Table 2 Reliability and association analyses

Measure	Left canal	Right canal	Interpretation
ICC (3, 1)	0.90 (95% CI: 0.81–0.95)	0.89 (95% CI: 0.79–0.94)	Excellent reliability
Spearman ρ (Effort × Gain change)	−0.04 (p = 0.78)	+0.02 (p = 0.88)	No association
Spearman ρ (Dizziness × Gain change)	+0.03 (p = 0.74)	−0.01 (p = 0.91)	No association

ICC = intraclass correlation coefficient (two-way mixed-effects model, consistency, single measures). ρ = Spearman's rank correlation coefficient. No significant associations were observed between perceived effort, dizziness, and gain changes ($p > 0.50$).