Original Paper

Cybersickness and Its Relationship With Vestibulo-Ocular Reflex and Ocular Motor Functions: Prospective Single-Arm Experimental Study

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Abstract

Background: Cybersickness increasingly limits the broader adoption of virtual environments as accessibility expands. Multiple factors contribute to cybersickness, and recently, several studies have reported associations between eye movements and cybersickness. Prior studies have largely focused on optokinetic responses, yet characteristics of the vestibular system and other ocular motor functions remain largely unclear.

Objective: This prospective, single-arm experimental study investigated the relationship between cybersickness and vestibular and ocular motor findings. We hypothesized that direct vestibulo-ocular reflex (VOR) function and other ocular motor functions are associated with cybersickness susceptibility in healthy individuals.

Methods: We prospectively recruited healthy volunteers for a VR experiment between September 2024 and 2024 at Korea University in South Korea. Each participant completed questionnaires, including the Dizziness Handicap Inventory (DHI); Vertigo Symptom Scale (VSS); University of California, Los Angeles Dizziness Questionnaire (UCLA-DQ); Motion Sickness Susceptibility Questionnaire (MSSQ); and Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ). Participants then underwent video-oculography and video head impulse testing to assess VOR, smooth pursuit (SP), and visuovestibular interaction before VR exposure. Next, participants viewed a snowy mountain scene while being passively navigated along a predefined path for 3 minutes using a head-mounted display. Each participant completed the Simulator Sickness Questionnaire (SSQ) immediately after the VR experience, and the SSQ scores were compared with the neurotologic test and questionnaire results.

Results: We analyzed 36 participants aged 21 to 32 (mean 25, SD 3) years, including 20 male and 16 female participants. The SSQ score showed no correlation with VOR gains measured using video head impulse testing (horizontal canal: Spearman ρ=0.12, 95% CI –0.25 to 0.44; *P*=.50; anterior canal: ρ=–0.22, 95% CI –0.51 to 0.13; *P*=.20; posterior canal: ρ=–0.20, 95% CI –0.53 to 0.20; *P*=.25), SP gain (rightward pursuit: ρ=–0.04, 95% CI –0.53 to 0.43; *P*=.85; leftward pursuit: ρ=–0.18, 95% CI –0.60 to

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0.28; *P*=.42), or cumulative saccadic amplitudes during low-frequency VOR, visually enhanced VOR, or VOR cancellation. The SSQ score also showed no correlation with motion sickness susceptibility or daily dizziness questionnaire scores, including those for the MSSQ (ρ=0.03, 95% CI –0.31 to 0.37; *P*=.87), VIMSSQ (ρ=0.07, 95% CI –0.28 to 0.40; *P*=.69), UCLA-DQ (ρ=0.07, 95% CI –0.26 to 0.40; *P*=.69), VSS (ρ=–0.12, 95% CI –0.39 to 0.18; *P*=.48), and DHI (ρ=0.05, 95% CI –0.27 to 0.36; *P*=.77).

Conclusions: Cybersickness does not appear to depend on vestibular afferent sensitivity or individual ocular motor function and may more likely reflect a higher-level mismatch in sensorimotor integration and adaptation. Given the expanding applications of VR in rehabilitation, entertainment, and professional training, our findings underscore the importance of evaluating cybersickness beyond direct VOR function and focusing on multisensory integration to accommodate individual susceptibility.

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KEYWORDS

cybersickness; virtual reality; video head impulse test; vestibulo-ocular reflex; motion sickness; dizziness

Introduction

Cybersickness describes a constellation of discomfort symptoms induced by virtual reality (VR) exposure [1]. Approximately 60% to 80% of VR users experience motion sickness–related symptoms, including dizziness, eye strain, headache, sweating, pallor, nausea, and vomiting [1,2]. Cybersickness represents a subtype of motion sickness in which an illusory sense of self-motion (vection) occurs during exposure to a head-mounted display (HMD) and conflicts with vestibular input in the presence of minimal head movement [3,4]. Multiple factors contribute to cybersickness, including display type, application design, and individual susceptibility. Increasing reports identify this discomfort as a barrier to broader adoption as virtual environments become more accessible [4].

VR has recently gained popularity in the medical field as a flexible tool for studying a wide range of human behaviors under high-fidelity, replicable conditions. In particular, VR has increasingly been adopted in rehabilitation, providing immersive, interactive environments that support task-specific training and patient engagement. VR-based rehabilitation has been applied to various neurological and vestibular disorders, including stroke, Parkinson disease, Alzheimer disease, traumatic brain injury, and vestibular neuritis [5-13]. VR can deliver controlled, customizable sensory stimuli and real-time feedback, allowing rehabilitation programs to be tailored to individual patients' functional impairments and recovery needs [11]. Although VR has not been widely studied in young individuals, its ease of use in older adults suggests that its utility can be expanded to patients requiring rehabilitation. In this context, understanding the physiological factors underlying individual susceptibility to cybersickness is essential for developing safe, personalized VR-based interventions [11,14].

Recently, several studies have reported associations between eye movements and cybersickness and have proposed eye movement patterns as potential feedback mechanisms during VR exposure [15-17]. Dynamic changes in visual and vestibular sensitivity following VR exposure imply that sensory reweighting consistently occurs to help individuals adapt to and modulate sensory conflict and reduce cybersickness [18]. Similarly, eye movement dynamics can stratify cybersickness susceptibility, suggesting that eye movements are somewhat linked to the development or mitigation of cybersickness. Reduced cybersickness following transcranial electrical stimulation of the vestibular cortex supports the assumption that modulating vestibular signals is linked with cybersickness [19]. Because discordance between static vestibular signals and visual information during VR exposure can cause cybersickness, quantifying and evaluating vestibular function can provide clues to understand the pathophysiology.

Previous studies have largely focused on indirect neuropsychological measures, optokinetic responses, or balance tasks [20-22], yet characteristics of the vestibular system comprising the direct vestibulo-ocular reflex (VOR) pathway and other ocular motor functions remain poorly characterized. Quantitative measures of vestibular and ocular motor function can be challenging to obtain, partly because validated assessment tools are not readily accessible to many VR researchers. Alternatively, evidence from motion sickness research offers useful context, but findings regarding the relationship between the VOR and motion sickness also remain inconsistent [23-25]. This knowledge gap highlights the need to examine associations between the VOR, other ocular motor functions, and cybersickness. Addressing this gap warrants multidisciplinary collaboration among VR system engineers, ergonomics researchers, and eye movement specialists. This perspective in VR research is timely, given the growing use of VR beyond the medical field, including education, gaming, driving or pilot training, and military applications of immersive tools such as first-person view drones. Understanding cybersickness in these contexts can help assess and potentially mitigate different levels of danger and seriousness associated with VR exposure, particularly when cybersickness could have serious consequences. This approach can help characterize the underlying pathophysiology and support the development of targeted interventions to mitigate cybersickness. We hypothesized that direct VOR function or other ocular motor functions are associated with cybersickness susceptibility in healthy individuals.

Methods

Conditions and Design

This prospective experimental study was conducted at Korea University Medical Center, and participants were recruited between September 2024 and December 2024. Reporting of this study was guided by the Journal Article Reporting Standards for Quantitative Research, and the study design was described

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according to the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) template (Checklist 1).

Inclusion and Exclusion

Eligible participants had no history of significant dizziness, headache, or severe motion sickness. We excluded participants who could not complete the VR experiment or vestibular evaluation, or who had severe motion sickness, defined as a Motion Sickness Susceptibility Questionnaire (MSSQ) score greater than 30 at screening.

Participant Characteristics

Baseline characteristics included demographic information and MSSQ scores, which were used to assess eligibility.

Sampling Procedures

Participants were recruited via convenience sampling using a flyer posted in the Computer Science and Engineering building at Korea University. All assessments, including questionnaires and vestibular and ocular motor testing, were conducted at the Neurology Department of Korea University Medical Center. The VR experiment was conducted at the Digital Experience Lab in the Computer Science and Engineering building at Korea University, which is adjacent to the hospital building, on the same day as the vestibular and ocular motor evaluations.

Sample Size, Power, and Precision

We estimated the sample size based on a previous study by Guo et al [20], which demonstrated a robust correlation between visually induced motion sickness scores and the indirect VOR pathway, quantified using the time constant of optokinetic after-nystagmus (Pearson r ranging from 0.51 to 0.74). On the basis of this finding, we conservatively assumed an anticipated Spearman rank correlation coefficient of 0.51 as the target effect size for the present study. Using a variance-adjusted Fisher z approximation for Spearman rank correlation, with a 2-sided significance level of .05 and 80% power, we estimated a minimum required sample size of 32 participants.

Measures and Covariates

Head and eye movements were recorded using a video head impulse test (vHIT) system (SLVNG; SLMED Korea), as previously described [26]. Peak head acceleration exceeded 3000°/s^2 for the horizontal canals and 2000°/s^2 for the vertical canals. VOR gain for each canal was calculated for individual impulse trials as the ratio of mean eye velocity to mean head velocity within a 40 ms window centered on peak head acceleration.

Ocular motor function was assessed using 3D video-oculography (SLVNG; SLMED Korea). The system recorded head and eye position and velocity at a sampling rate of 120 Hz, as previously described [26]. Smooth pursuit (SP) was evaluated, while participants tracked a horizontally moving target at 20°/s for 6 cycles. SP gain was calculated as the ratio of eye velocity to target velocity. Optokinetic nystagmus (OKN) was assessed, while participants viewed an OKN strip that filled the entire field of view and moved at 13°/s. OKN gain was calculated for each direction of motion: right, left, up, down, clockwise, and counterclockwise.

Three paradigms were used to evaluate visuovestibular interaction: low-frequency VOR, visually enhanced VOR (VVOR), and VOR cancellation (VORc). For low-frequency VOR testing, participants sat upright in a chair in complete darkness without visual fixation. The head was passively rotated horizontally at 0.5 Hz for 10 cycles paced by a metronome, followed by rotations at 1 Hz and 2 Hz for 10 cycles each. Vertical VOR was tested at 0.5 Hz and 1 Hz. For VVOR testing, participants fixated on a stationary target positioned 1.2 m in front of them while undergoing the same horizontal and vertical head rotation protocol. For VORc testing, participants fixated on a target mounted on the chair and maintained visual fixation while the chair rotated, thereby suppressing the VOR. Corrective catch-up saccades and reversed saccades were identified from eye-velocity traces using an automated saccade detection algorithm based on the saccadic main sequence [27]. Any spontaneous nystagmus (SN) was identified and corrected before calculating cumulative saccadic amplitude according to its direction and magnitude, using SN with visual fixation for VVOR and VORc, and SN in complete darkness without visual fixation for low-frequency VOR. Eye displacement attributable to SN was estimated from its slow-phase velocity and the corresponding time interval, after which it was subtracted from saccadic amplitudes in the same direction as SN and added to those in the opposite direction. Cumulative saccadic amplitude during leftward, rightward, upward, and downward head rotations, as well as saccadic asymmetry, were quantified for subsequent analyses [26].

Data Collection and Instrumentation

The study followed a fixed sequence: (1) completion of questionnaires, including the Dizziness Handicap Inventory (DHI), Vertigo Symptom Scale (VSS), University of California, Los Angeles Dizziness Questionnaire (UCLA-DQ), MSSQ, and Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ; approximately 30 minutes); (2) baseline vestibular and ocular motor assessments before VR exposure, including vHIT to assess VOR function and video-oculography to assess OKN, SP, and visuovestibular interaction (approximately 1 hour); (3) a 3-minute VR exposure to the “Snow World” program, delivered as passive navigation and intentionally designed to evoke cybersickness; and (4) administration of the Simulator Sickness Questionnaire (SSQ) immediately after VR exposure to assess the presence and severity of cybersickness (approximately 10 minutes; Multimedia Appendix 1).

The virtual environment was delivered using a VIVE Pro Eye HMD (HTC Corp), with a resolution of 1440×1600 pixels per eye and a combined resolution of 2880×1600 pixels, and a field of view of up to 110°. The VR system ran on a high-performance desktop equipped with an NVIDIA GeForce RTX 4080 graphics processing unit (NVIDIA Corp) and an AMD Ryzen 7 7700X 8-Core central processing unit (Advanced Micro Devices Inc). Content was presented at approximately 75 frames per second. Eye-tracking calibration was performed before each exposure.

Participants viewed a snowy mountain scene titled “Snow World,” delivered as passive navigation along a predefined path

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for 3 minutes through the HMD. The scene was designed to evoke cybersickness (Multimedia Appendix 2). Each participant completed the SSQ immediately after the VR exposure to report subjective cybersickness severity. The SSQ is a 16-item symptom checklist in which participants rate the severity of each symptom on a 4-point scale (0="none," 1="slight," 2="moderate," and 3="severe") [28]. The SSQ generates 3 symptom cluster subscales—nausea, oculomotor, and disorientation—as well as a total severity score. The nausea subscale reflects mainly gastrointestinal and autonomic symptoms such as nausea and sweating. The oculomotor subscale reflects visual strain, including eye strain and difficulty focusing. The disorientation subscale reflects dizziness and vertigo symptoms. Subscale scores were calculated using the standard weighted scoring procedure: symptom ratings were summed within each cluster and multiplied by the corresponding weighting factor (nausea×9.54, oculomotor×7.58, and disorientation×13.92). Total severity was calculated as the sum of the 3 weighted subscale scores multiplied by 3.74. Higher scores indicate greater cybersickness severity.

Quality of Measurements, Psychometrics, and Masking

Questionnaires were administered by a trained study investigator (JSK) using standardized procedures. Masking was not applicable because all participants received the same intervention. The UCLA-DQ, MSSQ, VSS, DHI, VIMSSQ, and SSQ were administered according to their established scoring procedures. These instruments have undergone previous psychometric evaluations, with published evidence supporting their reliability and validity, although the extent of validation varies by instrument and language version.

Data Diagnostics

Before analysis, the data were reviewed for completeness, out-of-range values, and internal inconsistencies. No participants were excluded after enrollment. Measurements that could not be obtained reliably were treated as unavailable, and missing values were not imputed. We performed the Little missing completely at random (MCAR) test for cumulative saccadic amplitudes during low-frequency VOR, VVOR, and VORc testing, as well as for SP gains, and it was not blinded to previous results. Questionnaires were distributed to participants, who completed them independently and nonanonymously. Participants could ask questions as needed, and the study investigator was present during questionnaire completion.

Analytic Strategy

Statistical analyses were performed to compare clinical characteristics and vestibulo-ocular and ocular motor measures, including gains from vHIT, OKN, and SP, as well as cumulative saccadic amplitudes during low-frequency VOR, VVOR, and VORc testing. Correlations were assessed using the Spearman rank correlation coefficient. Analyses were conducted using R (version 4.3.1; R Foundation for Statistical Computing). Statistical significance was defined as a 2-tailed P value of <.05.

Ethical Considerations

This study followed the tenets of the Declaration of Helsinki and was performed according to the guidelines of the institutional review board of Korea University Anam Hospital (2024AN0369). Written informed consent was obtained from all participants before enrollment, after they had been informed about the study purpose, procedures, and potential risks. All data used in the analyses were deidentified through the removal of direct personal identifiers and securely stored in password-protected files on institutional systems with restricted access. Each participant received ₩50,000 (approximately US $34) as compensation for their participation. No photographs or videos containing identifiable individuals were included in the figures or multimedia appendices.

Results

Clinical Characteristics

A total of 39 participants were initially enrolled. Of these, 3 participants could not complete the experiment because of cybersickness and were excluded from the analysis (Figure 1). The final sample included 36 participants aged 21 to 32 (mean 25, SD 3) years; 20 were male, and 16 were female. MSSQ scores ranged from 2 to 28, with a median of 13 (IQR 10-20).

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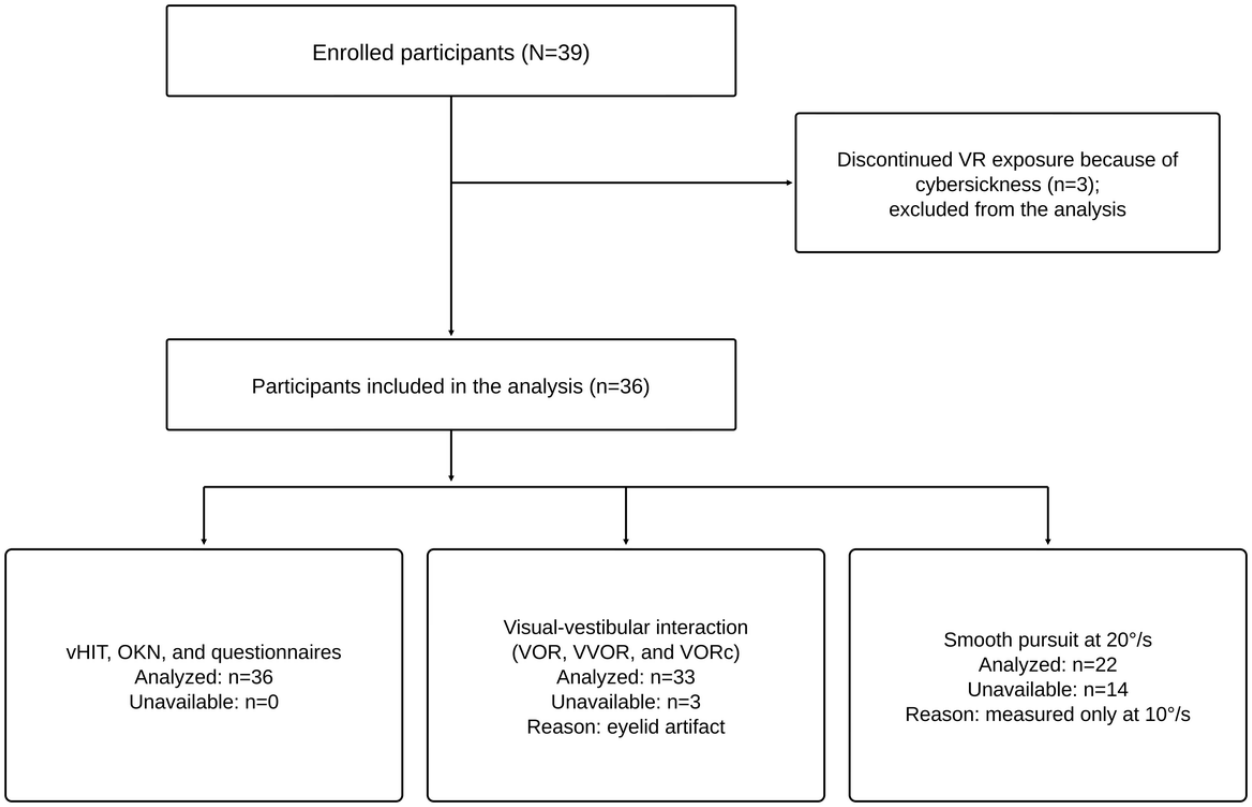
Figure 1. Study flow diagram for a prospective single-arm experimental study. The flow diagram shows participant enrollment, completion of baseline questionnaires, vestibular and ocular motor testing, and reasons for any dropout or missing data. The study was conducted at Korea University Medical Center, Seoul, South Korea, from September 2024 to December 2024. OKN: optokinetic nystagmus; vHIT: video head impulse test; VOR: vestibulo-ocular reflex; VORc: VOR cancellation; VR: virtual reality; VVOR: visually enhanced VOR.



vHIT and OKN

Mean VOR gains measured using vHIT were 1.16 (SD 0.10) for the horizontal canals, 1.08 (SD 0.12) for the anterior canals, and 1.06 (SD 0.12) for the posterior canals. Mean OKN gains were 0.50 (SD 0.14) for leftward, 0.47 (SD 0.17) for rightward, 0.49 (SD 0.21) for upward, 0.46 (SD 0.19) for downward, and 0.09 (SD 0.09) for both clockwise and counterclockwise optokinetic stimuli.

SP and Low-Frequency VOR, VVOR, and VORc

Median SP gain was 0.76 (IQR 0.68-0.94) for rightward tracking and 0.80 (IQR 0.66-0.89) for leftward tracking. SN was present in darkness in 7 (19%) patients, with slow-phase velocities ranging from 0.6°/s to 2.0°/s. The directions of SN were horizontal-vertical (n=6) and purely horizontal (n=1). None of the participants showed SN with visual fixation. Cumulative saccadic amplitudes during low-frequency VOR had a median of 170.77° (IQR 69.11°-308.41°) during rightward head rotations, 169.82° (IQR 95.60°-288.88°) during leftward head rotations, 94.69° (IQR 48.17°-158.28°) during upward head rotations, and 79.34° (IQR 38.85°-150.41°) during downward head rotations. During VVOR, cumulative saccadic amplitudes had medians of 26.72° (IQR 5.58°-64.52°) during rightward head rotations, 23.59° (IQR 10.45°-53.71°) during leftward head rotations, 53.31° (IQR 16.29°-86.12°) during upward head rotations, and 41.65° (IQR 17.89°-99.63°) during downward head rotations. During VORc chair rotation, cumulative saccadic amplitudes had medians of 108.83° (IQR 82.51°-150.68°) during rightward chair rotations and 105.92° (IQR 80.50°-145.61°) during leftward chair rotations (Table 1).

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Table 1. Summary of ocular motor and vestibulo-ocular reflex (VOR) measures.

Head rotation direction	Smooth pursuit gain, median (IQR)	Cumulative saccadic amplitude, median (IQR)		
		VOR	Visually enhanced VOR	VOR cancellation
Horizontal head rotations				
Rightward[a]	0.76 (0.68 to 0.94)	170.77° (69.11° to 308.41°)	26.72° (5.58° to 64.52°)	108.83° (82.51° to 150.68°)
Leftward	0.80 (0.66 to 0.89)	169.82° (95.6° to 288.88°)	23.59° (10.45° to 53.71°)	105.92° (80.50° to 145.61°)
Asymmetry	—[b]	–6.19° (–25.22° to 15.58°)	–8.68° (–55.48° to 25.55°)	–5.09° (–14.68° to 12.98°)
Vertical head rotations				
Upward	—	94.69° (48.17° to 158.28°)	53.31° (16.29° to 86.12°)	—
Downward	—	79.34° (38.85° to 140.41°)	41.65° (17.89° to 99.63°)	—
Asymmetry	—	8.82° (–15.7° to 27.53°)	–1.60° (–44.55° to 28.79°)	—

[a]Rightward head rotation for VOR and visually enhanced VOR, and rightward chair rotation for VOR cancellation.

[b]Data not available.

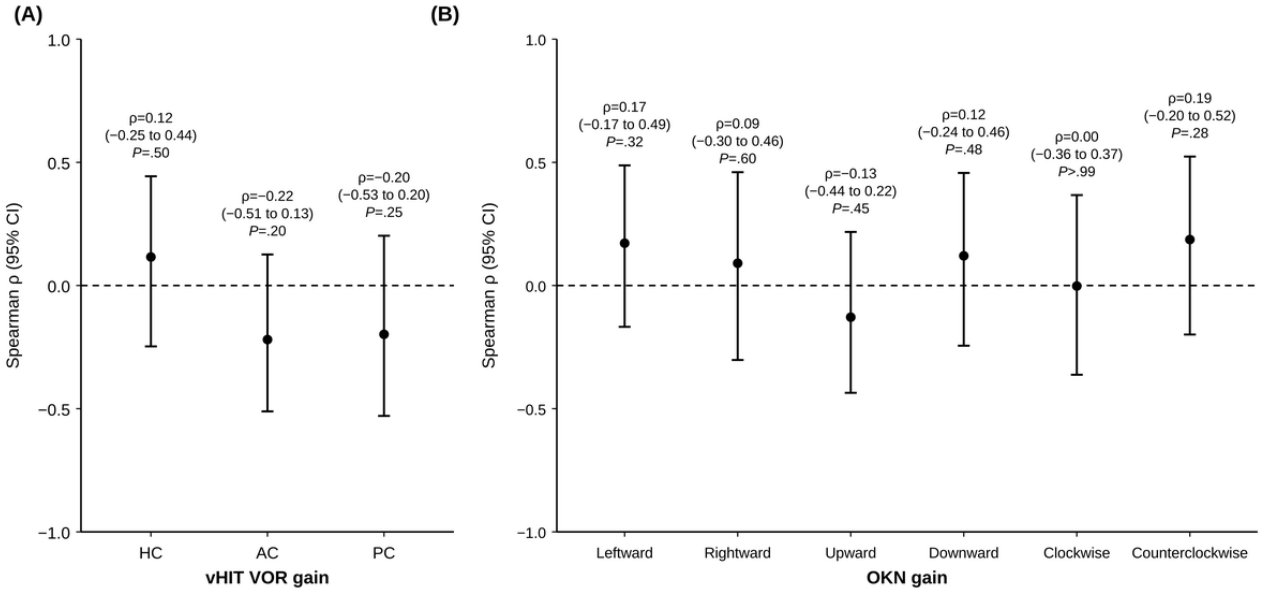
Cybersickness and Other Dizziness, and Motion Sickness Questionnaires

SSQ total scores ranged from 0 to 165, with a median of 69 (IQR 51-109). Median values were 57 (IQR 38-79) for the nausea subscale, 49 (IQR 36-76) for the oculomotor subscale, and 84 (IQR 52-153) for the disorientation subscale. Median values were 8 (IQR 7-10) for UCLA-DQ, 4 (IQR 0-7) for DHI, and 3 (IQR 2-7) for VSS.

Correlation Between Cybersickness and vHIT and OKN

SSQ total score showed no correlation with VOR gain in any semicircular canal (Figure 2A). SSQ total score also showed no correlation with OKN gain in any direction, including horizontal, vertical, or torsional directions (Figure 2B).

Figure 2. Correlations of Simulator Sickness Questionnaire (SSQ) scores with vestibulo-ocular reflex (VOR) gain during high-acceleration head rotation and optokinetic stimulation (N=36). Correlations between (A) SSQ scores and video head impulse test (vHIT) VOR gains for any canal and (B) SSQ scores and optokinetic stimulation gain. AC: anterior canal; HC: horizontal canal; OKN: optokinetic nystagmus; PC: posterior canal.



Correlation Between Cybersickness and Ocular Motor Tests

Among the 36 participants, cumulative saccadic amplitude data during low-frequency VOR, VVOR, and VORc testing were unavailable for 3 participants, and SP gains were unavailable for 14 participants, leaving 33 and 22 participants, respectively, for the correlation analyses. The Little MCAR tests did not reject the assumption that the data were missing completely at random for either cumulative saccadic amplitudes during visuovestibular interaction (χ^2_1=0.5; *P*=.47) or SP gains (χ^2_1=0.02; *P*=.89).

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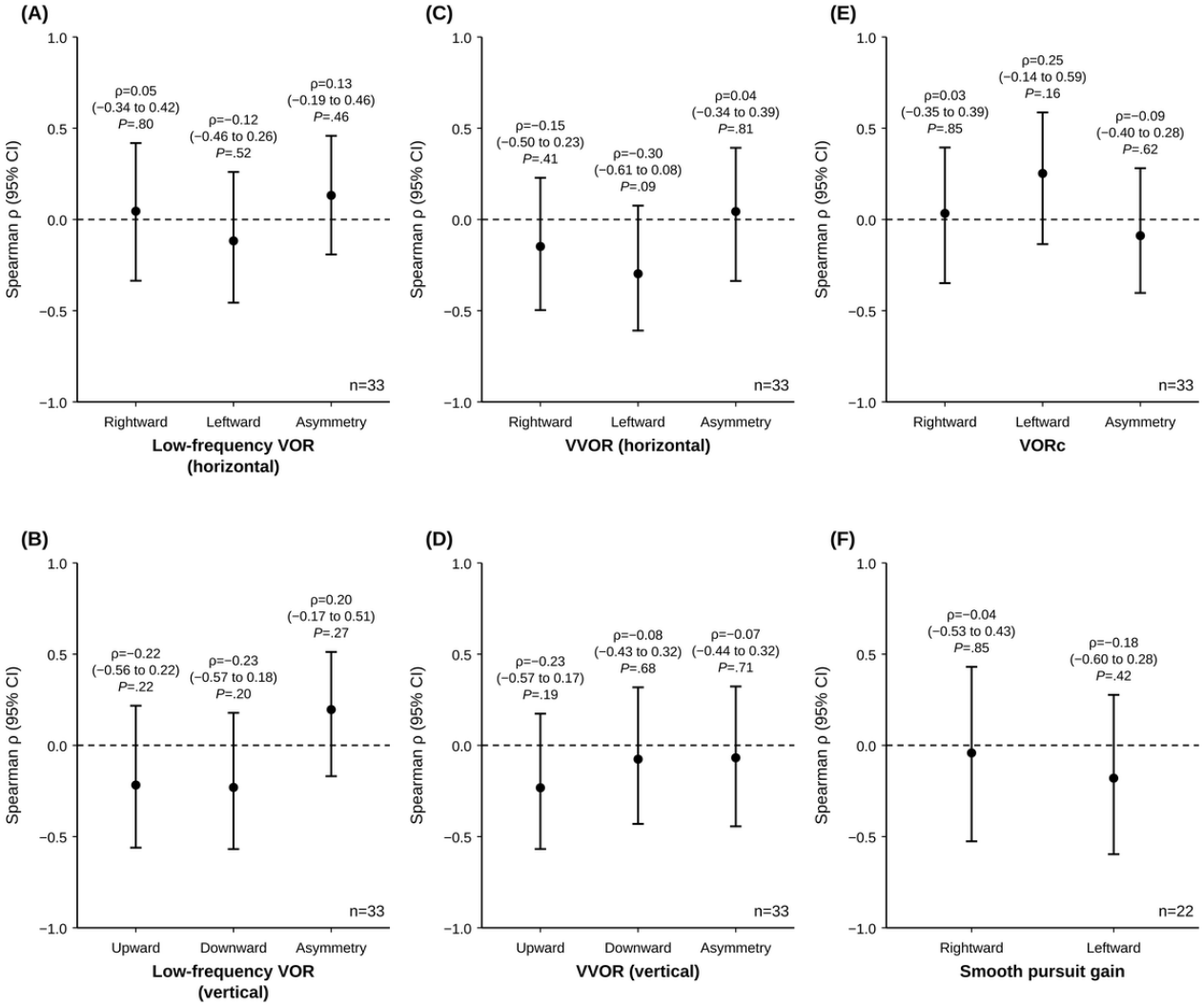
SSQ total score showed no correlation with SP gain in either direction (rightward tracking: ρ=–0.04, 95% CI –0.53 to 0.43; *P*=.85; leftward tracking: ρ=–0.18, 95% CI –0.60 to 0.28; *P*=.42). SSQ total score also showed no correlation with cumulative saccadic amplitude during low-frequency VOR, VVOR, or VORc (Figure 3).

Figure 3. Correlations between Simulator Sickness Questionnaire (SSQ) total scores and cumulative saccadic amplitudes during (A) and (B) low-frequency vestibulo-ocular reflex (VOR), (C) and (D) visually enhanced VOR (VVOR), and (E) VOR cancellation (VORc), and (F) with smooth pursuit gain. The SSQ total score was not correlated with cumulative saccadic amplitude during rightward, leftward, upward, or downward head rotations or with the corresponding asymmetry measures. Asymmetry was calculated as (R–L)/(R+L)×100 (%). No significant correlation was observed between SSQ total scores and smooth pursuit gain.



Correlation Between Cybersickness and Other Dizziness and Motion Sickness Questionnaires

SSQ total score showed no correlation with questionnaire scores assessing motion sickness or daily dizziness, including the MSSQ (Spearman ρ=0.03, 95% CI –0.31 to 0.37; *P*=.87), VIMSSQ (ρ=0.07, 95% CI –0.28 to 0.40; *P*=.69), UCLA-DQ (ρ=0.07, 95% CI –0.26 to 0.40; *P*=.69), VSS (ρ=–0.12, 95% CI –0.39 to 0.18; *P*=.48), and DHI (ρ=0.05, 95% CI –0.27 to 0.36; *P*=.77).

Discussion

Principal Findings

Key findings can be summarized as follows: (1) cybersickness quantified by the SSQ showed no correlation with VOR gain during high-velocity head acceleration or optokinetic stimulation; (2) cybersickness also showed no correlation with SP gain or visuovestibular interaction measures from low-frequency VOR, VVOR, and VORc testing; and (3) the SSQ score showed no correlation with other dizziness and motion sickness questionnaires, including the DHI, VSS, UCLA-DQ, MSSQ, and VIMSSQ. These results indicate that cybersickness is not directly related to VOR performance or the ocular motor functions involved in visuovestibular interaction. To our knowledge, this is the first study to systematically characterize eye movements according to their underlying physiological mechanisms using established clinical vestibular and ocular motor assessments. By distinguishing the contributions of different ocular motor and vestibular functions, our findings provide a foundation for understanding the pathophysiology of cybersickness and for conducting future

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mechanistic investigations. Collectively, our findings support a model in which cybersickness reflects a mismatch in higher-level sensorimotor integration rather than vestibular afferent sensitivity or basic ocular motor function.

Mechanism of Cybersickness

Cybersickness generally arises from conflict among visual, vestibular, and somatosensory inputs during exposure to virtual environments [22]. Sensory conflict theory, first proposed to explain motion sickness, posits that mismatches between expected and actual sensory signals—particularly between visual motion cues and reduced or absent vestibular feedback during VR exposure—trigger maladaptive neural responses that produce nausea, oculomotor strain, and disorientation [4]. Postural instability theory offers an alternative explanation, attributing symptoms to difficulty maintaining stable postural control in unfamiliar environments [29,30].

Individual susceptibility to cybersickness varies and likely reflects maladaptive plasticity in multisensory integration circuits associated with impaired sensory reweighting [31]. Optimal multisensory integration assigns greater weight to more reliable inputs [32]. In real-world settings, vestibular signals may receive excessive weighting relative to that predicted by optimal integration. Some individuals overweight vestibular cues beyond Bayesian expectations, which may explain variability in susceptibility [33]. Resolving VR-related sensory conflict therefore requires substantial down-weighting of vestibular input and up-weighting of visual input [31]. Cybersickness severity increases when VOR gain rises artificially, such as when VR systems amplify the range of head movement [34]. Multiplane visual rotation also worsens symptoms compared with single-plane rotation [35]. These observations align with our results and support the view that peripheral vestibular input or basic ocular motor function plays a limited role in cybersickness, which more likely depends on higher-level sensorimotor integration processes.

Risk Factors for Cybersickness

Susceptibility to cybersickness reflects a complex interaction among individual, technical, and environmental factors. At the individual level, younger age, female sex, prior motion sickness, and vestibular or migraine disorders are associated with an increased risk [4]. Ocular motor features, including interpupillary distance, vergence-accommodation conflict, and visual fatigue, also influence vulnerability [36,37]. Technical factors such as display latency, low refresh rate, limited field of view, and optic flow characteristics increase sensory conflict and symptom severity [1,38,39]. Environmental factors include longer exposure duration, content that induces vection, excessive visual acceleration, and limited prior VR exposure or familiarity [30,40]. Together, these findings show that cybersickness does not arise from a single cause but rather from cumulative effects of individual susceptibility shaped by user traits and system design. These findings support personalized adaptation strategies and ergonomic optimization in virtual environments [41-43].

Relationship of VOR and Ocular Motor Functions With Cybersickness

VOR gain during rapid head acceleration and optokinetic stimulation showed no correlation with cybersickness in this study. These results indicate that the direct VOR pathway itself does not drive cybersickness and point instead to a higher-level sensorimotor integration mechanism rather than simple vestibular sensitivity. Current models describe cybersickness as a consequence of central multisensory mismatch, not abnormal responsiveness within a single sensory channel [3]. Visually driven self-motion cues create persistent visuovestibular conflict during VR exposure and require dynamic sensory reweighting to maintain stable self-motion estimates [31]. Failure of this adaptive reweighting likely contributes to symptom development [3]. The known anatomical convergence of sensory inputs from the vestibular nuclei to the parietoinsular vestibular cortex supports this framework [44]. These findings differ from some earlier reports that suggested vestibular abnormalities in motion sickness [45]. Other studies, however, found that motion sickness severity relates more strongly to the time constant of sinusoidal harmonic acceleration than to VOR gain [46]. Individuals with profound labyrinthine dysfunction often report little or no motion sickness [47-49], and the prevalence of motion sickness remains lower in individuals with unilateral or bilateral vestibulopathy than in healthy controls [48]. Taken together, these observations support a central integration model rather than a peripheral VOR-based mechanism.

Difference Between Cybersickness and Motion Sickness

Cybersickness is often considered a VR-induced form of the broader motion sickness spectrum [50]. Both conditions share common symptoms and physiological responses, including nausea, vomiting, pallor, and sweating [50,51]. They also share risk factors such as older age (typically more than 60 years), female sex, anxiety, fatigue, and migraine [52,53], and individuals susceptible to motion sickness often report higher cybersickness susceptibility [53]. Both conditions are commonly explained by sensory conflict theory [22]. However, cybersickness arises mainly from dominant visual input that conflicts with other sensory signals because vestibular stimulation and inertia remain minimal in virtual environments. In contrast, motion sickness results from conflict among visual, vestibular, and somatosensory inputs during actual movement [3,22].

In this study, the VIMSSQ score obtained before VR exposure correlated positively with the MSSQ score, whereas the postexposure SSQ score showed no correlation with the MSSQ score. This pattern suggests that although cybersickness shares core mechanisms with motion sickness, the underlying dynamics of the 2 conditions differ [50]. VR exposure likely triggers adaptive sensory reweighting, with reduced dependence on visual input to limit conflict. Supporting evidence shows that VOR suppression and OKN performance decrease by approximately 13% after VR exposure [21], and reliance on proprioceptive input also declines [54]. These changes reflect the down-weighting of sensory channels judged less reliable during integration, regardless of their true accuracy. The

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mismatch between MSSQ and SSQ, therefore, indicates that cybersickness does not represent solely a fixed vulnerability trait but rather emerges from dynamic multisensory processing and the convergence of visual, vestibular, and proprioceptive inputs during VR exposure.

Minimal Association of Cybersickness With Daily Dizziness or Motion Sickness Susceptibility

Perception of self-motion in daily life depends on coherent integration of visual, proprioceptive, and vestibular inputs [55]. In this study, cybersickness showed little association with the severity of daily dizziness or baseline motion sickness susceptibility. This result indicates that cybersickness is not simply an extension of everyday dizziness or a direct analogue of conventional motion sickness. Individuals prone to motion sickness may still face a higher risk of cybersickness [50], but symptom development appears to depend more on how the system handles visually driven self-motion cues and updates the internal model of motion through adaptive sensorimotor integration [3]. The lack of association with daily dizziness and motion sickness measures suggests that cybersickness does not represent solely a fixed vulnerability trait. Instead, it can arise in any individual when adaptive sensory rebalancing fails during VR exposure. This pattern supports personalized strategies that target the resolution of visuovestibular mismatch to reduce cybersickness [56].

Implications of Studying VOR and Ocular Motor Function for VR Experience

Vestibular and ocular motor tests remain standard tools in clinical practice, whereas VR continues to gain acceptance as a promising adjunct for assessment and rehabilitation in neurotology [11]. Many VR studies lack access to objective laboratory measures of VOR and ocular motor function, which represents a key strength of the present work. Instead, prior research has often relied on neuropsychological or symptom-based measures of cybersickness [20-22], which reflect multifactorial processes and map poorly onto specific neural circuits. Our results show that conventional ocular motor and vestibular assessments can inform our understanding of cybersickness pathophysiology. Incorporating standardized vestibular and oculomotor metrics into VR research may improve cross-disciplinary comparability and clarify the underlying mechanisms and phenotypes of cybersickness.

Caveats and Limitations of Our Study and Suggestions For Future Studies

This study has several limitations. First, cybersickness severity was measured using a questionnaire, making the assessment subject to interindividual reporting variability. Objective physiological metrics such as heart rate, respiratory rate, forehead skin conductance, or pupil size could provide more quantitative assessments in future studies [50,57-59]. Additionally, a dedicated measure of visually induced dizziness, such as the Visual Vertigo Analogue Scale, could have delineated the association between preexisting visual motion sensitivity and cybersickness independently of vestibular or ocular motor function [59,60]. Second, selection bias may have influenced the results. Three participants discontinued VR exposure owing to severe cybersickness, which may have introduced a ceiling effect and reduced the observed association with VOR or visuovestibular interaction measures. As this may affect the external validity of the findings, future studies could use quantitative metrics that account for total VR exposure duration in cases of censored or discontinued VR exposure. Finally, the findings apply to healthy participants and do not establish whether similar patterns occur in central or peripheral vestibular disorders. Because vestibular disease can either reduce or increase motion sickness susceptibility [48], cybersickness responses may also vary in conditions that affect VOR pathways. Studies in individuals with peripheral and central vestibulopathy could further clarify these mechanisms. Longitudinal designs that measure vestibular and ocular motor function before and after VR exposure would also help characterize sensory reweighting and adaptive responses related to cybersickness.

Conclusions

This study evaluated cybersickness in relation to vestibular and ocular motor function using standard neurotologic assessments. Cybersickness showed no association with VOR gain during head impulse or optokinetic stimulation, nor with ocular motor measures of visuovestibular interaction. These results support a model in which cybersickness reflects a mismatch in higher-level multisensory integration and reweighting rather than abnormal peripheral vestibular or ocular motor sensitivity. Given the expanding applications of immersive VR in rehabilitation, entertainment, and professional training, our findings underscore the importance of evaluating cybersickness beyond direct VOR function and focusing on evaluating multisensory integration to accommodate individual susceptibility.

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Generative AI Use

The authors declare that they did not use generative AI tools for any part of the manuscript generation, proofreading, editing, or visualization.

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Authors' Contributions

Jungha Kim analyzed and interpreted the data and wrote the manuscript. HK, Jueun Kim, HS, YK, TW, EP, GK, and JSK analyzed and interpreted the data and revised the manuscript. SUL designed and conceptualized the study, interpreted the data, and revised the manuscript.

Conflicts of Interest

SUL serves as an associate editor of Research in Vestibular Sciences. JSK serves as an associate editor of Frontiers in Neuro-otology and is a member of the editorial boards of Frontiers in Neuro-ophthalmology, Journal of Neuro-ophthalmology, Journal of Vestibular Research, and Clinical and Translational Neuroscience. All other authors declare no other conflicts of interest.

Multimedia Appendix 1

Schematic illustration of the experimental procedure.
[PNG File , 336 KB-Multimedia Appendix 1]

Multimedia Appendix 2

Short version of snowy mountain scene delivered as passive navigation along a predefined path for 3 minutes using a head-mounted display.
[MP4 File (MP4 Video), 94155 KB-Multimedia Appendix 2]

Multimedia Appendix 3

STROBE checklist.
[PDF File (Adobe PDF File), 166 KB-Multimedia Appendix 3]

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Abbreviations

DHI: Dizziness Handicap Inventory
HMD: head-mounted display
MCAR: missing completely at random
MSSQ: Motion Sickness Susceptibility Questionnaire
OKN: optokinetic nystagmus
SN: spontaneous nystagmus
SP: smooth pursuit
SSQ: Simulator Sickness Questionnaire
STROBE: Strengthening the Reporting of Observational Studies in Epidemiology
UCLA-DQ: University of California, Los Angeles Dizziness Questionnaire
vHIT: video head impulse test
VIMSSQ: Visually Induced Motion Sickness Susceptibility Questionnaire
VOR: vestibulo-ocular reflex
VORc: vestibulo-ocular reflex cancellation
VSS: Vertigo Symptom Scale
VR: virtual reality
VVOR: visually enhanced vestibulo-ocular reflex

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