Towards General Motion Sickness Reduction via Semi-random Galvanic Vestibular Stimulation

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Figure 1: We present a novel scene-independent approach to mitigate motion sickness by *desensitizing* the vestibular system using semi-random Galvanic Vestibular Stimulation (GVS). Unlike existing scene-dependent methods that enhance vestibular feedback based on visual motion, our technique applies a low-frequency signal with mild stochastic modulation to disrupt natural vestibular responses. This avoids the discomfort commonly associated with fully stochastic (noisy) GVS while preserving its beneficial effects. The method operates independently of user motion or scene content, demonstrating potential for generalization beyond VR to real-world motion scenarios.

Abstract— Cybersickness remains a major barrier to the widespread adoption of virtual reality (VR) across professional domains and public acceptance. This work explores semi-random Galvanic Vestibular Stimulation (GVS) as a scene-independent method to mitigate cybersickness by reducing vestibular sensitivity and, consequently, visual-vestibular conflicts. In contrast to prior approaches that align vestibular input with scene motion (e.g., omnidirectional GVS), our method introduces stochastic vestibular disruption without relying on any motion data. We developed a custom VR application with active user control to evaluate semi-random GVS in comparison with a state-of-the-art technique. Results show that semi-random GVS matches the effectiveness of scene-dependent GVS in reducing motion sickness symptoms, while improving practicality by being scene independent. Thereby, its independence from the visual content makes semi-random GVS a robust and broadly applicable solution for VR motion sickness, and potentially for real-world motion sickness scenarios.

Index Terms—Cybersickness, GVS, Motion Sickness, Semi-random Stimulation

1 Introduction

VR technology has made significant advances in recent years, with modern head-mounted displays (HMDs) offering higher resolutions, increased frame rates, and lower latencies. Despite these technical improvements, user acceptance of VR remains limited due to the persistent issue of *cybersickness*. Studies report that between 40% to 70% of users experience symptoms of cybersickness during typical VR use, with some abandoning the technology entirely after a single negative experience [26, 43].

Cybersickness is a subtype of general motion sickness. It is triggered when the visual motion cues that are perceived in the VR display do not match the user's vestibular perception, such as when the camera moves via a game controller while the user remains physically stationary [57]. This sensory mismatch results in a collection of symptoms that are identical to those of classical motion sickness. These symptoms range from mild discomfort, such as blurred vision, oculomotor strain, and dry eyes, to more severe effects, including nausea and disorientation [41].

The exact physiological mechanisms behind motion sickness remain debated, and many theories have been formed. The common sensory conflict theory attributes the sickness to unresolved and unexpected discrepancies between sensory modalities [57]. The postural instability theory posits that prolonged instability in body posture leads to sickness symptoms [59]. Despite their different explanations, most theoretical concepts converge on a central cause: the interpretation discrepancy between incoherent signals from the visual and vestibular systems.

Cybersickness is driven by visual stimuli motion in a (mostly) stationary user, making it an inverse case to conventional motion sickness scenarios, such as seasickness or carsickness, where the vestibular system signals most of the movement. Yet, both share the same underlying principle of sensory conflict. Prior research has shown that cybersickness occurs across a broad range of VR content, including interactive games [25, 66] and 360-degree videos [26, 37], indicating that the issue is content-agnostic.

The most widely adopted countermeasure for cybersickness involves reducing optical flow in the user's peripheral vision to suppress vection—the visually induced sensation of self-motion—which was shown to be the key contributor to cybersickness [3, 7, 25, 26, 42, 62]. This reduced optical flow is typically achieved through peripheral occlusions [7, 17, 42, 62], blurring techniques [26, 29, 43], or, more recently, gaze-

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contingent image warping [23]. However, visual countermeasures can compromise the user's performance or immersion when important scene elements become less visible, e.g., by a reduced FOV [25].

To address these limitations, researchers have recently turned to techniques that enhance the vestibular feedback instead [27, 66]. A promising method is Galvanic Vestibular Stimulation (GVS), which uses low-level electrical currents applied via adhesive electrodes to modulate the activity of the vestibular system. GVS has been shown to effectively reduce cybersickness by artificially aligning vestibular feedback with visual motion cues in VR. Recent approaches, such as the work by Groth et al. [27], even implement omnidirectional stimulation models. The omnidirectional stimulation provides rich vestibular cues based on the full 3D angular velocity of the virtual scene.

However, these methods are fundamentally tied to the visual scene and user head pose. As such, they are not generalizable to real-world motion sickness scenarios, where such information is unavailable or unreliable. A method capable of counteracting motion sickness in arbitrary environments must operate independently of the surrounding scene and any knowledge of user motion.

To this end, we propose a scene-independent approach to mitigate motion sickness by modulating the sensitivity of the vestibular system. Rather than enhancing vestibular signals to match the visual input, our method aims to *desensitize* the vestibular system. This reduction lowers its weight in the brain's sensory integration process. This is achieved by applying semi-random GVS waveforms during exposure to sickness-inducing environments, effectively overriding and disrupting natural vestibular responses. This disruption is temporary and does not prolong beyond the GVS exposure (see Sec. 6). We evaluate our method in a controlled VR experiment designed to elicit cybersickness across a range of motion scenarios. VR serves here as a proxy platform for motion sickness research, offering full control over visual stimuli and allowing for reproducible experimentation. Crucially, the proposed method does not depend on the scene or motion profile, and is thus generalizable beyond VR to traditional motion sickness contexts such as cars, boats, or aircraft. In our study, we compare the effectiveness of the proposed semi-random GVS with a state-of-the-art, scene-dependent method: omnidirectional GVS. Results indicate that our technique significantly reduces cybersickness to approximately half of the control condition, while matching the scene-dependent approach in the metrics.

2 Related Work

We first review the phenomenon of cybersickness and explore mitigation strategies to situate our approach, discuss galvanic stimulation, and examine prior use of GVS for cybersickness reduction.

2.1 Cybersickness and Mitigation Techniques

Cybersickness is a common issue in virtual reality (VR), particularly in user-controllable environments with six degrees of freedom (6 DoF). A range of mitigation strategies has been proposed, which can be categorized into general system and design guidelines, and visual rendering techniques applied during presentation.

2.1.1 General Design and System-Level Recommendations

For the mitigation of cybersickness, the movement design plays a critical role. Accelerated motion leads to the strongest sickness symptoms, followed by linear constant-speed movement. Teleportation, on the other hand, is the least provocative as it eliminates visual motion cues like optical flow [30]. However, non-continuous movements like teleportation were also shown to increase disorientation in users [2].

Reducing latency and ensuring high refresh rates are foundational to cybersickness mitigation. Latency should remain below 20 ms to minimize sensorimotor conflicts [68]. Values under 50 ms are generally perceived as responsive. Refresh rates above 120 Hz have been shown to significantly reduce discomfort without compromising user experience [21, 70].

High graphic realism is another risk factor; stylized graphics with stable frame rates are preferable over photorealism in terms of cybersickness [2, 13]. Exposure duration should be kept below 10–15 minutes when possible, as symptoms tend to increase with time [34, 52].

Camera control should remain user-driven. Forced cinematic movement or scripted cutscenes are known to induce disorientation and should be avoided in interactive applications [26].

2.1.2 Rendering-Based Visual Techniques

A growing number of techniques address cybersickness by manipulating the visual stimulus itself. These approaches primarily target peripheral vision to reduce perceived motion and limit sensory conflict without restricting user interaction.

Opaque occlusions have been used to reduce vection by masking parts of the visual field either statically [7, 42, 62] or gaze-contingently [3, 25, 26]. While effective in reducing cybersickness, these methods often come at the cost of reduced presence and scene awareness.

Blurring of peripheral regions is a less intrusive alternative that acts as a spatial low-pass filter. This technique reduces contrast and high-frequency content, diminishing motion sensitivity in the periphery [26, 29, 55]. Fixed outer regions [43] and object-based filters [48, 49] are alternative methods. Such methods effectively suppress peripheral motion signals. However, they may impair perception in tasks requiring fast reaction or full-scene awareness, such as action-driven games. These limitations might be slightly reduced by using gaze guidance to redirect the user's attention [31, 38, 39] or gaze generation methods for headsets without eye tracking [32].

Learning-based methods for motion field suppression have also emerged. Kaplanyan et al. [33] demonstrated perceptual motion reduction via neural networks, highlighting the potential of adaptive content-aware modulation to reduce vection. However, these methods are prone to visual distortions [11]. In contrast, Groth et al. used controlled noise signals in the periphery to reduce vection [22].

Rest frame designs aim to mitigate cybersickness by introducing stable visual references that align with the user's physical motion to reduce sensory conflicts. Common implementations include head-fixed elements (e.g., virtual noses, glasses) or world-locked overlays [64]. More recently, Nie et al. [50] proposed peripheral teleportation, a dynamic rest frame rendered in the periphery using discretely updated auxiliary cameras. Their study showed significantly reduced discomfort and longer immersion times compared to traditional FOV restrictors, highlighting the potential of rest frames as a viable alternative for VR comfort.

Overall, these techniques exploit known limitations of peripheral motion perception, such as lower receptor density and spatial pooling of ganglion cells [5], to manipulate optic flow without compromising central vision. While some approaches sacrifice visual detail or presence, recent methods focus on subtle, gaze-contingent, and content-aware modulations to reduce cybersickness while preserving the user experience.

Recently, Groth et al. [23] introduced a technique for mitigating cybersickness by applying subtle, gaze-contingent image deformations that reduce vection without compromising scene fidelity. Instead of blurring or masking peripheral content, their method modulates the perceived motion by adjusting object velocities and geometrical size based on eccentricity. Their implementation operates as a real-time post-process, using screen-space warping driven by motion flow and gaze input.

2.2 Galvanic Vestibular Stimulation

GVS is the targeted stimulation of the vestibular system using low-intensity electrical currents [4, 69]. It is a specific form of transcranial direct current stimulation (tDCS), a noninvasive technique widely used in medical contexts such as therapy and tumor treatment [8, 51, 65]. While tDCS typically uses electrodes placed on the scalp, GVS electrodes are positioned on the mastoid processes to directly stimulate the vestibular apparatus. Both tDCS and GVS are considered safe, noninvasive, and cost-efficient when standard protocols are followed [69].

GVS has been used extensively in medical research. Reported benefits include improvements in motor, sensory, attentional, cognitive, and vestibular functions, as well as in the treatment of various neurological and psychiatric disorders [69].

Beyond medicine, GVS has been investigated for interactive applications. Byrne et al. [9] introduced Balance Ninja, a two-player game where players influence each other's balance through GVS. Their findings suggest that GVS can be used effectively as a game design element, with participants showing positive engagement.

Research also shows that GVS can enhance vection, the visually induced illusion of self-motion. Maeda et al. [44] demonstrated that synchronizing GVS with visual stimuli increases vection strength, provided that sensory conflicts are minimized.

Aoyama et al. [6] further explored this concept using a 4-pole GVS system in VR, modulated by a capacitor-resistor circuit. Their results showed that counter-current stimulation strengthens the perception of acceleration, with longer stimulation durations increasing the perceived effect.

Thereby, the most commonly used configuration for GVS is bilateral bipolar stimulation, in which two electrodes are placed on the mastoids. This setup typically elicits a strong roll and a weaker yaw rotation sensation toward the cathode [14, 18]. However, more targeted setups have been proposed that better control the direction of the stimulated movement. Such layouts include 4-electrode setups [6] or 5-electrode configurations when a ground electrode is used [10, 27].

2.3 GVS for Cybersickness Mitigation

The application of GVS to reduce cybersickness in virtual reality (VR) was first explored by Reed et al. [58]. In their study, participants performed a driving task while visual and vestibular stimuli were selectively activated. GVS was manually controlled, yet results already indicated its potential to alleviate cybersickness symptoms.

Subsequent research has employed bilateral GVS, though often without a specific focus on cybersickness [20, 44, 47, 67]. One notable exception is the work by Sra et al. [66], who developed a neck-mounted, two-electrode GVS device synchronized via a mobile app. This setup delivered stimulation along a single predefined axis and resulted in reduced cybersickness and enhanced immersion.

Groth et al. [27] advanced the field by introducing omnidirectional GVS in VR. Using a five-electrode system based on the Oculo-Vestibular Recoupling (OVR) model, they delivered dynamic stimulation aligned with real-time visual motion in 360° video. Two methods were compared: one stimulating the dominant rotation axis and another interpolating across yaw, pitch, and roll. Both approaches significantly reduced cybersickness relative to a no-stimulation control, with the interpolated method offering additional benefits in comfort, session duration, and motion realism. GVS did not adversely affect users who were not prone to cybersickness.

Alternative approaches have also been investigated. Weech et al. [71] demonstrated that bone-conducted vibration can reduce cybersickness, although its efficacy is lower than electrical stimulation [72]. Later, the same researchers investigated the application of fully random electrical noise to the vestibular system to address VR scenarios with unpredictable visual motion [72]. Their investigations showed a reduction in cybersickness severity only for high-intensity VR content. A formal comparison to scene-dependent stimulation models was not provided. Despite this, their results gave important insights indicating that the vestibular function rapidly returns to baseline after the stimulation is suspended.

In comparison, our work proposes a scene-independent GVS technique that deliberately desensitizes the vestibular system by applying semi-random current patterns. Rather than enhancing or mimicking scene motion, our method disrupts natural vestibular input to lower its contribution in sensory integration. Since our method does not rely on scene data or motion tracking, it can be generalized to real-world motion sickness contexts beyond VR.

3 Semi-random GVS

In this work, we propose a novel method that applies a *semi-random* GVS signal, combining a deterministic base with controlled stochastic variability.

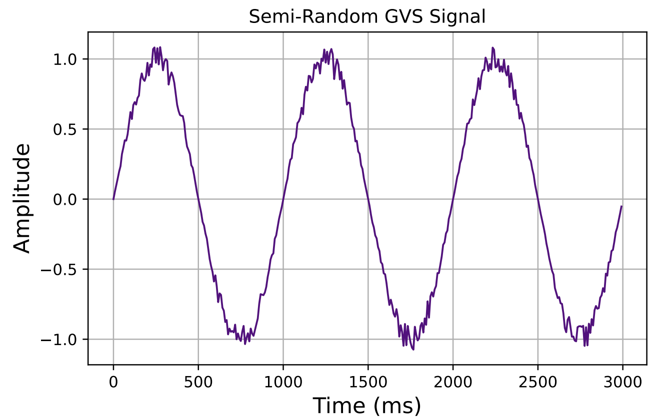

Figure 2: Sample of the semi-random GVS signal. In the experiment, the amplitude is modulated by the individual participant's threshold obtained during calibration.

Motivation and Design. The signal design follows two constraints motivated by prior findings in GVS and sensory stimulation research. First, the signal must maintain a stable temporal structure to avoid abrupt or irregular stimulation patterns. Second, the signal must prevent predictable periodic stimulation that could lead to perceptual adaptation or anticipation.

The first constraint is motivated by observations that purely stochastic GVS signals, such as broadband noise stimulation, can induce unpleasant or distracting sensations in some users [16]. Rapid and irregular changes in current amplitude increase the likelihood of discomfort events during stimulation. For example, a spike in current from $0mA$ to $1mA$. A temporally smooth signal minimizes abrupt changes in current, and allows for a more stable vestibular stimulation profile.

The second constraint follows findings in sensory adaptation research. Repeated periodic stimulation with a fixed temporal structure can lead to neural adaptation or perceptual habituation [15]. In such cases, the response of the sensory system decreases over time because the stimulus becomes predictable [19, 63]. Introducing small stochastic variations reduces the predictability of the signal while preserving the overall stimulation pattern [15].

Both constraints are addressed by our semi-random design: A low frequency sinusoidal signal with a mild stochastic modulation. Specifically, we define the signal as

$$s(t) = \sin(2\pi f t) \cdot \varepsilon(t), \tag{1}$$

where $f = 1\,\text{Hz}$ is the fixed frequency of the sinusoidal base, and $\varepsilon(t) \sim \mathscr{U}(0.9, 1.1)$ is a uniformly distributed random variable sampled independently at each time step. This formulation ensures a periodic structure with mild random modulation in amplitude. Figure 2 shows an example of how the semi-random GVS signal value propagates with time.

The sinusoidal component f defines a smooth and continuous temporal profile of the stimulation without sharp transitions in amplitude. The choice of 1 Hz is physiology-driven: vestibular responses to head motion are strongest in the 0.1–2 Hz range, which corresponds to natural head movements during locomotion [53]. We select 1 Hz as a representative mid-range frequency within this band. The noise term ε introduces small variations in signal strength while preserving the global oscillatory structure. The magnitude of the stochastic modulation is intentionally limited, since it only has to be strong enough to break the strict periodicity and avoid adaptation. Specifically, amplitude variations are restricted to $\pm 10\%$ of the deterministic signal. This limit directly follows common physiological modeling of sinusoidal modulations [28, 60]. We further confirmed these choices in preliminary testing among the authors.

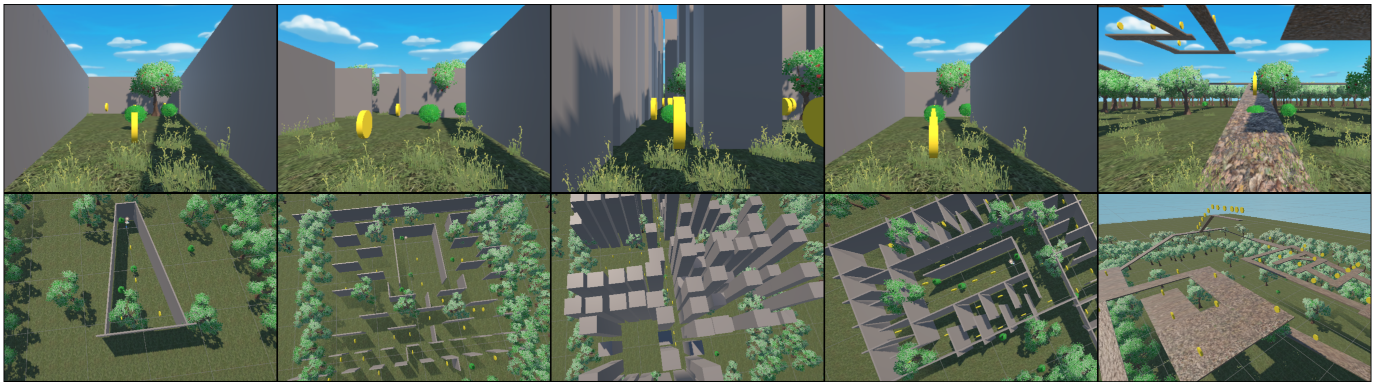

Figure 3: From left to right: Introductory zone, Level 1, Level 2, Level 3, Level 4. The upper row represents the participant's view, while the overview displayed in the lower row is unseen by the participants.

Physiological Mechanisms. GVS injects current across the mastoids that directly modulates the spike-initiation zones (the start region of action potentials) of primary vestibular afferents (sensory nerve fibers) in both canal and otolith organs [40]. Through GVS, the biomechanical sensation of the hair cells, the mechano-transduction, is bypassed. Anodal currents hyperpolarize and reduce firing, and cathodal currents depolarize and increase firing [12]. A key determinant of the effect is afferent regularity: regular fibers fire with low variability and show low responses to currents at high thresholds. Irregular fibers fire with high variability and show large, low-threshold responses. Semi-random GVS can be assumed to predominantly stimulate irregular afferents in both semicircular canals and otolith pathways. The sinusoidal component periodically biases afferent firing (entrainment), whereas the stochastic component elevates response variance and lowers the vestibular signal-to-noise ratio. In a multisensory view, the reduced vestibular reliability triggers sensory reweighting in the brain with down-weighted vestibular cues and up-weighted vision. The dominant effect is functional desensitization during stimulation through reliability loss instead of adaptation.

Distinction from Noisy GVS. Our approach contrasts with *noisy GVS*, which is typically modeled as

$$n(t) \sim \mathcal{N}(0, \sigma^2), \tag{2}$$

where the signal is sampled from zero-mean Gaussian white noise [16, 72]. This fully stochastic signal introduces high-frequency fluctuations that have been reported to cause discomfort, even when the amplitude is limited to only 80% of the individual's perceptual threshold [16]. In contrast, our semi-random method combines deterministic and random elements. This approach avoids unpleasant high-frequency peak signals but retains the noise-like benefits through the variations in $\varepsilon(t)$. Preliminary testing confirmed these observations: participants exposed to noisy GVS experienced unpleasant sensations even with lower signal strength, nullifying potential benefits for cybersickness reduction. In contrast, the semi-random signal was reported as significantly more comfortable. Several participants described the stimulation as a "slight constant pulsating sensation," and in some cases, they even reported no noticeable current.

4 Experiment

We conducted an experiment to investigate how semi-random GVS affects cybersickness for VR gaming content, where the user has full control over their movement. The game was chosen as a representative VR scenario with user-control and similar movement between sessions was engaged through time pressure (see Section 6.4 on a extended discussion of this choice). For the experiment, we chose a within-subjects design. Every participant took part in three sessions, each on a separate day and with at least 48 hours in-between to avoid cybersickness-related carry-over effects. While the virtual environment and task remained the same in every session, the type of GVS stimuli changed on each occasion. These GVS conditions comprise the proposed semi-random stimulation, omnidirectional GVS, and a control condition without stimulation. The order in which the three conditions were applied was counterbalanced using a 3×3 Williams Latin square to control for learning effects. The experiment was reviewed and approved by the university's ethics committee under the identification number <*blind for review*>. Furthermore, we were advised by a physician with direct personal experience with GVS.

4.1 Virtual Environment

We chose a time trial game with score-based collectibles as the VR scenario. For the design of the virtual environment, we focused on both designing mechanics that are likely to evoke cybersickness, and implementing levels that leverage those mechanics with increasing intensity. In terms of VR content, the game comprises a total of four levels and an introductory area at the beginning.

4.1.1 Locomotion and Contradicted Guidelines

To reliably induce cybersickness, the virtual locomotion system was designed to contradict established comfort guidelines. Movement through the environment followed linearly accelerated translation, maximizing visual motion and vection. To further amplify postural instability, exaggerated vertical "head bobbing" was added to simulate real-world gait oscillations. Teleportation-based movement was excluded. For rotation, continuous angular motion was directly mapped from raw joystick input, avoiding step-based methods like snap-turning that are known to reduce sickness. Both translation and rotation speeds were configured at high, discomfort-inducing levels to ensure a strong and consistent cybersickness response as a baseline. Furthermore, we include high-frequency content like grass to improve the perception of vection [56, 61].

4.1.2 Level Design

The experimental environment was constructed to systematically violate established VR design principles, with the explicit goal of inducing cybersickness at increasing intensity. The sequence consists of an introductory zone followed by four levels, each escalating in sensory conflict and instability (see Figure 3).

The **introductory zone** allowed the participants to acclimate to VR. Participants familiarize themselves with the virtual environment, the GVS stimulation, and the control scheme in a small, open area without time pressure or strong sickness triggers.

Level 1 introduced the first discomfort stimulus by encouraging frequent rotation. Although relatively open, strategically placed view-blocking obstacles force participants into continuous turning.

Level 2 increased visual motion and spatial compression. Tall, densely arranged objects form narrow corridors, enhancing the sensation of rapid motion and limiting visual stability.

Level 3 focused on repeated, alternating turns. The layout consists of a single path with tightly spaced left–right direction changes, promoting

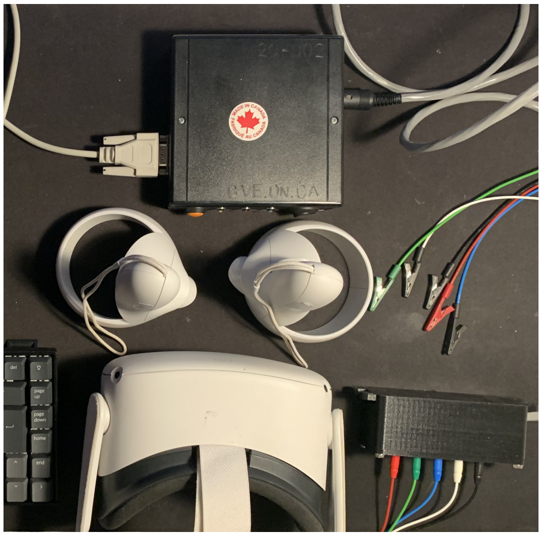

Figure 4: Vestibulator and HMD.

frequent rotational input and disrupting postural control.
Level 4 added vertical motion by integrating ramps and elevation changes into the layout. The level structure ensures continuous movement across varying altitudes. All surrounding walls were removed to amplify the perception of height and induce a sense of vertigo. Although falling from the platforms is not possible in the game, participants are unaware of this constraint, further contributing to perceived instability and discomfort.

4.2 Conditions

We investigate three different conditions to assess the GVS's impact on cybersickness: semi-random stimulation, omnidirectional GVS, and a control condition to establish a baseline. All GVS signals were generated at runtime.

4.2.1 Control

In the control condition, no electrical current was applied. Participants wore the GVS device with electrodes attached and underwent the standard calibration procedure, but the stimulation remained inactive throughout the experiment. Participants were not informed that no current would be delivered, maintaining the same expectation of stimulation across all conditions.

4.2.2 Omnidirect

The omnidirectional GVS condition served as a scene-dependent baseline for active vestibular stimulation. For this condition, the strength of the current was dynamically modulated based on the participant's translational and rotational movement inputs. Specifically, the current ranged from $0mA$ when there were no inputs to the maximum current established during calibration, when movement or rotation inputs were at maximum speed. The signals were directionally consistent with the perceived motion and implemented based on the model proposed by Groth et al. [27], assuming full access to scene motion data. This means that all motion inputs were merged into a unified stimulation signal, considering both the direction and speed of the participant's movement.

4.2.3 Semi-random

In the semi-random GVS condition, a stochastically varied sine signal was continuously applied during the entire VR exposure. Unlike the omnidirectional method, this stimulation was not linked to the participant's movement or scene dynamics.
To account for the higher frequency of stimulation events and the high efficiency of semi-random GVS, the current amplitude was limited to 60% of each participant's calibrated maximum.

4.3 Measurements

We analyzed participant feedback using the simulator sickness questionnaire (SSQ) [35] and the Fast-Motion Sickness scale (FMS) [36]. The behavior of the participants was analyzed based on the linear acceleration and angular velocity of the participants in the virtual environment over the duration of the experiment. The performance of each participant during the experiment was measured by logging the number of coins gathered per level. Lastly, small interviews took place after each session for subjective insights of the participants.

4.3.1 SSQ

The Simulator Sickness Questionnaire (SSQ) is a widely used method for measuring cybersickness [35]. It works through self-assessment of the participant on a series of cybersickness symptoms and their severity (scale 0 to 3). Following common procedure, we let participants fill in the SSQ once before and after each session, to counteract any difference in the daily conditions. The total sickness score as well as the corresponding subscores of the SSQ are calculated according to the original procedure of Kennedy et al. [35].

4.3.2 FMS

The Fast-Motion Sickness (FMS) scale was administered during the experiment session itself [36]. With the FMS, we aim to measure temporal changes in the discomfort of the participant. In regular intervals, participants were asked to rate their self-assessed sickness severity level on a scale from 0 (no sickness) to 20 (extreme sickness). This value was recorded once after each level was finished, so approximately once every 90 seconds for a total of 5 times.

4.3.3 Movement data

Objective virtual movement data, including linear acceleration (m/s^2) and angular velocity (degrees/s), were recorded continuously during each session of the experiment. These metrics are used to identify changes in the participants' motion patterns that could be linked to cybersickness or general discomfort.

4.3.4 Task performance

Each level of the experiment contains a certain number of coins and lasts at most 90 seconds. The ways in which a level can end are either collecting all the coins, or letting the 90 seconds run out. We collected data showing how many coins per level were gathered, and how much time (if any) was left on the timer at the end of the level.

4.3.5 Post-session interviews

After each session small interviews provided subjective insights on their perception of cybersickness and the GVS. Participants rated and described their impression of the GVS stimuli and whether the stimuli felt synchronized with their movements. They also identified specific discomfort triggers. The explicit questions were the following:

[Q1] Were the electrical stimuli noticeable, bothering, or unnoticeable?

[Q2] Were the electrical stimuli helpful, neutral, or distracting for the VR experience?

[Q3] When did you feel most and least comfortable? Please describe the situation.

[Q4] Did you notice any connection between your movements and the electrical stimuli?

4.4 Hardware

The experiment was conducted with a specialized GVS device, a Meta Quest 2 HMD, and a Dell XPS 17 Laptop (see Figure 4). The game was implemented in Unity.

4.4.1 GVS Device

We use the Vestibulator GVS device from Good Vibrations Engineering [1]. It has four current outputs and one ground electrode. The device, by design, is only able to generate low-intensity electrical currents, ranging from -2.5mA to 2.5mA. Therefore, the current output is kept within a range safe for human use. For further safety, the device is designed to prevent any unintended power transmission by operating on battery power and using air-gapped fiber optics for data communication. Adhesive electrodes measuring 13×16 mm are used to attach the GVS to the participants. The vestibulator offers the possibility of controlling the device in real-time through the serial port, with a latency of less than 15ms.

4.4.2 HMD

A Meta Quest 2 headset was used for the experiments, with an FOV of approximately 90° and a refresh rate of 90 Hz. The device features a resolution of 1832 × 1920 pixels per eye.

4.4.3 Computer

A Dell XPS 17 laptop, with 32GB RAM, an NVIDIA 2060 GPU with 6GB VRAM, and an i7-10875H CPU was used to handle the simulation for the experiment, the tracking of data, and the interface between the devices. From the laptop, both the GVS and the Quest2 were connected by cable.

4.5 Participants

We recruited participants with a variety of different backgrounds, ages, genders, and VR experiences. The group consisted of 8 females and 19 males, with an age range of 24 to 65 (age average = 37.89, SD=11.36). A total of 27 participants completed all three sessions. The order in which the three sessions took place was counterbalanced. The experiment followed a full within-subjects design.
To ensure safety above all, each potential participant underwent a medical pre-screening to exclude anyone with a disqualifying condition. These disqualifying conditions included: Pregnancy, underage status, head implants, or neurological/vestibular disorders.

4.6 Procedure and Task

Every participant underwent three sessions with one of the conditions each (control, omnidirect, and semi-random) in counterbalanced order. The procedure and task of each session were the same and consisted of the following four subsequent stages:
1. Pre-Session Phase: After signing an informed consent form, passing a medical prescreening, and receiving a verbal explanation of possible side effects of the GVS, participants completed the pre-exposure SSQ to establish their baseline for the day. The GVS was then attached via adhesive electrodes to both mastoids behind the ear, on the forehead, and two in the neck (one stimulation electrode and one ground electrode), following the setup of Groth et al. [27].
2. Calibration: For all conditions, including control, we then ran a calibration of the GVS, following the procedure of Groth et al. [27]. With the participants having their eyes closed, the current was incrementally increased in small steps starting from 0 mA. Participants were instructed to report their sensations continuously. As soon as the participants reported a "noticeable but acceptable" sensation from the stimulation, this value was chosen as the experiment's maximum current. This maximum current, by design of the vestibulator, cannot be over 2.5 mA. The control condition followed the same calibration routine to promote unbiased results, but no stimulation was delivered during the control trials. Once calibration was finished, the headset was given to the participants and adjusted.
3. VR Exposure: The exposure began with the initialization phase to allow participants to acclimate to the virtual environment. Here, participants had no time pressure and could decide by themselves when to move on. After that, participants navigated four progressively provocative levels (approximately 7 minutes total), collecting coins under time pressure. During navigation, their linear acceleration and angular velocity were tracked continuously. FMS scores were recorded after each level (at least every 1.5 minutes) via verbal prompts (0 = no issues; 20 = extreme sickness).
4. Post-Session Phase: Directly after the VR exposure, the post-exposure SSQ was administered to quantify the symptoms. Afterwards, participants underwent a small interview inquiring about GVS perceptibility and providing comparative information across conditions in the case that they performed the last session.

5 Analysis and Results

We performed a statistical analysis to evaluate the effect of the three within-subject conditions (control, omnidirect, semi-random) on cybersickness. Shapiro–Wilk tests were non-significant ($p > 0.05$); therefore, the normality assumption was accepted. We then conducted a repeated-measures ANOVA on the SSQ scores of 24 participants. We excluded the results of three participants who terminated sessions due to severe sickness symptoms. Still, their exposure times differed substantially between conditions and were subjected to a small separate analysis.

Figure 5 shows that both active GVS conditions (omnidirect and semi-random) produced substantially lower SSQ scores than the control condition. On average, both conditions reduced the SSQ score by approximately half. The FMS scores (Figure 6) show a similar pattern. The control condition produced a stronger escalation of symptoms, whereas omnidirect and semi-random showed flatter trajectories (Tab.3). The differences increase in later levels, that is, after longer exposure times. These trajectories indicate improved sustained comfort. Table 2 reports the SSQ results for each participant.

The ANOVA confirmed statistically significant differences across conditions $F(2,46) = 12.7, p < 0.0001$. The analysis also revealed a large effect size $\eta^2 = 0.1$. Post-hoc Bonferroni-corrected pairwise comparisons helped us identify the conditions with strong effects: both directional ($T = 18.4$, $p < 0.001$) and semi-random GVS ($T = 16.3$, $p < 0.001$) significantly outperformed control. No significant difference is present for comparing omnidirect and semi-random ($T = 0.02$, $p = 0.88$). To quantify the strength of the observed effects Cohen's d was calculated between the significant pairs: Semi-random to control ($d = 0.824$), and omnidirect to control ($d = 0.874$). The Cohen's d's establish a strong effect for both cases ($d > 0.8$). This statistical analysis, together with the SSQ and FMS trends, strongly supports the use of active GVS to mitigate cybersickness in user-controlled VR environments.

The analysis of behavioral metrics, linear acceleration (m/s^2) and angular velocity ($degrees/s$), revealed no statistically significant differences across conditions. Participants exhibited similar motion patterns within all sessions, regardless of stimulation type. This finding suggests that GVS did not measurably alter movement behavior and primarily exerted a passive effect on participants. Task performance metrics, including coins-per-minute ($\bar{X}_{Control} = 18.8, \bar{X}_{Omnidirect} = 18.4, \bar{X}_{Semi-Random} = 18.7$) and level completion times ($\bar{X}_{Control} = 78.5s, \bar{X}_{Omnidirect} = 78.1s, \bar{X}_{Semi-Random} = 78.4s$), also showed negligible variation between conditions. With no statistical difference between conditions, the consistency of these results suggests that GVS had no negative effect on motor control or task execution.

In the interviews, participants consistently reported that the electrical stimulation was noticeable but neither disturbing nor painful for both GVS conditions (omnidirect and semi-random) `[Q1]`. An interesting difference emerged when comparing both GVS conditions. In 8 of the semi-random interviews, participants reported that the sensation of stimulation became less noticeable or unnoticeable after the first couple of minutes. This behaviour was not reported for any of the omnidirect experiments `[Q1]`. Thereby, the scene that evoked the highest feeling of discomfort was the third scene, which involved frequent and rapid yaw rotations `[Q3]`. This finding is consistent with previous work identifying rotational motion as a primary trigger for cybersickness [27]. Regarding the impact of GVS on the VR experience, in 46 out of 54 interviews, the stimulation was rated as neutral. In six cases, it was found beneficial for the VR experience, all of whom were in the omnidirectional GVS condition `[Q2]`. In the two remaining interviews, the impact of the GVS on the VR experience was rated as negative. These responses came from a single participant who was unable to

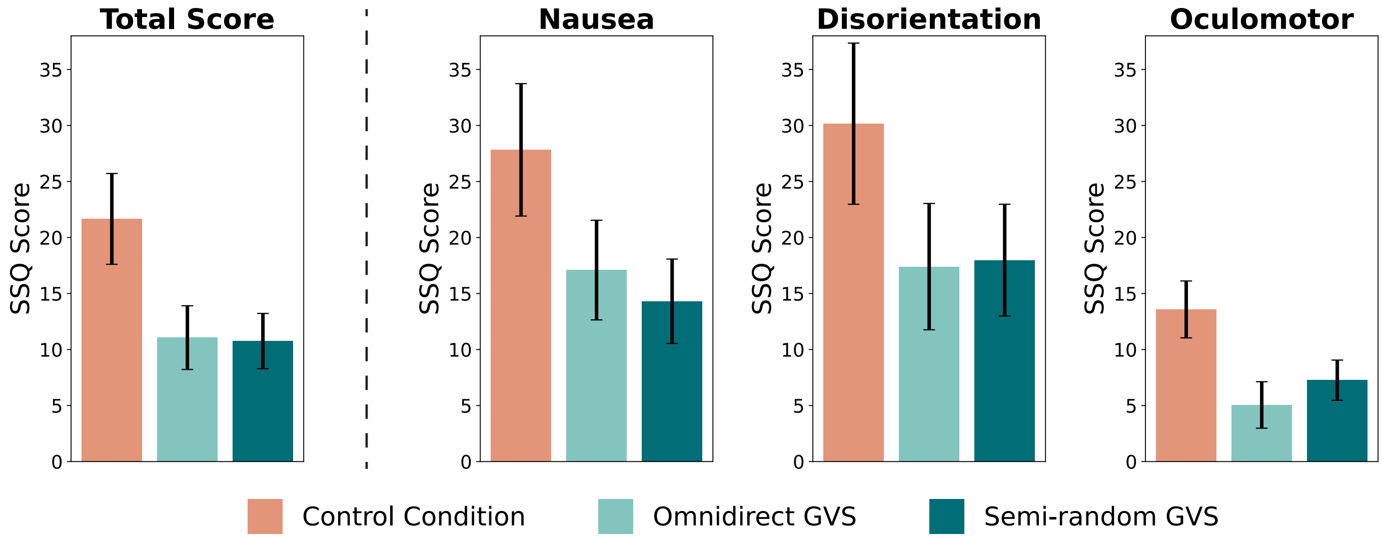

Figure 5: Illustration of the average SSQ results (N=24). We compare a control condition (control) and the state-of-the-art directed GVS condition (omnidirect) to our proposed semi-random GVS stimulation approach without scene knowledge (semi-random). The error bars represent the standard error of the mean (SEM).

Table 1: Duration of exposure to the VR experience, from the three participants who withdrew during some sessions, due to severe sickness symptoms. Times in seconds.

Participant ID	Semi-random	Omnidirect	Control
25	384	204	143
26	217	390	121
27	240	32	123
Average	**280.3**	**208.6**	**129**

complete any of the three sessions. Nonetheless, the participant was able to stay remarkably longer in the VR experience when the GVS stimulation was active compared to the control session. Participants did not report any noticeable correlation between their movements and the semi-random stimulation, while they did for the omnidirectional stimulation [Q4].

As previously mentioned, three participants withdrew from some sessions due to severe sickness symptoms. We compared the duration of their exposures separated by condition, and found significant differences regarding the GVS's effectiveness in delaying symptom onset. An average session lasted approximately 390 to 420 seconds, mainly depending on how long the participant stayed in the introductory level. As seen in Tab. 1, the sessions of the three quitting participants are significantly shorter in most cases. An analysis of their average exposure time for each condition shows that the duration of the control experiments was significantly shorter than both GVS conditions in the experiment, with less than half the time.

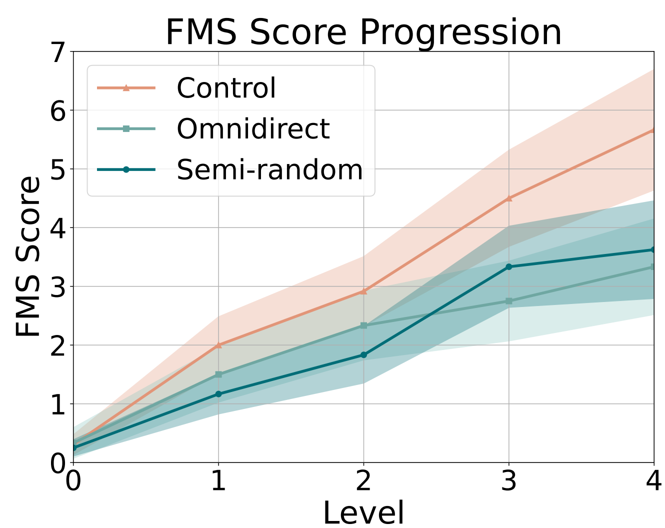

Figure 6: The FMS results over consecutive levels. Values were reported in 90-second intervals. Higher values indicate greater sickness symptoms. The error represents the SEM.

6 Discussion

In the following, we will discuss the implications of the results regarding ethical questions, broader applicability and other approaches.

6.1 Ethical Considerations

The use of semi-random GVS to reduce motion sickness in VR and real-world contexts introduces important ethical considerations. Current scientific evidence supports the safety of GVS when applied at moderate currents (≤ 2.5 mA) in healthy individuals [8, 69]. In particular, the large-scale analysis by Brunoni et al. [8] on over 200 tDCS studies (of which GVS is a subset) found that adverse events were infrequent and mild, with no serious incidents reported. These findings are consistent with our own observations. All side effects were temporary, limited to minor skin irritation or brief disorientation, and resolved immediately after stimulation. All experiments were short in duration (≤ 10 minutes), reviewed and approved by an ethics board, and supervised by a medical expert with relevant qualifications.

Despite this, care must be taken when considering the broader use of GVS beyond controlled laboratory settings. While the mechanism is non-invasive and well understood in the short term, there is limited data on long-term or frequent exposure. Applications that aim to suppress vestibular sensitivity may interfere with natural balance regulation if used excessively or without proper supervision. Although the technology has strong potential to reduce sickness symptoms, particularly in artificial environments like VR, its use in everyday motion scenarios remains an open area of investigation. Responsible deployment should acknowledge these limitations while continuing to prioritize user safety and informed participation.

Table 2: Total SSQ score per participant. Sessions denoted by * were withdrawn. Negative numbers indicate that a participant felt slightly better after the experiment than before (which may be considered statistical noise).

Participant ID	Semi-random	Omnidirect	Control
1	3.74	0.00	7.48
2	3.74	3.74	11.22
3	3.74	3.74	14.96
4	0.00	3.74	11.22
5	14.96	26.18	48.62
6	3.74	11.22	18.70
7	0.00	0.00	0.00
8	18.70	18.70	33.66
9	3.74	14.96	26.18
10	-14.96	-7.48	-3.74
11	18.70	22.44	37.40
12	14.96	-3.74	11.22
13	11.22	-3.74	18.70
14	0.00	0.00	3.74
15	11.22	33.66	14.96
16	14.96	7.48	11.22
17	7.48	33.66	52.36
18	29.92	29.92	33.66
19	0.00	0.00	0.00
20	22.44	14.96	14.96
21	41.14	41.14	71.06
22	7.48	-3.74	7.48
23	11.22	3.74	14.96
24	29.92	14.96	59.84
25	71.06	153.34*	127.16*
26	127.16*	127.16	119.68*
27	97.24*	71.06*	82.28*

Table 3: FMS score differences induced by individual game levels. Values represent the change in score from the previous level (e.g., Level 3 value = Score Level 3 − Score Level 2).

Condition	Level 0	Level 1	Level 2	Level 3	Level 4
Control	0.30	1.70	0.92	1.58	1.17
Omnidirect	0.33	1.17	0.83	0.42	0.58
Semi-Random	0.25	0.92	0.67	1.50	0.29

6.2 Omnidirectional vs. Semi-random GVS

Both GVS conditions tested in this study (omnidirectional and semi-random) led to significantly reduced cybersickness symptoms compared to the control condition. These findings are consistent with prior research demonstrating the effectiveness of GVS as a method for enhancing comfort in VR environments [27, 66].

Comparing semi-random GVS and omnidirectional GVS directly, no statistical evidence is present in the SSQ and FMS results that indicates a difference in effectiveness. However, given the participants' responses to Q4, the mode of action of the methods is clearly distinct. We consider the comparable effectiveness a very promising result, given the fact that the motion patterns were fully unknown for semi-random GVS, while they are required for the omnidirectional method [27]. It is important to note that omnidirectional GVS modulates vestibular feedback based on virtual rotational motion. However, it does not directly address conflicts arising from linear accelerations. In contrast, semi-random GVS disrupts vestibular signals more generally, which can also mitigate conflicts caused by linear movement patterns common in VR experiences. In our experiment, we provoked many rotations as they are known to cause strong cybersickness responses. For scenarios that mostly feature linear accelerations, semi-random GVS might be more suitable.

However, in VR environments where full control over the visual scene, head orientation, and motion parameters is available, omnidirectional GVS may offer advantages. By reinforcing consistent multimodal cues, it supports the alignment of visual and vestibular feedback. This coherence has been shown to enhance presence and immersion in virtual environments, as consistent multisensory integration is a key contributor to perceived realism and immersion [24, 45]. In such controlled VR setups, the facilitation of sensorimotor congruence may outweigh the benefits of general desensitization. In other scenarios, particularly where motion information is unavailable, unreliable, or where the environment cannot be fully controlled, semi-random GVS is preferable. Its independence from external tracking and scene-specific parameters enables robust application across a wide range of VR and real-world motion sickness contexts.

For both stimulation types, proper calibration was essential to ensure the method's unobtrusiveness and effectiveness. Users exhibit highly individual sensitivity thresholds, and personalized adjustment of the stimulation intensity was necessary to avoid discomfort while maintaining the effectiveness of the effect.

6.3 Comparison with Visual Approaches

Most existing cybersickness mitigation techniques act directly on the visual signal [23, 26, 50]. These approaches often exploit gaze-contingent rendering or localized visual manipulations, which require precise eye-tracking to remain subtle and effective. However, many consumer devices still lack reliable eye-tracking hardware, and in general motion sickness scenarios outside VR (e.g., cars, boats, or airplanes), manipulation of the visual scene is not possible at all.

In contrast, semi-random GVS provides a more generalizable solution. Its independence from the visual stimulus enables application across a wide range of contexts where visual access is either unavailable or impractical. Direct comparison with visual techniques is limited by the available data. Yet, the reduction in SSQ scores relative to the control condition indicates that the performance of semi-random GVS might be on par with current state-of-the-art visual methods. However, further systematic studies are required to establish whether semi-random GVS can consistently match or exceed visual interventions under controlled conditions.

6.4 Game-Based Validation vs. Fixed-Path Scenarios

Using a coin-collection game for validation introduces a semi-controlled environment that differs from fully-controlled fixed-path experiments, such as rollercoaster simulations or prerecorded videos. Unlike passive viewing, our game scenario requires participants to actively navigate and perform tasks under time pressure, creating consistent and uniform motivation across sessions. We argue that this objective ("collect as many coins as possible in the given time") better standardizes participant engagement and allows for measuring cybersickness under naturalistic interaction. At the same time, the coin collection maintains comparable motion activity through the strict time pressure, as the requirement to maximize coin acquisition drives participants into fast movement patterns and velocities. In contrast, in fixed-path experiments, participants often exhibit high engagement during initial exposure but engagement decreases significantly in subsequent sessions, as the content is shown repeatedly. Such change in engagement may confound multi-session cybersickness data.

Furthermore, user control is itself a common requirement in VR applications. Because user-directed navigation is common in VR, using an active control scenario allows to better investigate the relationship between intended and perceived motion of the user. We hope that through this methodology, the findings are more generalizable to real-world VR usage than results derived from restrictive, non-interactive environments.

6.5 Generalization to Motion Sickness

The results of our study demonstrate that semi-random GVS significantly reduces cybersickness symptoms in virtual reality environments. The underlying mechanism of vestibular desensitization demonstrates potential as a foundation for generalizing the technique beyond VR. However, with our current study generalization may be affected by the gender imbalance in our participant sample (8 females, 19 males). To confirm generalization, more studies are necessary, addressing the gender imbalance. We consider the generalizability of this technique highly relevant, as both cybersickness and classical motion sickness stem from sensory conflicts, particularly between visual and vestibular signals. Although the direction of the conflict differs (visual over vestibular in VR, vestibular over visual in real-world motion) the physiological and perceptual mechanisms are closely aligned [46, 54].

Prior approaches, e.g., by Groth et al. [23, 27], attempt to resolve the sensory mismatch by generating output that considers the exact visual motion. These approaches depend on detailed knowledge of the scene, head orientation, and motion parameters, making them unsuitable for real-world applications where such data is unavailable or unreliable. In contrast, our method eliminates this dependency by reducing the coherence of vestibular signals through semi-random stimulation. This interference lowers the reliability of the vestibular input during multisensory integration, thereby reducing the perceived sensory conflict.

Because the method is scene-agnostic and does not rely on motion data or environmental context, it would be of interest to study in a broader range of motion sickness scenarios. The principle of vestibular desensitization remains effective irrespective of the direction or origin of motion. This makes an application in conventional motion sickness contexts such as car travel, maritime transport, or aviation interesting. Thus, a compact and portable GVS device could be employed to reduce motion sensitivity during critical events such as airplane takeoff or landing to improve user comfort and perceived quality of travel.

In this study, VR was used as a controlled test environment to validate the proposed method under reproducible conditions. Given the substantial reduction in cybersickness in these experiments, we hypothesize that semi-random GVS can also mitigate motion sickness in non-visual contexts. In future work, we plan to confirm these assumptions.

6.6 Limitations

The parameters of the stimulation were chosen based on physiological plausibility rather than empirical optimization. The base frequency of 1 Hz lies within the dominant range of natural vestibular stimulation during typical head and body motion and therefore provides a smooth and realistic temporal structure. However, this value should not be interpreted as an optimal parameter. Different frequencies may lead to stronger or more robust effects. They could also further increase the achievable threshold. The same limitation applies to the stochastic modulation term. The $\pm 10\%$ amplitude variation was selected as a conservative bound that preserves the global sinusoidal structure while introducing variability. Other modulation magnitudes or noise models may lead to improved stimulation characteristics. Future work could systematically explore the parameter space of base frequency and stochastic modulation to identify more effective stimulation profiles.

Given the unequal gender distribution in our experiment, the influence of gender on the susceptibility to cybersickness and the efficacy of semi-random GVS, particularly in female participants, remains unclear. Although prior studies have reported gender differences in motion sickness sensitivity, we were, unfortunately, unable to recruit a balanced set of participants. This limitation was primarily due to constraints in participant acquisition, as compensation could not be offered for participation.

Another limitation lies in the duration of the VR exposure scenarios. The current study employed relatively short sessions to ensure participant safety and comfort. However, it remains unclear how the observed benefits of semi-random GVS scale with longer or repeated exposures. Prolonged use may introduce adaptation effects, altered symptom dynamics, or delayed after-effects that were not captured in the current evaluation.

Finally, although the technique proved successful in mitigating cybersickness, its impact on users' feelings of presence remains undetermined. While traditional GVS approaches aim to reinforce naturalistic vestibular cues and may enhance the sense of presence [27], the desensitizing nature of semi-random stimulation could potentially interfere with perceptual realism. While the interview did not indicate a reduced presence, future studies should systematically assess the trade-off between cybersickness reduction and presence to determine the optimal balance for different use cases.

7 Conclusion

This work introduces a scene-independent method for reducing motion sickness through semi-random GVS. Unlike prior approaches that require visual scene or motion information, the proposed technique desensitizes the vestibular system to reduce sensory conflict. Our results demonstrate a substantial reduction in cybersickness symptoms in VR with comparable performance to motion-dependent approaches. The method demonstrates high efficacy and independence from environmental input. Consequently, it demonstrates great potential for generalization across both VR and real-world contexts.

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