Evaluation of a Galvanic Vestibular Stimulation System to Reduce Cyberscikness in Virtual Reality

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***Abstract* — This work presents the evaluation of a Galvanic Vestibular Stimulation (GVS) system designed to reduce cybersickness and enhance the sense of immersion during Virtual Reality (VR) exposure. The system integrates a dual-channel Howland current source, an ESP32-based control platform, and embedded safety mechanisms to ensure compliance with established safety guidelines. A complete experimental protocol was developed and applied within the Virtual Reality Substation Laboratory (VRSL), combining technical validation and a user-based evaluation with 20 participants. The results showed that prior exposure, without an adequate washout period, can affect the effectiveness of the stimulation and, consequently, the severity of cybersickness symptoms. Overall, the findings support the preventive potential of controlled vestibular stimulation for mitigating cybersickness and improving user comfort during VR immersion.**

Keywords- Cybersickness; Galvanic Vestibular Stimulation; Virtual Reality; Motion sickness; Washout;

I. INTRODUCTION

This section presents the background and motivation for investigating Galvanic Vestibular Stimulation (GVS) as a potential approach to reducing cybersickness in Virtual Reality (VR).

A. State of the Art in Galvanic Vestibular Stimulation and Virtual Reality Immersion

In recent years, the use of VR has expanded rapidly, beyond video games, VR is now used for professional training, simulation, education [1], rehabilitation and remote collaboration. In the entertainment field, VR has transformed user interaction by providing highly immersive and realistic experiences. However, despite its potential benefits the exposure to VR environments has been associated with certain side effects, supporting the hypothesis that VR may induce a conflict between sensory and spatial integration [2]. Simón-Vicente *et al.* [2], through a systematic review, reported that the most frequent symptoms following VR immersion are disorientation, nausea, and oculomotor disturbances.

The most widely accepted hypothesis regarding the origin of these symptoms is that they result from a mismatch between sensory and spatial integration, in which the user perceives motion visually while the vestibular system signals no corresponding movement [3]. The term commonly associated with these symptoms in VR is cybersickness, traditionally considered a form of visually induced motion sickness that occurs when sensory information and internal predictions about orientation and self-movement are inconsistent [4].

To explore whether it is possible to physically mitigate this issue, it is necessary to consider the vestibular system, the sensory organ responsible for spatial orientation and balance. The vestibular nerve transmits information about self-motion and orientation relative to Earth's gravity from the vestibular organs (the semicircular canals, saccule, and utricle) to the brain [5].

As proposed by Weech *et al.* [6], the addition of noisy Galvanic Vestibular Stimulation (nGVS) to the vestibular system can reduce vestibular reliability, thereby decreasing the conflict between sensory and spatial cues. When processing sensory information, the brain re-weights these inputs, assigning greater trust to visual self-motion cues rather than to the vestibular information [7]. This mechanism suggests that controlled vestibular stimulation could enhance the sense of immersion by reducing cybersickness during VR exposure.

B. Objectives and Contributions of the Work

The main contribution of this work is to validate a GVS system. This system is designed to enhance the sense of immersion and to avoid cybersickness in a VR environment, specifically in a medium-voltage substation simulation, which will be further explained in the next section. The proposed system aims to stimulate the vestibular system in a controlled and safe manner, with the goal of reducing the symptoms of cybersickness.

To provide a clear overview of this work, the remainder of the paper is organized as follows. Section II describes the development of the GVS system, while Section III presents the VR environment used in this study. Section IV details the experimental methodology and evaluation procedures, and Section V presents the results and discussion. Finally, Section VI provides the conclusions and future perspectives.

II. Design and Development os the Galvanic Vestibular Stimulation System

This section details the technical development of the proposed GVS system, including its hardware architecture, safety mechanisms, and software implementation.

A. *System Specifications and Hardware Architecture*

The general concept of the circuit is a voltage-to-current converter, commonly known as a *Howland Current Source* [9], and seen in Figure 1. In this work, the converter is integrated with an ESP32 microcontroller and a broader electronic circuit to ensure precise signal control and amplification.

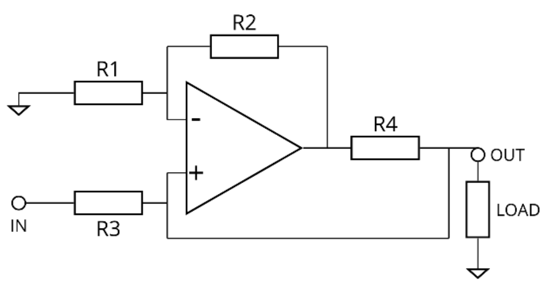


Figure 1. Howland Current Source

The system responsible for generating GVS stimulation is composed of two primary components:

- an ESP32 microcontroller responsible for digital control and generating voltage signals.
- two independent Howland current sources capable of generating distinct signal types across the electrodes.

The setup allows for the connection of the electrodes to the participant. Different GPIO (General-Purpose Input/Output) ports of the ESP32 are used to independently control each Howland source and, consequently, each pair of stimulation electrodes (active electrode – reference electrode).

As highlighted by Liu *et al* [10], previous work often provides insufficient technical information for reproducibility and rarely reports detailed rigorous performance assessments. Although a known circuit topology was employed, our implementation differs from others, such as the one proposed by Liu *et al.* [10], by including two protection mechanisms: one electrical and one software based. These safeguards ensure that the user does not experience any leakage current either during power-up or operation.

Regarding user safety, circuit design follows the guidelines proposed by Antal *et al.* [11], which recommend limiting the current output to ±4 mA. In this work, the system restricts the output to ±2.6 mA. Several studies have reported variations in human impedance between the mastoids [10], which depend on factors, such as electrode placement, physiology, and tissue moisture. To ensure the feasibility and reliability of the system under this variability, the electronics were designed to adapt to impedances of up to 9 kΩ.

B. *Software Implementation and Code Development*

The software architecture for GVS stimulation was developed to control the key features of the signals, including amplitude, frequency, and waveform type. The ESP32 microcontroller was programmed using the PlatformIO extension in VS Code, which offers greater flexibility for integrating both analog and digital control functions. The firmware manages the active electrodes independently, enabling the generation of simultaneous stimulation patterns across the user's vestibular system.

To make the system more practical and functional, both during testing and in future industrial applications, such as the commercialization phase, a dedicated application was developed to provide a visual and user-friendly interface for programming the stimulation parameters.

As part of the data collection process, an Inertial Measurement Unit (IMU) was incorporated to capture movement data. Specifically, the MPU6886 sensor was used, which integrates a 3-axis gyroscope and a 3-axis accelerometer, both equipped with a 16-bit Analog-to-Digital (ADC). The IMU was programmed using the Arduino IDE to control data acquisition and analyze how body sways varied across the axes. The sensitivities were configured as:

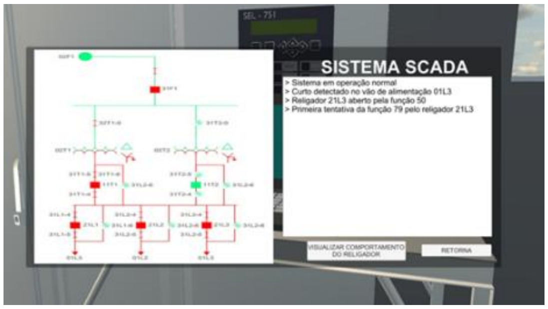
- Gyroscope Sensitivity: 32.8 LSB per °/s (with a ±1000 °/s range)
- Accelerometer Sensitivity: 4096 LSB per g (with a ±8 g range).
- The sampling frequency was set at 200 Hz, following the approach described by Goel *et al*. [8].

III. Description of the Virtual Reality Application

For these tests, the software "Virtual Reality Substation Laboratory (VRSL)" [1] was used. It was developed by the Smart Electrical Grids Laboratory (GREI) at the Federal University of Ceará (UFC). The software was designed to accurately reproduce the power distribution substation located on the UFC campus. The virtual environment is composed of two main areas:

- Outdoor Yard: Users can visualize and interact with various components, such as current transformers, potential transformers, and other equipment, as shown in Figure 2c.
- Control House: Users can access the protection and automation panels, which include interactive components and graphical interfaces displaying real data acquired from the physical substation.

All interactions are performed in first-person mode using a VR headset. Users can explore the environment through three different modes of navigation: Walking using console controls; Flying through the area using an integrated drone; Watching simulations of real operational events and accidents within the substation (as shown in Figure 2a).



(a)


(b)


(c)

Figure 2. Virtual Reality Substation Laboratory (VRSL) interface. (a) View of simulation, (b) Done-mode navigation, (c) First-person view

The VRSL software was selected because its three distinct modes of navigation (walking, video playback, and drone flight) offer a wide range of motion experiences for the user. To ensure proper operation with the system, the software requires a computer and a VR headset meeting the recommended specifications in Table I.

TABLE I. RECOMMENDED HARDWARE SPECIFICATIONS

Component	Specification
RAM Memory	16 GB DDR4
Graphics Card	4 GB
Processor	Intel i5-13450HX
Storage	256 GB SSD
VR Headset	Meta Quest 3

IV. EXPERIMENTAL METHODOLOGY AND EVALUATION PROTOCOL

This section presents the experimental results and discusses their implications for immersion tolerance and cybersickness reduction.

A. *Creation of the Experimental Protocol*

During the development of the experimental protocol, two main research questions were defined:

- Does the use of GVS stimulation improve the sense of immersion?
- Can the combination of GVS stimulation with a VR headset reduce symptoms of cybersickness?

To address these questions, five questionnaires were selected to ensure comprehensive data collection. First, a health questionnaire was administered to identify any pre-existing medical conditions or regular medication use. Participants reporting relevant health issues were excluded from the experiment to ensure that only healthy individuals were tested.

The System Usability Scale (SUS), developed by Brooke in 1986 [12], consisting of ten items, was used to evaluate participants' perceptions of the overall system, in this case, the VRSL and the Stimbox. Additionally, the Simulator Sickness Questionnaire (SSQ) [13] was applied to measure the level of sickness symptoms and compute individual subscale scores.

To finalize the experimental protocol, participants were given 15 minutes of free exploration within the VR environment. They received minimal instructions, being allowed to move freely and interact naturally. The only requirement was that, during each immersion, participants should test the three available modes of interaction, video simulation, first-person navigation, and drone control.

B. *Validation and Testing Procedures*

The validation of the proposed experimental protocol was conducted in two complementary phases: a technical validation to assess the performance of the stimulation, and a user-based evaluation to examine the perceptual and usability aspects of the system.

During the technical validation, the reliability of the electrical signals generated by the device was verified prior to the experiments. Both sinusoidal and white noise waveforms were tested to confirm amplitude stability and to ensure that signal values did not change abruptly, thereby guaranteeing participant safety.

Before the test each participant completed a set of pre-screening questionnaires to confirm eligibility for the experiment and signed a consent form, accordingly to the Declaration of Helsinki, and then proceeded through two stages: the initial assessment phase and the testing phase, both carried out using the GVS system.

For each participant, the application synchronized the stimulation amplitude data with the inertial measurements, generating normalized graphs for each amplitude indicator.

Similarly to Goel *et al.* [14], the electrodes were positioned symmetrically over the mastoids. The skin surface where the electrodes were placed was cleaned and dried, followed by the application of a thin layer of conductive gel to ensure uniform current density, improve electrode fixation, and minimize skin irritation.

Each participant underwent two VR immersion sessions (using the VRSL + GVS system), each lasting 15 minutes: one without stimulation (sham) and one with white noise stimulation (nGVS), with the order of exposure being randomized (A: sham → nGVS; B: nGVS → sham), using the system presented at Figure 3.

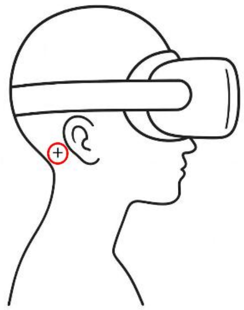


Figure 3. Complete system for the test; VRSL + GVS system

To analyze the efficacy of the nGVS stimulation in reducing cybersickness, two complementary indicators were evaluated: the symptoms measured by the SSQ and its sub-scores, as well as the tolerance to immersion, measured by the duration of time each participant was able to remain in the VR environment (maximum 15 minutes). The total SSQ score was computed using (1).

$$SSQ_{total} = \frac{(9.54*nausea)+(7.58*oculomotor)+(13.92*disorientation)}{3.74} \quad (1)$$

Asymmetric continuous variables were analyzed using the Wilcoxon signed-rank test [15]. Ordinal variables were examined using either the sign test or Bowker's test of symmetry [16], while binary variables were analyzed with McNemar's exact test [17]. Paired risk differences (RD) and their exact 95% confidence intervals (CI) were calculated for clinical interpretation and effect size estimation.

V. RESULTS AND DISCUSSION

This section outlines the main limitations of the present study and discusses future perspectives for improving the experimental design and expanding the application of nGVS in VR environments.

A. *Quantitative and Qualitative Results*

Firstly, the age distribution of the participants was analyzed. As shown in Figure 4, the 20 participants ranged from 19 to 65 years, with an average of 33 years. The distribution reflects the availability of volunteers and the location where the tests were conducted.

Table II presents the first parameter evaluated: whether participants were able to complete the full 15-minute VR immersion. During the sham condition, 15% of the participants did not complete the entire session. In contrast, under nGVS stimulation, all participants reached the 15-minute target. The paired contingency table showed 3 discordant pairs in favor of nGVS and none in the opposite direction, corresponding to a +15% paired improvement (RD = +0.15). Although this difference did not reach statistical significance in the McNemar test ($\chi^2 = 1.33$, $p = 0.25$), the discordance pattern and the absence of any dropouts under nGVS indicate a clear positive trend in immersion tolerance. This preliminary analysis indicates that nGVS enabled all participants to tolerate the full 15-minute immersion, whereas 15% failed to complete the session under sham stimulation. This represents a +15% paired improvement in immersion tolerance, suggesting that the stimulation may meaningfully mitigate cybersickness symptoms.

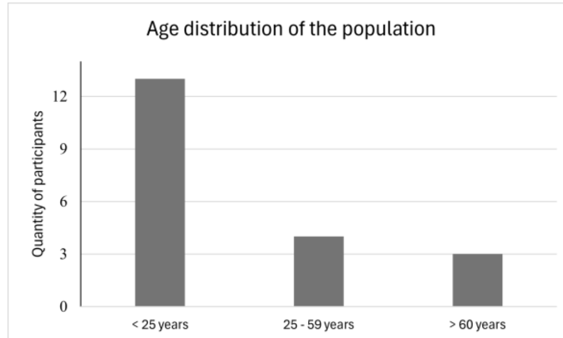


Figure 4. Age distribution of the studied population

TABLE II. IMMERSION PERIOD OF THE PARTICIPANTS

Condition	Did not complete	Completed
Sham	3 (15 %)	17 (85 %)
nGVS	0	20 (100%)

After the trials, when examining all the information collected, it was observed that, due to participants' availability, it was possible to divide them into two groups based on the time interval between immersions, as described in Table III. According to Fujimoto *et al.* [18], avoiding crossover effects between sham and nGVS requires a minimum washout period, where the subject didn't received any stimulation or was using the VR system, of approximately 4 hours. Therefore, the results were reanalyzed using this new grouping to better quantify the influence of this interval within the ISF group (≤ 1 hour) and the SF group (> 1 hour).

TABLE III. DIVISON OF THE PARTICIPANTS BASED ON THE WASHOUT

Group	Quantity of participants
ISF (<1h)	13
SF (>1h)	7

The analysis of the ten items of the SUS questionnaire was performed using box-plot representations. For the ISF group, shown in Figure 5a, the SUS scores displayed very similar distributions between the sham and nGVS conditions. Both median and mean values remained close to 80, indicating consistently high perceived usability in both cases. Since the SUS reflects only the overall usability of the system, a paired Wilcoxon test was also conducted, yielding $W = 47.0$ and $p = 0.7609$, indicating no significant difference between the two immersions.

For the SF group, shown in Figure 5b, the SUS scores demonstrated greater dispersion under the nGVS condition compared to sham, indicating increased variability in perceived usability. Under nGVS, both the mean and median were slightly lower, with a broader interquartile range shifting toward lower ratings, whereas in the sham condition the median and mean remained around 80. Despite this increased

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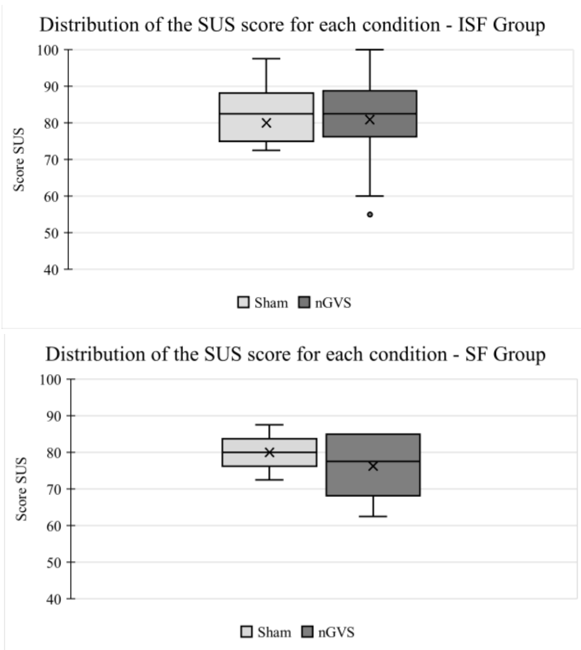
variability, the paried Wilcoxon test revealead significant difference between conditions, with W = 3.5 and p = 0.2763. These patterns suggest that, for the SF group, nGVS may influence usability perceptions, though the variability indicates that the effect is not uniform across participants.



(a)
(b)

Figure 5. Box-plot of the SUS questionnaire scores (a) ISF (b) SF Group

For the SSQ, the total score and its sub-scores were analyzed, to determine whether the time between immersions affected the results. The difference between washout categories was not statistically significant (W = 31.5, p = 0.41). However, the sub-scores defined in (1) revealed a more specific pattern centered on the nausea sub-score. The distribution of values was more positive in the SF group (W = 20, p = 0.067), whereas the oculomotor (W = 26, p = 0.20) and disorientation (W = 49, p = 0.59) sub-scores did not show significant differences. Overall, within this study, the potential benefits of nGVS appear primarily in the nausea dimension.

When considering the intra-subject analysis and the order of exposure, the pattern of responses becomes clearer, as illustrated in Figure 6. In Group B (nGVS→sham), nausea tended to be reduced (HL > 0), with confidence intervals generally favoring the nGVS immersion, even with descriptive p-values in the 0.10–0.20 range. In contrast, in Group A (sham→nGVS), nausea did not improve and, in some cases, worsened, consistent with a carryover effect between immersions.

In conclusion, the different analyses of the SSQ data and immersion tolerance converge toward the interpretation that nGVS may primarily exert a *preventive* effect on nausea during VR immersion. This effect is most evident in conditions where stimulation is applied before or early in exposure and when sufficient washout time is allowed between sessions, as suggested by the higher completion rate and the more favorable nausea sub-scores in the SF group. In contrast, when nausea is already present from the first immersion or when the washout interval is short, nGVS does not reliably reduce symptoms and may, in some cases, fail to counteract carryover effects from the initial exposure. The oculomotor and disorientation dimensions show weaker, non-significant changes, but their overall trends remain directionally consistent with the nausea findings, supporting the interest of nGVS for future, larger-scale testing phases.

B. *Limitations and Perspectives*

Even with positive results, this work was subject to several limitations. The number of participants was restricted due to the limited availability of volunteers and the short experimental timeframe. Therefore, the results had to be analyzed according to the washout interval between immersions, which was essential to determine whether vestibular stimulation could truly improve immersion quality and reduce cybersickness symptoms. Short washout periods introduced potential carryover effects, particularly in the nausea dimension, which may have attenuated or reversed the expected benefits of nGVS in some participants.

Moreover, because the study used the VRSL environment, participation was limited to individuals with prior knowledge of electrical distribution substations. This ensured that participants could properly evaluate the realism and immersion of the virtual substation but, at the same time, reduced the diversity of the sample and limited the generalizability of the findings. The use of a professional-training VR environment may also have produced task-specific sensory demands, which could differ from those observed in entertainment-based or non-technical VR applications.

Looking ahead, future work will include a new round of experiments using a different VR environment, allowing for a larger and more heterogeneous sample of participants. Expanding the diversity of VR contexts will help determine whether the preventive effect of nGVS on nausea generalizes across various types of immersive content. Additional test sessions distributed over multiple days and with controlled washout intervals are also planned to better evaluate the reproducibility, robustness, and long-term effects of nGVS stimulation on comfort, posture stability, and immersion during VR exposure.

VI. Conclusion and Future Work

This work presented the development and validation of a GVS system designed to improve immersion and comfort in VR environments. The system integrates hardware and software capable of delivering controlled vestibular stimulation and was successfully implemented within the VRSL platform for experimental evaluation. Technical tests confirmed that the device operates safely and reliably, providing stable current output and respecting user safety constraints.

The experimental results showed encouraging trends in this study. Participants exposed to nGVS showed lower SSQ scores, particularly in the nausea dimension, and demonstrated a higher tolerance to VR exposure, remaining longer in the virtual environment under stimulation than under sham. Although the SUS did not reveal statistically significant differences in perceived usability, the distribution of scores suggested a slight shift toward more positive evaluations during nGVS immersion. Importantly, the analysis considering washout duration and exposure order indicated that the benefits of nGVS are primarily preventive, emerging when stimulation is applied before VR exposure, whereas a short washout interval can attenuate or even reverse these effects.

Overall, the findings support the hypothesis that controlled vestibular stimulation can help mitigate cybersickness and enhance immersive experience in VR environments. Future work will involve testing the system with a more diverse participant pool, exploring different VR contexts, and conducting extended multi-day experiments to improve reproducibility and refine stimulation parameters. Such developments will help determine the broader applicability of nGVS as a practical, low-cost tool for improving comfort and stability in immersive VR applications.

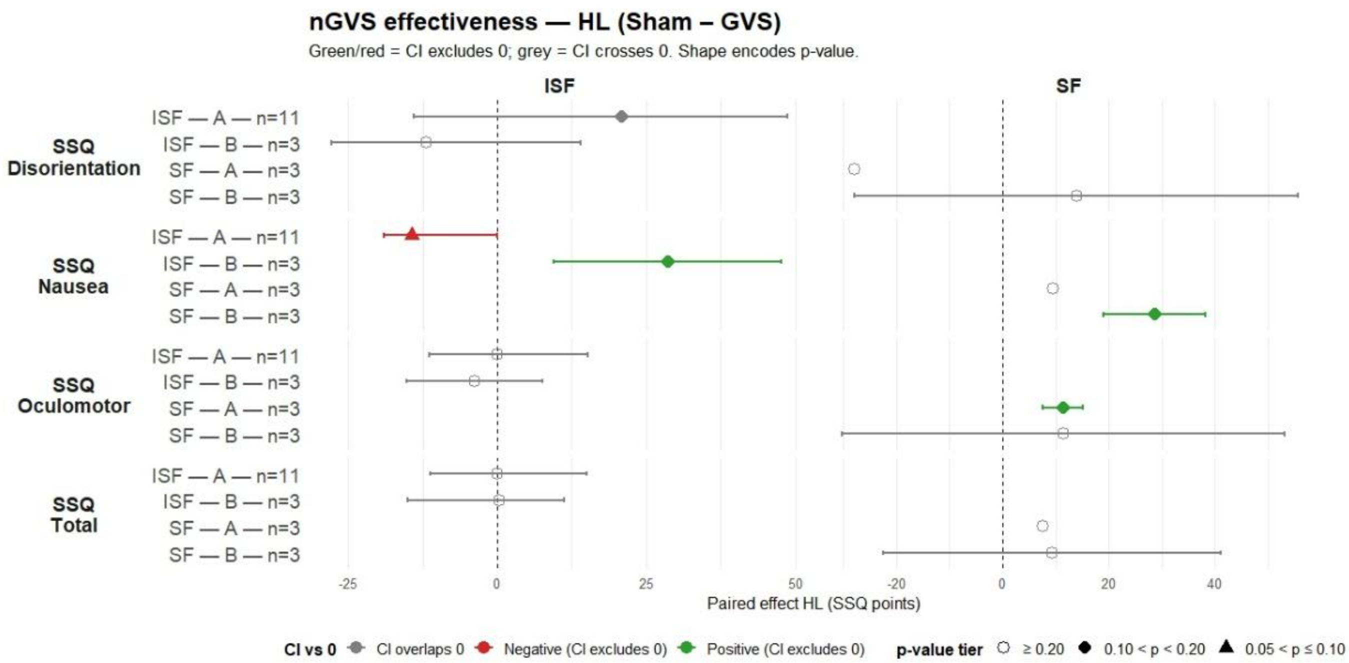


Figure 6. nGVS effectiveness when considering the order of exposure A or B

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All experiments were conducted in accordance with the Declaration of Helsinki, and all participants provided written informed consent prior to the beginning of the study.

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