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Who says you are so sick? An investigation on individual susceptibility to cybersickness triggers using EEG, EGG and ECG

Nana Tian, and Ronan Boulic

Abstract—In this research paper, we conducted a study to investigate the connection between three objective measures: Electrocardiogram(ECG), Electrogastrogram (EGG), and Electroencephalogram (EEG), and individuals' susceptibility to cybersickness. Our primary objective was to identify which of these factors plays a central role in causing discomfort when experiencing rotations along three different axes: Roll, Pitch, and Yaw. This study involved 35 participants who were tasked with destroying asteroids using their eye gaze while undergoing passive rotations in four separate sessions. The results, when combined with subjective measurements (specifically, Fast motion sickness questionnaire (FMS) and Simulator sickness questionnaire (SSQ) score), demonstrated that EGG measurements were superior in detecting symptoms associated with nausea. As for ECG measurements, our observations did reveal significant changes in Heart Rate Variability (HRV) parameters. However, we caution against relying solely on ECG as a dependable indicator for assessing the extent of cybersickness. Most notably, EEG signals emerged as a crucial resource for discerning individual differences related to these rotational axes. Our findings were significant not only in the context of periodic activities but also underscored the potential of aperiodic activities in detecting the severity of cybersickness and an individual's susceptibility to rotational triggers.

Index Terms—Virtual Reality, Cybersickness, Individual Susceptibility,Electrocardiogram, Electrogastrogram, Electroencephalogram

1 Introduction

The adoption of Virtual Reality(VR) is still hampered by the prevalence of cybersickness whose causes are difficult to identify due to a high number of factors. The individual susceptibility has not received sufficient attention as recently stressed in [44].

1.1 Individual susceptibility to cybersickness

Understanding the factors contributing to an individual's vulnerability to cybersickness is currently a top priority [44]. However, this area of research faces significant challenges. The issue of individual susceptibility to cybersickness can be divided into two perspectives: sensitivity levels and sensitivity triggers. In simple terms, the first category revolves around why one person, individual A is more susceptible than another individual B. Previous studies often categorized participants into low, medium, and high sensitivity groups using tools like motion sickness history questionnaires (MSSQ) or other subjective measures such as the Simulator Sickness Questionnaire (SSQ). Recently, research was predominantly centered on demographic factors like gender and age, as well as past experiences like a history of motion sickness or previous exposure to games and VR. Despite the growing number of research papers in this area, the findings remain inconsistent [29,30,44]. The second, less explored problem pertains to individual sensitivity to specific triggers of cybersickness. While some individuals may predominantly experience cybersickness due to one factor, others may attribute it more to the presence of a different factor [44]. To the best of our knowledge, despite numerous studies investigating various factors that may trigger cybersickness, no prior scholarly publication has specifically focused on identifying individual susceptibility to cybersickness triggers. Hence, the first objective of our study is to examine an individual's susceptibility to the three rotational axes (Roll, Pitch, Yaw) as they have previously been identified among the most prominent factors inducing cybersickness [44].

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1.2 Subjective vs Objective Measurements

Subjective measurements are challenging to standardize because they can be influenced by participants' psychological states. Participants may mask their discomfort to appear courageous or intentionally inflate their scores to expedite an early exit from the study. On the other hand, objective measurements can be intrusive, and the quality of the signals depends on the expertise of the researchers. Currently, the SSQ is still considered the gold standard for subjective measurement. The standard SSQ comprises 16 typical symptoms, some of which can be correlated with physiological measures. For example, eye strain can affect eye blink frequencies, and dizziness may lead to postural sway. Notably, one crucial category of symptoms is nausea and its associated sensations like stomach awareness and burping, which have been recently identified using electrogastram (EGG). While the mentioned physiological measures can directly relate to SSQ-defined symptoms, some measures are indirectly linked but play a pivotal role in the neurological mechanisms involved in cybersickness. For instance, heart-related activities measured by electrocardiogram (ECG) and brain activities assessed through electroencephalogram (EEG) are essential because they offer insights into the underlying neural mechanisms. Therefore, our second objective is to verify the effectiveness of three objective measures (ECG, EGG and EEG) in assessing an individual's susceptibility to cybersickness sensitivity levels. Our third objective is to investigate the use of objective measures, particularly EEG, in characterizing an individual's susceptibility to rotational axes.

1.3 Summary of Research questions

To comprehensively explore the individual susceptibility of participants towards the three rotational axes (Roll, Pitch, and Yaw), the research questions related to various physiological signals are:

- Electrogastrogram (EGG):
  - Are there discernible differences in EGG signals, such as alterations in frequency or power, when comparing participants during periods of sickness with those without or less sickness?
  - Which specific EGG features are indicative of nausea?
- Electrocardiogram (ECG):
  - Do EGG signals exhibit any differences, such as changes in frequency or power, when comparing participants when they are experiencing sickness versus those when they are not?

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  - Which specific parameters of heart rate variability (HRV) act as indicators of cybersickness?

- Electroencephalogram (EEG):
  - Do EEG signals exhibit any differences, such as changes in frequency or power, when comparing participants when they are experiencing sickness versus those when they are not?
  - Do EEG signals show variations, such as alterations in frequency or power, when comparing individuals with low sensitivity to those with high sensitivity?
  - Does a distinction in brain signals exist among groups characterized as roll-dominant, pitch-dominant in terms of individual sensitivity?

1.4 Contributions

The contributions can be summarized as follows:

- To our best knowledge, This paper is the first to conduct an original investigation into individual susceptibility to cybersickness triggers, with a specific focus on rotational axes.
- The findings from EEG measurements provide insights into differentiating individuals influenced by roll movements from those affected by pitch movements.
- As far as we know, the paper is the first to analyze aperiodic activities in EEG during cybersickness, highlighting their relevance in identifying cybersickness and rotation dominance.
- The study integrates three distinct objective measures - ECG, EGG, and EEG - to evaluate their effectiveness in measuring cybersickness severity. EEG also offers additional data regarding an individual's susceptibility to cybersickness triggers.

2 Related work

Since the main goals of this paper are related to the three objective measurements, we present a detailed review on each of them.

2.1 ECG

Previous research that utilized ECG (Electrocardiography) to investigate cybersickness primarily yielded two categories of results, or a combination thereof: heart rate and heart rate variability. Heart rate variability (HRV) represents the physiological phenomenon characterized by fluctuations in the time intervals between successive heartbeats. HRV serves as an index of neurocardiac function and emerges from the intricate interactions between the heart and the brain, as well as the dynamic, nonlinear processes within the autonomic nervous system (ANS). HRV metrics can be categorized into time-domain indices, frequency domain indices, and non-linear measurements. Oh and Son investigated the Heart beat, Time domain parameters (SDNN and RMSSD) and their relationships with cybersickness and they could not find any statistical significance between ECG parameters and cybersickness severity [34]. Islam et al. explored the prediction of cybersickness severity using heart related parameters and they found that the increased heart rate and decreased HRV were positively correlated with cybersickness severity [18]. Increased heart beat reported with higher cybersickness was also reported in [14, 21], a fluctuation of heart rate was found in previous study as well [47]. A recently investigated heart-related measure of cybersickness is known as the Heartbeat-Evoked Potential (HEP). HEP represents the brain's response to each individual heartbeat and is believed to reflect how the heart communicates with central autonomic regions in the brain. It has been proposed as a potential indicator of a person's awareness of their internal bodily processes. Chang et al. found that the magnitude of the HEP activity at the frontal area might reflect the level of arousal caused by cybersickness [5]. Park et al. found a decrease of magnitude of HEP activity, and an increase in the Alpha power during cybersickness [36].

2.2 EGG

Electrogastrography (EGG), also known as electrograstrogram, is a noninvasive method for assessing gastric myoelectrical activities. It involves the use of surface Ag/AgCl electrodes with conductance gels applied to the skin surface in the stomach area [41]. In healthy individuals in a fasting state, the normal EGG frequency is typically around three cycles per minute, with a range of 2-4 cycles per minute [6, 41]. Moreover, the normal EGG ratio in healthy individuals is expected to be above 70% or even higher [40]. It's important to note that the rhythm of stomach activities can be influenced by various stimuli, including food and emotions [40].

EGG signals have proven to be clinically useful for detecting stomach motor dysfunctions, particularly dysrhythmias such as tachygastria (0.5-2 cycles per minute) or bradygastria (4-9 cycles per minute) [6, 24, 50]. Nausea is a common symptom experienced during virtual reality (VR) exposure, but its underlying physiological mechanism remains poorly understood [12, 25, 41]. Recent research has investigated the use of Electrogastrogram (EGG) as a tool for detecting cybersickness, which is a form of discomfort induced by virtual reality (VR) experiences. Several studies [10, 12, 21, 43] have delved into this area. These studies have reported that when individuals experience cybersickness due to exposure to VR, there is an increase in a specific type of stomach activity known as "tachygastria." Furthermore, in some instances, there is a decrease in another stomach activity pattern called "bradygastria" [10].

It's important to note that only Dennison et al. and a recent study by Tian et al. employed actual VR systems to induce cybersickness [10, 43]. Interestingly, [10] stated that when individuals were in a resting state, they displayed a high percentage of bradygastria (over 70%). This finding contrasts with earlier reviews, which suggested that healthy individuals should exhibit a dominant pattern of normal gastria activity. In line with a standard clinical EGG reference [40], [43] confirmed that bradygastria remains relatively stable during cybersickness in VR, while there is an increase in tachygastria and a decrease in normal gastria.

2.3 EEG

The electroencephalogram (EEG) has frequently been used to identify instances of cybersickness, with certain brain signal characteristics considered crucial for predicting the severity of cybersickness. However, previous research has faced challenges in determining the specific features sensitive to cybersickness severity. These challenges arise from variations in the virtual reality (VR) content used, individual differences in susceptibility, and disparities in data processing methods across different studies. According to Chang et al., the data preprocessing procedure is typically standardized into five major steps: re-referencing, resampling, filtering, artifact rejection, and epoching [49]. However, there exist differences in the order of these steps and the parameters applied. Among these steps, artifact rejection is particularly critical because it involves manual selection, which relies heavily on the experience and expertise of the researchers. Notably, some previous studies have failed to completely remove eye-related artifacts, leading to noisy results [32, 46, 49]. The data processing stage often involves categorizing results into either cybersickness or no cybersickness, grouping electrodes based on their positions, and classifying them into four or five distinct areas (e.g., PreFrontal, Frontal, Occipital, Central Parietal, Temporal). Importantly, the specific areas highlighted in these classifications vary among studies. The grouping of electrodes also differs significantly across research papers, influenced by the researchers' choices and the number of channels available on the EEG devices used. Feature extraction in EEG analysis commonly involves various techniques such as frequency analysis, which includes power spectrum analysis (e.g., FFT), time-frequency analysis (e.g., Short-time Fourier transform), or other methods like Event-related spectral perturbation analysis. These methods help extracting meaningful information from EEG data. The results of these analyses often provide information about the power within classified frequency bands, typically consisting of five main bands: Alpha, Beta, Delta, Theta, and Gamma. Absolute power quantifies the raw strength of brain activity within a specific fre-

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quency band. In contrast, relative power measures the portion of power within a particular frequency band in relation to the total power present in the entire EEG spectrum. The decision to report either absolute or relative power depends on the research objectives and the specific goals of the EEG analysis. Researchers choose the most appropriate measure based on what they aim to understand and convey in their study. It is precisely because of these differences that we find it difficult to compare or summarize the features describing the increase or onset of cybersickness in the brain from the previous literature.

The findings from a comprehensive review of numerous studies provide insights into the complex relationship between brainwave patterns and cybersickness [44]. Prior studies on the relationship between brainwave patterns and cybersickness can be classified into two types: 1) within-group analyses (studies often involve baseline conditions or less cybersickness inducing conditions, and Cybersickness-inducing conditions, and 2) between-group analyses (studies often group participants into low sensitive and high sensitive by either MSSQ/VISSQ score or SSQ/FMS scores). We found that these two types of results are often mixed during reviews which lack of rigor. For papers conducting the within-group analyses, a decrease in Alpha band activity was observed during cybersickness condition in paper [19]. Interestingly, there are also reports in the literature that indicate an increase in Alpha activity during cybersickness [7, 15, 26, 49]. When it comes to Beta power, the consensus among earlier studies is a reduction in Beta activity during cybersickness in [21]. Similarly, the Delta frequency power exhibits variability in response to cybersickness, with some studies reporting a decrease [31] and others documenting an increase [19, 26]. The Theta power appears to show a more consistent pattern across studies, predominantly indicating an increase as cybersickness becomes more pronounced [7, 15, 26, 35, 35, 49]. Comparatively, there are less studies found with between-group analyses. For papers conducting the between-group analysis, it is suggested that a lower Beta [9, 19, 27], a lower gamma [19], a lower Theta [27], increased Delta [2] and decreased Alpha [2] are observed in the sensitive group. In contrast, it is also suggested that a higher Theta, a decreased delta [9] and increased alpha [1] can be observed in the sensitive group. These collective insights underscore the intricate nature of neurophysiological responses to cybersickness, with variations in Alpha, Beta, Delta, and Theta brainwave activities depending on the specific study and experimental conditions. What's more the brain location of these changes are different among studies. Understanding these nuances is essential for unraveling the underlying mechanisms of cybersickness and advancing research in this field.

EEG signals encompass not only the rhythmic signals we mentioned earlier, such as periodic activities like Alpha and Beta oscillations, but also aperiodic activities that lack a rhythmic pattern or characteristic frequency [48]. The aperiodic component of EEG signals received little attention in EEG literature until recently, frequently being labeled as 'noise' and considered to have limited physiological significance [16]. However, recent studies have revealed valuable insights into the significance of aperiodic activities, particularly in relation to aging, psychiatric disorders, levels of arousal, and task performance [11, 16]. This physiological information could be instrumental to understand the neural mechanisms behind cybersickness. Drawing inspiration from these studies, this paper takes the initiative to examine the aperiodic activity and its relationship with cybersickness.

3 Controlled Experiment

Note: In this experiment, we introduced a new protocol called Least increasing aversion (LIA). Full protocol details (Experiment Protocol, Game design, Materials, Ethics, etc) are in the supplementary material due to page limits. It is worth to mention that the protocol design and subjective measurement analysis are discussed in another paper. Here is a short summary of the experiment protocol (Figure 1):

S1: The first session among the four activates the three rotation factors hence resulting in an exposition to the worst-case scenario. Following the twenty-minute VR exposure, the post-SSQ was administered, and participants were interviewed to rank their sensitivity to each axis using a relative score on a scale of 0 to 10, with 10 representing the highest degree of sickness.

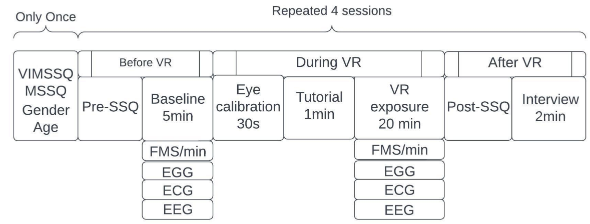

Fig. 1: The whole experiment commenced with participants completing a consent form and providing demographic information, motion sickness history initially for once. For each session, they began with a pre-SSQ assessment. Subsequently, participants underwent a 5-minute baseline recording while wearing physiological sensors without VR. Following this, a one-minute tutorial was conducted, and participants engaged in a 20-minute VR game utilizing eye-based interaction. Throughout the VR experience, participants used the FMS to report their discomfort levels every minute [20]. They were instructed to minimize movements and promptly notify staff if they felt unwell. The sessions concluded with a post-SSQ assessment, followed by an interview to capture their experiences.

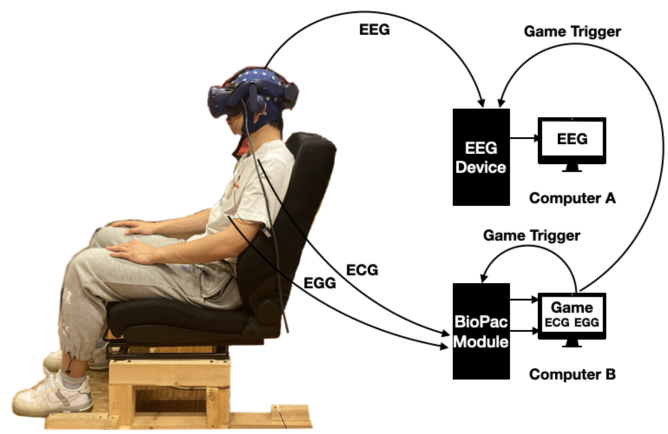

Fig. 2: Experiment setup

S2: The second session acted as a baseline with no rotations, In this session, participants were solely required to engage in the gaze-shooting game.

S3: According to the protocol design the participant is exposed to the activation of a single factor, by design of the protocol it is their chosen Least cybersickness-inducing rotation axis. **S4:** In the 4th (and last) session, a second factor is activated in addition to the one chosen in session 3. Again it is their next chosen Least cybersickness-inducing rotation axis. By design of the protocol participant are not re-exposed to the worst-case scenario, hence motivating their choice of least avoidance axes for sessions 3 and 4.

4 Result

4.1 Participants

In this study, 35 healthy human subjects (18 females; age range of 20 to 45 years, mean = 23.3, standard deviation = 4.4) completed all four sessions. Seven participants chose to end their participation early during the first session. The data from the remaining 28 subjects (14 females) were included in the statistical analysis (7 who force quit during one or more sessions were excluded), and the data from the participants who discontinued their involvement were also included for specific purposes (as indicated in the results). Participants were recruited within and

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around local higher education institutions through the intranet. Eligible subjects were instructed to adhere to strict guidelines, including refraining from consuming alcoholic or motion-sickness related substances for up to 12 hours prior to the experiment, and not consuming food or drinks within 2 hours prior to the experiment. The final outcome of the study reveals that out of the participants involved, 18 individuals chose roll as their most sickness-inducing axis, 8 individuals chose pitch, and 2 individuals demonstrate dominance in yaw.

4.2 Subjective result basics

While the primary focus of this paper is not on subjective results, it is important to note that subjective measures remain the most standard means of comprehending the severity of cybersickness. In the supplementary material, we present an overview of participants' selected paths under the LIA protocol, including the count of each selected path, along with the mean and standard deviation of Delta TS (Post SSQ total score - Pre SSQ total score). The in-depth subjective results are presented in another paper.

4.3 Data Processing

Due to the page limit, the data processing details are presented in the supplementary material document.

4.4 Statistical Analysis

All analyses were carried out using custom Python code. Shapiro–Wilk test were applied to determine whether the sample data have been drawn from a normally distributed population. The paired t-test was used for parametric data in normal distribution and the wilcoxon-signed rank test was used for the non-parametric data. For comparisons among groups with different sample sizes, we used the permutation test. To address the issue of false positives, we employed validation tests that utilize multiple testing correction methods, including the Bonferroni correction [3]. Moreover, we assessed the effect size using Cohen's d.

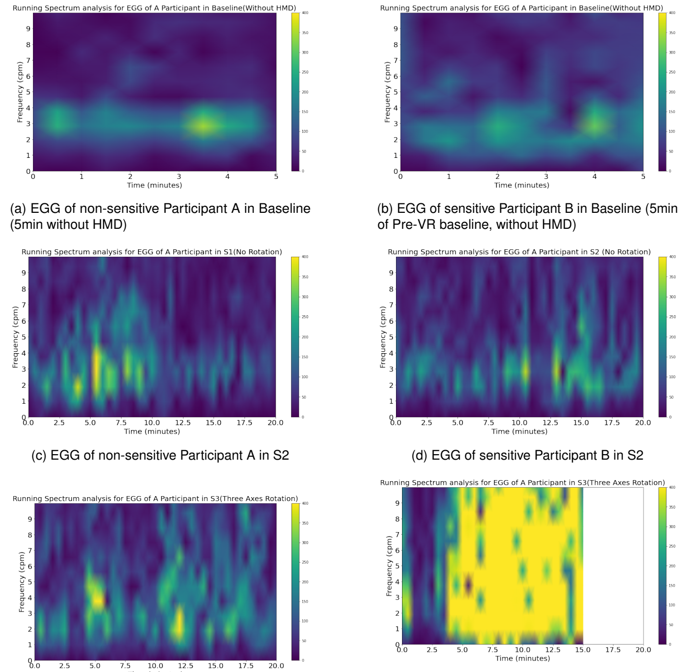
4.5 EGG results

EGG results are gathered in Fig.4. Regarding the mean dominant frequency, statistical findings indicate that participants demonstrated a higher dominant frequency in S1 compared to the other sessions (S1 vs S2, $p < 0.001$; S1 vs S3, $p > 0.05$; S1 vs S4, $p > 0.05$). Conversely, the dominant frequency appears significantly lower in S2 than in the other sessions (S2 vs S3, $p < 0.005$; S2 vs S4, $p < 0.001$). No significant difference is observed in any pair among S1 S3, and S4.

Regarding the normal ratio, a discernible trend of decreasing normal ratio with an increase in the number of axes is evident in the figure 4a. The ranking of the normal ratio is precisely negatively correlated with the Delta SSQ TS, with S1 exhibiting significantly lower normal ratio than the other three groups (S1 vs S2, $p < 0.001$; S1 vs S3, $p < 0.01$; S1 vs S4, $p < 0.05$). Conversely, S2 displays a significantly higher normal ratio than the other sessions as anticipated (S2 vs S3, $p < 0.05$; S2 vs S4, $p < 0.001$). Similarly to the SSQ data, no significant difference is observed between S3 and S4 ($p > 0.05$).

The evaluation of the tachy ratio, established as a nausea indicator in previous studies, aligns overall with the Delta SSQ TS, with S1 having the highest and S2 the lowest ratio. Compelling evidence of an increased tachy ratio is evident in S1 when compared to S2 ($p < 0.001$). Participants in S3 display a significantly heightened tachy ratio compared to S2 ($p < 0.05$). The tachy ratio experiences further elevation in S4, although no significant difference is found ($p > 0.05$). This pattern is consistent with the results from Delta SSQ TS, normal ratio, and mean dominant frequency. Furthermore, no significant reduction is observed in S4 when compared to S1 ($p > 0.05$), whereas a significant reduction is noted in S3 when compared to S1 ($p < 0.05$).

A noteworthy cybersickness indicator highlighted in this study is the normal to tachy ratio. The significant decrease in S1 compared to S2 implies that participants experienced more pronounced stomach activity in S1, largely driven by nausea. A decrease in nausea is evident in S3 compared to S1, as reflected by a significantly increased normal-tachy ratio in S3 ($p < 0.05$). The discomfort experienced by participants also improved when opting for the two less sick axes in S4 compared to S1



(a) EGG of non-sensitive Participant A in Baseline (5min without HMD)

(b) EGG of sensitive Participant B in Baseline (5min of Pre-VR baseline, without HMD)

(c) EGG of non-sensitive Participant A in S2

(d) EGG of sensitive Participant B in S2

(e) EGG of non-sensitive Participant A in S1

(f) EGG of Sensitive Participant B in S1, force quit at the 15th minute

Fig. 3: Running Spectrum analysis of EGG data of a non-sensitive participant A on the left. And a sensitive participant B on the right. The first row is the 5 minutes Pre-VR baseline showing the EGG spectrum without VR headset. Obviously, the dominant frequency stably stays within the normal range (2-4 cpm). The second row is the S2. The EGG dominant frequencies mostly stay within the normal range. Finally, the third row is the worst-case Session. The EGG DF of A still mostly stays within the normal range; the last minute FMS of Participant A in S1 is 2 while Participant B force quit in the 15th minute, and the last minute FMS is 15.

($p < 0.05$). Similarly to the aforementioned outcomes, no significant difference is observed between S3 and S4 ($p > 0.05$).

4.5.1 EGG correlation with SSQ Nausea subscale

The subjective perception of nausea varied among individuals. Especially, an inevitable problem is that the same subjective rating does not objectively represent the same level of discomfort. Hence, we did a correlation analysis with the EGG key parameters and SSQ Nausea subscale. The results show a medium positive correlation between the EGG tachy ratio and Delta_N (coefficient = 0.32, $p < 0.001$). Also, there is a medium negative correlation between EGG normal ratio and Delta_N (coefficient = -0.33, $p < 0.0001$). Similarly, the normal-tachy ratio and Delta_N are negatively correlated as well (coefficient = -0.33, p = $p < 0.0001$). Finally, there is also a medium positive correlation between mean dominant frequency and Delta_N (coefficient = 0.30, $p < 0.0001$).

Since both FMS and EGG were recorded during the VR exposure, we also conducted the correlation analysis between EGG parameters and the FMS 20th-minute score. Results indicate that FMS and EGG have stronger correlations than SSQ with EGG. The 20th-minute FMS is negatively correlated with normal ratio (coefficient = -0.42, $p < 0.0001$) and normal-tachy ratio (coefficient = -0.36, $p < 0.0001$), positively correlated with tachy ratio (coefficient = 0.35, p = $p < 0.0001$).

4.5.2 EGG levels per FMS sensitivity groups

Since EGG is more correlated with FMS, we further investigated the classification through FMS sensitivity groups and the comparison of EGG parameters across these groups. Since S1 is the worst-case scenario, it has the most potential to induce cybersickness and was the first experienced session. This session can best assess the individual

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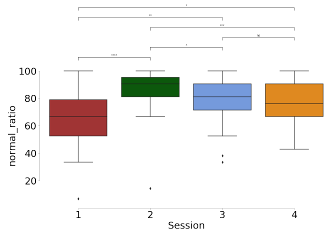
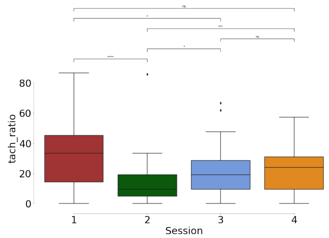
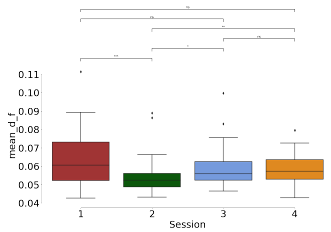


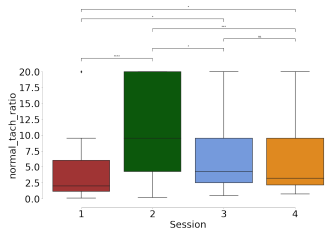
(a) Overview results of the Normal ratio for each session



(b) Overview results of the Tachy ratio for each session

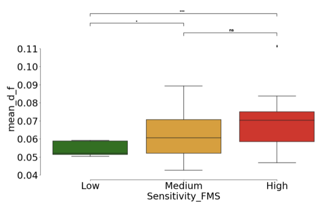


(c) Overview results of the Mean dominant frequency for each session

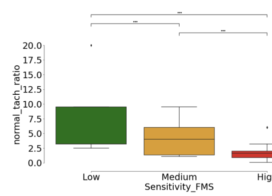


(d) Overview results of the Normal-Tachy ratio for each session

Fig. 4: Overview of EGG parameters and comparison across sessions

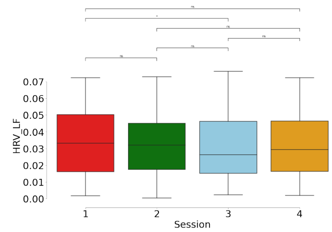


(a) Mean dominant Frequency per FMS sensitivity groups (statistical analysis performed with permutation test)

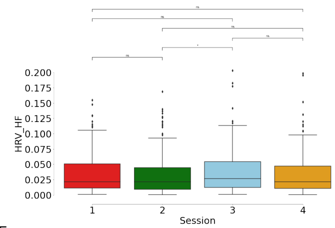


(b) Normal_tachy ratio per FMS sensitivity groups, (statistical analysis performed with permutation test

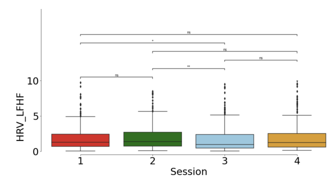
Fig. 5: EGG level of participants grouped by individual FMS sensitivity



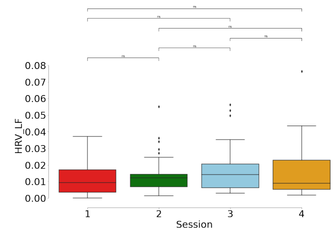
(a) Overview of HRV LF ((s^2/Hz)) in each session, LF is calculated with 2 min epoch for each session of each participant



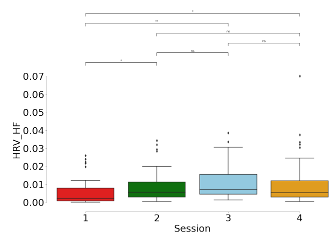
(b) Overview of HRV HF ((s^2/Hz)) in each session, HF is calculated with 2 min for each session of each participant



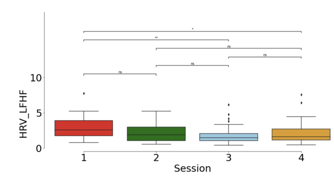
(c) Overview of HRV LF/HF ratio in each session, LF/HF ratio is calculated with 2 min epoch for each session of each participant



(d) Overview of HRV LF ((s^2/Hz)) in each session, LF is calculated with 20 min epoch for each session of each participant



(e) Overview of HRV HF ((s^2/Hz)) in each session, HF is calculated with 20 min for each session of each participant



(f) Overview of HRV LF/HF ratio in each session, LF/HF ratio is calculated with 20 min epoch for each session of each participant

Fig. 6: Overview of the HRV parameters by sessions

susceptibility free from the possible adaptation effect over multiple exposures. Inspired by [13], the individual FMS susceptibility was classified by the 20th minute FMS score in S1 (Low: FMS ≤ 6, Medium: $6 <$ FMS ≤ 14 , High: FMS > 14). We did not exactly use the same classification thresholds due to the relatively smaller sample size. Eventually, we got 10 participants in the high group, 12 in the medium group, and 5 in the low group. As shown in Fig.5a and in Fig.5b, the high sensitivity group's higher mean dominant frequency shifted toward the tachygastric activity. Conversely, the majority of the low group maintained their dominant frequency within the normal range. Due to the unbalanced numbers of people in each group, we performed the permutation test to examine the difference among groups. We did not find a significant difference between the high and medium groups in mean dominant frequency ($p > 0.05$). However, a significant difference was found between the other two pairs (High vs. Low: $p < 0.0001$, Medium vs. Low: $p < 0.05$). Concerning the normal-tachy ratio, the permutation test showed there was a significant difference between each pair of sensitivity groups (High vs Medium:$p < 0.001$, High vs Low: $p < 0.001$,Medium vs Low: $p < 0.001$)

4.6 ECG and Heart rate variability

4.6.1 ECG in the time domain

Concerning the heart rate, we computed the heart rate per minute to get a better understanding of the dynamic changes over time. Generally, we can observe a significant increase in heart rate in S1 over S2 ($p < 0.0001$). Also, there is an increasing trend in S2, S3, and S4. Unlike the high consistency in the EGG and subjective measures, there is no significant difference between S1 and S4 ($p > 0.05$), but a significant difference between S3 and S4 ($p < 0.05$). MeanNN shows the opposite pattern as S1 has lower NN intervals than S2 ($p < 0.0001$).

4.6.2 ECG in the frequency domain

According to the review papers in HRV [37, 42], we computed the LF, HF and LF/HF ratio in both 2 minutes epochs and whole 20 minutes as shown in Fig.6. As a result, we do not get any significant findings in all the pair comparisons among sessions in LF, HF and LF/HF ratio within a two minutes duration. As for the 20 minutes duration analysis, we did not find any significant results in LF, but interesting results were found in HF and LF/HF ratio in Fig. 6e and Fig.6f. We discuss these results in detail below.

4.7 EEG

In order to maximize potential distinctions in EEG signals between states of sickness and non-sickness, we conducted a comparative analysis of relative bandpowers across predefined frequency ranges between S1 and S2 sessions. To enhance the localization of signal variations, we organized electrodes into spatial groupings, namely the Frontal, Temporal, Parietal, and Occipital regions, as in Fig.7 . Subsequently, signal averages within these four groups were computed. The violin plots depicting relative bandpower variations, along with statistical comparisons, are depicted in Fig.8.

Within-group analysis can successfully control variations among subjects. However, some criticisms have been raised, suggesting that the observed differences in brain signals might be linked to content disparities, particularly related to rotation, rather than being solely indicative of cybersickness. Identifying the origin of brainwaves is challenging, especially since rotation itself is the cause of cybersickness. To address this, we conducted another investigation into the differences in brain signals between individuals with low sensitivity and high sensitivity in S1. We categorized participants into low sensitivity and high sensitivity groups based on their Delta_TS scores (Low:Delta_TS < 60, High:Delta_TS > 60) . To analyze the brain signals, we organized the

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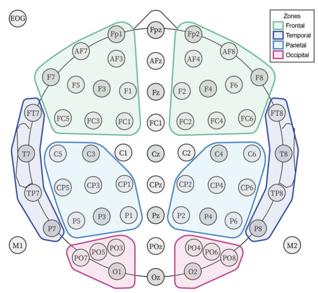

Fig. 7: Brain electrodes map with the definition of the four regions analyzed in the present study: Frontal (green), Temporal (blue), Parietal (light blue) and Occipital (pink) [17]

electrodes by regions, computed violin plots, and performed statistical comparisons and effect size calculations, as illustrated in Figure 10.

To investigate potential disparities in brain signals based on participants' susceptibility to pitch and roll rotation axis, we undertook a comparative examination of relative bandpowers within four distinct frequency bands across four brain regions: Frontal, Occipital, Parietal, and Temporal. This analysis was conducted among distinct participant groups defined by their dominant sensitivity type (Roll-dominant, Pitch-dominant). Note that we removed the two persons in Yaw-dominant group for this specific analysis because these participants were generally very robust to cybersickness, independently of the rotation axis, see Table**??**. Given the unequal sample sizes across these groups, we employed a permutation test methodology. Specifically, the tmax method was utilized to adjust the p-values of individual variables within the context of multiple comparisons. This approach, akin to the Bonferroni correction, effectively manages the family-wise error rate. Importantly, the permutation technique exhibits enhanced efficacy compared to the Bonferroni correction in scenarios where the various variables under examination are correlated [33]. The conclusive outcomes are presented in Fig. 12

5 Discussion

5.1 Electrogastrogram (EGG) as an Indicator

Nausea, a prevalent discomfort experienced during Virtual Reality (VR) exposure, exhibits considerable variability and is subjectively perceived. The sensation is defined as a distressing feeling located in the upper abdomen, often preceding vomiting. Clinical investigations have established a close association between nausea and irregular stomach contractions known as myoelectrical dysrhythmias.

In this study, we propose an assumption: the transition from normal gastric activity to gastric dysrhythmias (either tachy or brady) strongly correlates with the onset of nausea. To illustrate, we present two contrasting cases in Figures Fig.3a and Fig.3b. The first depicts a non-sensitive individual, reporting minimal sickness across all sessions, with consistently regular stomach patterns. Conversely, the second example portrays a sensitive individual who abruptly terminated the first session and exhibited an abrupt shift from normal to tachygastric activity. Although some fluctuations towards the tachy range are noticeable in subsequent sessions, the dominant rhythm remains within the normal range. Statistical analysis across sessions revealed an increase in the tachy ratio, consistent with previous findings [21, 24]. Additionally, novel EGG parameters were identified: a decrease in EGG normal ratio and dominant mean frequency, coupled with an increase in EGG tachy ratio and normal-tachy ratio, signifying the presence of nausea.

Notably, our study differs prior research by Dennison et al. [10], who linked decreases in the brady ratio to heightened cybersickness. In contrast, our healthy participants exhibited negligible or no brady gastric ratio during baselines and experimental sessions.

We delved further into the correlation of EGG parameters with different subscales of the SSQ and the FMS score, recorded during VR exposure. EGG exhibited a stronger correlation with FMS scores than the SSQ nausea subscale, likely due to their temporal congruence with VR exposure.

Moreover, our investigation extended to exploring EGG parameters alongside individual susceptibility and aversion to rotational axes. Our findings indicated that heightened sensitivity corresponded to increased tachygastria and dominant mean frequency during nausea. Similarly, more sensitive individuals exhibited diminished ratios of normal gastric activity and normal-tachy ratios. Combining subjective and objective measures, our analysis suggests that, from a population perspective, the dominant axis ranking in contributing to cybersickness is Roll $>$ Pitch $>$ Yaw. However, the relationship with Yaw dominance remains less certain due to the limited sample size.

In conclusion, our study underscores the potential of EGG as an indicator of nausea during VR exposure. We present compelling evidence linking EGG parameters to subjective discomfort and propose new insights into the dynamics of cybersickness.

5.2 Electrocardiogram (ECG) as an Indicator

Our investigation provide insights into the relationship between heart rate and certain ECG parameters with the level of cybersickness experienced within our experimental framework. Specifically, we observed an upward trend in heart rate and Mean NN intervals corresponding to heightened cybersickness. Additionally, higher cybersickness was associated with increased LF power and decreased HF power, consistent with previous research [22, 45]. Our findings align with the established notion that an elevated LF/HF ratio signifies increased activity of the sympathetic nervous system [38].

It's worth noting that the outcomes over a 20-minute interval differ somewhat from those observed in 2-minute epochs. This disparity can be attributed to the significant impact of recording duration on the measurement of heart rate variability (HRV) in both time-domain and frequency-domain analyses [42]. However, we must emphasize that the complex and nonlinear dynamics of autonomic nervous system activities limit our ability to draw overarching conclusions about ECG parameters. The intricate interplay between the parasympathetic and sympathetic nervous systems during cybersickness, both in linear and nonlinear aspects [42], remains a topic of ongoing investigation. No significant changes or easily interpretable distinctions were noted in the time-domain ECG parameters (such as SMSDD, SDNN, pNN50, pNN20). Furthermore, although the intricate connection between the heart and gut was not the primary focus of this study, we observed correlations and potential interactions that may occur during cybersickness. A preliminary assumption suggests that shifts in stomach frequency might be accompanied by corresponding changes in HRV frequencies, preceding alterations in EGG patterns. Notably, changes in ECG patterns tend to occur more frequently than those in EGG.

5.3 EEG as an Indicator

Electroencephalogram (EEG) has emerged as a promising tool for objectively assessing discomfort levels. However, reported changes in spectral power within different frequency bands have varied across studies [4, 44]. In our investigation, we categorized EEG signals into four primary brain regions to ensure that potential changes would not be obscured by averaging signals from all electrodes. Also, as we indicated earlier, we fit models to parameterize neural power spectra, which is further described by a combination of periodic and aperiodic activity.

5.3.1 Do EEG brainwaves differ between most sickness-inducing and the baseline sessions?

Periodic Activity Our findings indicate no significant alteration in the Alpha band power across all positions. However, during higher levels of cybersickness, we observed noteworthy changes in other frequency bands. Notably, there was a notable decrease in Delta power in the occipital brain region, an increase in Beta power in the temporal region, and a decrease in Theta power across all regions. The increase in Beta power and decrease in Theta power align with previous research, such as the study by Choi et al. [8].

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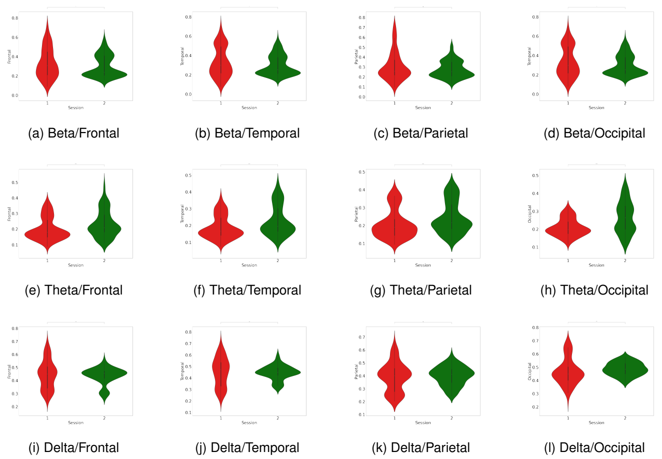

Fig. 8: Each line compares the relative bandpowers (Beta, Theta, Delta) for the four regions (from left to right: Frontal, Temporal, Parietal, Occipital), for worst-case scenario (red) and the baseline (green)

Interestingly, the results diverged from a study by Krokos and Varshney [26], where an increase in Delta, Theta, and Alpha power was observed. This discrepancy might stem from factors like exposure duration, as Choi et al. used a 60-minute VR exposure while Krokos and Varshney's exposure was only 61 seconds. The temporal fluctuations in Beta power reported by Choi et al. further suggest that the shorter exposure might not adequately capture changes in slower waves like Delta and Theta.

Other factors influencing the results could include the number of EEG channels used (64 in our study compared to 14 in Krokos and Varshney's), as well as the methodology. Unlike our approach, Krokos and Varshney initiated the selection of the sickness group directly from Independent Component Analysis (ICA) results. Typically, ICA is employed for artifact removal, which diverged from our methodology.

It's noteworthy that the decrease in Delta power contrasts with previous research [4,21]. Conversely, the increase in Beta wave power aligns with anxiety-related patterns [39]. This could partly explain the cybersickness symptoms, as participants often exhibit anxious behaviors during discomfort, marked by movements, sweating, and restlessness.

The decrease in Delta wave activity is interesting since Delta waves are associated with deep relaxation and restorative sleep. The decrease might contribute to the uncomfortable feelings experienced during cybersickness, characterized by nausea, sweating, and restlessness. Given the association of the occipital region with the visual cortex, one may infer that Delta waves play a role in regulating visual-vestibular conflict.

To sum up, the phenomenon of cybersickness involves a decrease in Delta and Theta brainwave activity, which is originally associated with sleep and drowsiness. Simultaneously, there's an increase in Beta brainwave activity, signifying heightened alertness and cognitive engagement. This shift in brainwave patterns suggests a transition from a relaxed state to heightened attention and cognitive activity during cybersickness experiences.

S1 vs S2	Frontal	Effect size	Temporal	Effect size	Parietal	Effect size	Occipital	Effect size
Alpha	$p > 0.05$	0.17	$p > 0.05$	0.19	$p > 0.05$	0.08	$P > 0.05$	0.05
Beta	$p < 0.05$	0.24	$p < 0.05$	0.27	$p > 0.05$	0.28	$p > 0.05$	0.24
Delta	$p > 0.05$	0.17	$p > 0.05$	0.45	$p > 0.05$	0.09	$p < 0.001$	-0.25
Theta	$p < 0.00001$	-0.39	$p < 0.00001$	-0.52	$p < 0.00001$	-0.49	$p < 0.00001$	-0.78

Table 1: Statistical analysis of periodic activities between S1 and S2 with p values and effect size

Aperiodic Activity As shown in Fig.9, a conceptual illustration describe the comparative relationship between aperiodic activities under the "Worst case" S1 and "Baseline" S2. It is worth to mention that this picture only conceptualizes the results which describe the relative

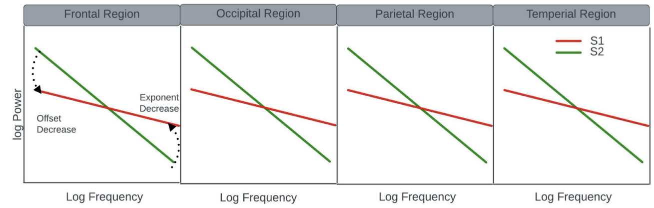

Fig. 9: Conceptual illustration depicting the comparison of aperiodic activities between the worst-case and the baseline scenarios inspired by [16]; The associated violin plots are available in the Supplementary material

S1 vs S2	Frontal	Effect size	Temporal	Effect size	Parietal	Effect size	Occipital	Effect size
exponent	$p < 0.00001$	-0.33	$p < 0.00001$	-0.42	$p > 0.05$	0.08	$p > 0.05$	0.05
offset	$p < 0.001$	-0.55	$p < 0.0001$	-0.54	$p < 0.0001$	-0.46	$p < 0.01$	-0.24

Table 2: Statistical analysis of aperiodic activities between S1 and S2 with p values and effect size

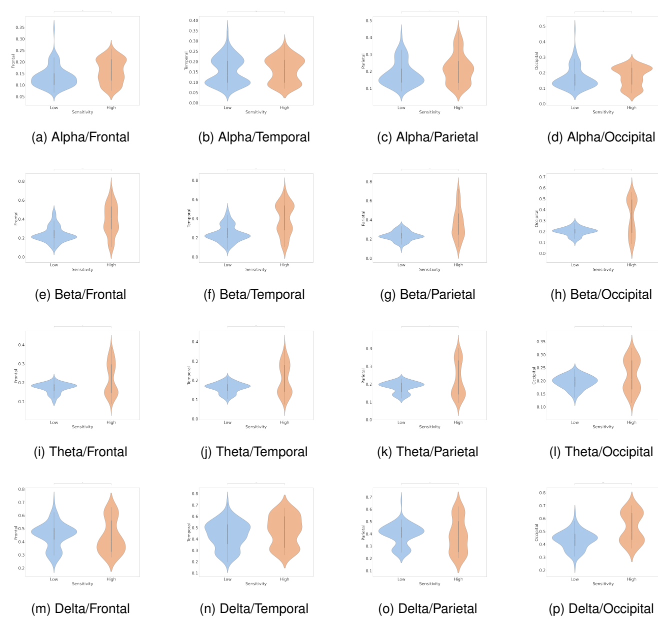

Fig. 10: Each line compares the relative bandpowers (Alpha, Beta Theta, Delta) for the four regions, from left to right: Frontal, Temporal, Parietal, Occipital) and for the two types sensitivity individuals (Blue: Low sensitive; Orange: High sensitive).

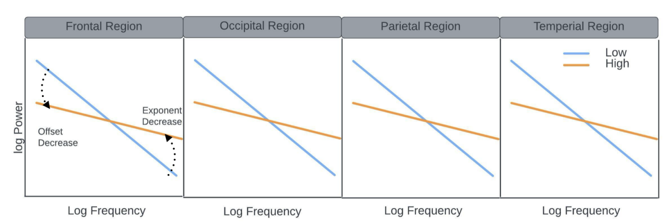

Fig. 11: Conceptual illustration depicting the comparison of aperiodic activities between low and high sensitive individuals; Associated violin plots are available in the supplementary material

increase or decrease trends, the actual results are shown with violin plots and statistical differences are presented in supplementary material due to the page limits. Interestingly, we found a significant decreased exponent and offset in the S1 compared to S2 in all the four brain regions. In the current theoretical framework, the 'offset' is typically

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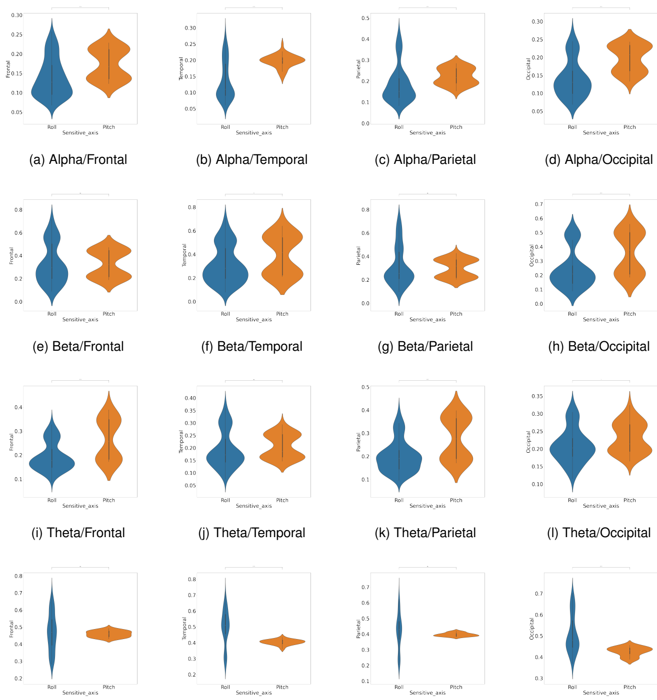
Low vs High	Frontal	Effect size	Temporal	Effect size	Parietal	Effect size	Occipital	Effect size
Alpha	$p < 0.001$	-0.51	$p > 0.05$	-0.07	$p < 0.05$	-0.34	$p > 0.05$	-0.08
Beta	$p < 0.00001$	-1.16	$p < 0.00001$	-1.11	$p < 0.00001$	-1.01	$p < 0.00001$	-1.02
Delta	$p > 0.05$	0.09	$p > 0.05$	-0.27	$p > 0.05$	0.04	$p < 0.0001$	-1.01
Theta	$p < 0.05$	-0.72	$p < 0.01$	-0.70	$p > 0.05$	0.05	$p < 0.05$	-0.55

Table 3: Statistical analysis of periodic activities between low and high sensitive groups with p values and effect size.

Low vs High	Frontal	Effect size	Temporal	Effect size	Parietal	Effect size	Occipital	Effect size
Exponent	$p < 0.001$	0.42	$p < 0.001$	0.40	$p < 0.05$	0.07	$p < 0.0001$	0.02
Offset	$p < 0.00001$	0.79	$p < 0.00001$	0.70	$p < 0.001$	0.57	$p < 0.00001$	0.61

Table 4: Statistical analysis of aperiodic activities between low and high sensitive groups with p values and effect size



(a) Alpha/Frontal (b) Alpha/Temporal (c) Alpha/Parietal (d) Alpha/Occipital

(e) Beta/Frontal (f) Beta/Temporal (g) Beta/Parietal (h) Beta/Occipital

(i) Theta/Frontal (j) Theta/Temporal (k) Theta/Parietal (l) Theta/Occipital

(m) Delta/Frontal (n) Delta/Temporal (o) Delta/Parietal (p) Delta/Occipital

Fig. 12: Each line compares the relative bandpowers (Alpha, Beta Theta, Delta) for the four regions, from left to right: Frontal, Temporal, Parietal, Occipital) and for the two types of rotation axis sensitivity (Blue: Roll-dominant; Orange: Pitch-dominant).

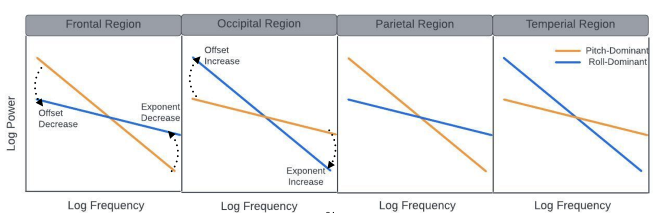


Fig. 13: Conceptual illustration depicting the comparison of aperiodic activities between the pitch-dominant and the roll-dominant groups inspired by [16]; The associated violin plots are available in the Supplementary material

interpreted as a representation of the spiking activity within a group of neurons, while the 'exponent' is seen as indicative of how synaptic currents are being integrated. It reflects the equilibrium between excitatory (E) and inhibitory (I) currents in the neural system [16, 48]. Previous studies indicate that a flatter exponent is a sign that there's more sporadic firing of neurons in the brain, which could mean that certain brain circuits are becoming more active and ready to send signals [16].

Roll vs Pitch	Frontal	Effect size	Temporal	Effect size	Parietal	Effect size	Occipital	Effect size
Alpha	$p < 0.00001$	−0.76	$p < 0.00001$	−0.78	$p < 0.00001$	−0.47	$p < 0.00001$	−0.83
Beta	$p > 0.05$	−0.05	$p < 0.01$	−0.51	$p > 0.05$	0.10	$p < 0.00001$	−0.85
Delta	$p > 0.05$	0.10	$p < 0.00001$	0.10	$p > 0.05$	0.87	$p < 0.00001$	0.93
Theta	$p < 0.00001$	−0.79	$p > 0.05$	−0.20	$p < 0.00001$	−0.76	$p < 0.05$	−0.45

Table 5: Statistical analysis of periodic activities between Roll-dominant and Pitch-dominant group with p values and effect size

Roll vs Pitch	Frontal	Effect size	Temporal	Effect size	Parietal	Effect size	Occipital	Effect size
exponent	$p < 0.001$	−0.33	$p < 0.00001$	0.52	$p < 0.001$	−0.79	$p < 0.0001$	0.72
offset	$p < 0.05$	−0.39	$p < 0.01$	0.91	$p < 0.00001$	−0.52	$p < 0.01$	0.80

Table 6: Statistical analysis of aperiodic activities between Roll-dominant and Pitch-dominant group with p values and effect size

Also, there are studies showing that the power spectral density (PSD) patterns during wakefulness exhibit a flatter exponent and a reduced offset [11, 16]. This change might be important for understanding how the brain reacts to the onset of cybersickness.

5.3.2 Do EEG brainwaves differ between low and high sensitive individuals

Periodic Activity Previous research has investigated differences in EEG brain waves among individuals with low and high sensitivity levels [2, 15]. Findings presented in Figure 10 and Table 3 showcase the results in this paper. Our observations highlight a significant increase in the Alpha band within the Frontal and Parietal lobes among high-sensitive individuals, which is aligned with [1, 15]. Specifically, Alpha band activity has been linked to the inhibition of neural responses associated with task-irrelevant information [15]. In the context of high-sensitive individuals, this heightened Alpha band activity suggests a potential suppression mechanism for sensory conflict. Interestingly, we could see that unlike the result when comparing S1 and S2, the Alpha band showed a difference in high sensitive individuals in the Frontal and Parietal, which could be marked as the specific differences among sensitive individuals when dealing with visual contents or sickness. Moreover, the Beta band showed significant increase across all brain regions in individuals with high sensitivity. The Beta waves changes aligned with the changes in brain signals observed between S1 and S2. Additionally, high-sensitive individuals exhibited heightened Delta wave activity in the Occipital region, accompanied by increased Theta wave activity in the Frontal, Temporal, and Parietal regions. A previous study linked Delta and Theta power changes to the brain's response to visual-vestibular conflicts, with increased power correlating to more severe conflicts. [2]. Hence, our finding in the Theta and Delta changing trend confirms this assumption. The observed outcome differs from comparisons between most sickness inducing and baseline sessions, possibly owing to the influence of rotation-induced changes in brain signals and inherent individual variations.

Aperiodic Activity In Fig.11 and Table 4, we elaborate on the comparative dynamics of aperiodic activities between individuals with low sensitivity and high sensitivity. The violin plots and statistical differences are detailed in the supplementary material, adhering to page constraints. Notably, a pronounced reduction in both exponent and offset is observed in the high sensitivity group across all four brain regions when compared to the low sensitivity group. This finding aligns with the changes in brain signals observed between S1 and S2. By combining these outcomes, we can infer that individuals experiencing more severe cybersickness exhibited lower exponents and offsets in their brain activities.

5.3.3 Can EEG brainwaves differ for Roll vs Pitch dominant groups?

Periodic Activity Regarding individual susceptibility towards cybersickness triggers, When we compare the periodic activities among sensitive individuals to different rotation axes, we could find that here is a decreased Alpha band in the Roll-dominant group compared to the Pitch dominant. The Alpha band power being significantly involved in sensory inhibition and attention modulation [23], a decrease in Alpha

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activity can indicate an increase in alertness and mental engagement. This could be explanatory because the Roll axis rotation is seldomly experienced in daily life compared to the other two axes [28]. We also found an increased Delta and Beta power in the occipital and temporal area in Roll dominant group compared to the Pitch, and the Pitch dominant group has increased Theta wave compared to the Roll.

Aperiodic Activity The examination of aperiodic activities unveils distinct patterns of neural engagement as shown in Fig.13. In the context of Roll dominance, it shows a decreased exponent and decreased offset in Frontal and Parietal Region. Simply put, we can see that Roll dominance group has more active neurons spiking activities in the Frontal and Parietal lobe. While the Pitch dominance group comparatively has more active neurons spiking activities in the occipital and temporal lobe.

Due to the limited knowledge in the field of neuroscience regarding aperiodic activities, we exercise caution when interpreting the neurological significance of these results. Nevertheless, the observed distinctions in active and inactive regions between the Pitch and Roll dominant groups could potentially assist in identifying individuals with heightened sensitivity or predicting their preferred rotation axes during experiments.

5.4 Three objective measures

To sum up, in the context of ECG analysis, our observations revealed distinct patterns. However, we caution against directly employing ECG as a reliable indicator for assessing the extent of cybersickness. Future research could explore the intricate interplay between the heart, brain, and gut, given their connections through the vagus nerve.

Despite the cost associated with EGG devices, we strongly advocate for their utilization due to their potential to serve as valuable indicators of cybersickness severity. Notably, nausea ranks among the top three significant symptoms and is also indicative of an individual's susceptibility to cybersickness severity. Individuals with higher susceptibility are prone to experience nausea more swiftly and intensely. Nevertheless, it's important to acknowledge that EGG is not without its limitations. Ensuring the quality of EGG measurements often demands prolonged VR exposure to capture its slow-wave nature accurately. Moreover, the proper placement of electrodes requires both skill and experience to ensure accuracy.

Among our findings, EEG results stand out as particularly promising for identifying individual susceptibility to cybersickness. This is because EEG directly correlates with the initial integration of signals that lead to feelings of discomfort. Consequently, EEG signals not only possess the capability to detect an individual's susceptibility to the cybersickness levels but also have the potential to differentiate an individual's susceptibility to specific triggers of cybersickness. To further advance our understanding in this area, there is a need for additional research, involving more standardized applications and refined signal processing for EEG data.

While our current findings offer insights, they have not yet yielded a complete comprehension of the complex processes underlying the onset of cybersickness. Consequently, a compelling need exists to delve into the brain-gut interaction during episodes of cybersickness. Investigating this interaction could provide deeper insights into the mechanisms driving nausea and contribute to a more comprehensive understanding of cybersickness phenomena.

5.5 Limitation and Future work

Our study is not without limitations. Initially, we designed the eye-based interaction to prevent boredom during the 20-minute gameplay session and to minimize upper body motion compared to traditional joystick controls. However, the extensive use of eye interaction introduced unanticipated noise and complicated data analysis. As a result, the availability of valid data for analysis was restricted. Also, the Yaw-dominant group is significantly limited because of the sample size and nature of population distribution. Our model examination confirmed that individuals dominant in Yaw rotation are considerably less common compared to the other two groups. To overcome these challenges in the future, we suggest to include a larger number of participants and explore alternative interaction methods.

Furthermore, the design of the game in this experiment is restricted solely to rotations, aligning with the experiment's specific objectives. Therefore, we are cautious when attempting to generalize the results to encompass typical VR games with more complex interactions. Future studies should aim to expand upon this research by incorporating common VR games into their experiments.

6 Conclusion

In this paper, we took advantage of objective measures to explore the individual susceptibility towards factors potentially contributing to cybersickness. The paper mostly focused on the evaluation of the individual susceptibility to three rotational axes (Yaw, Pitch, and Roll) to identify the individual dominant rotational axis; we mainly focus on the objective signal data collected from the experiment (details on the "Least increasing aversion" protocol are presented in the supplementary material).

Our results showed that the EGG parameters had a strong predictive power of nausea towards rotational axes (three of them are newly identified through our contribution). Specifically, the tachy ratio and mean-dominant frequency are positively correlated with nausea, normal ratio and normal-tachy ratio are negatively correlated with nausea. Concerning the ECG in the time domain, heart rate and MeanNN increase when cybersickness increases. In the frequency domain, LF power and LF/HF ratio are positively correlated with cybersickness while HF is negatively correlated with cybersickness. We highlight the HRV as dynamic linear and non-linear complexes [42]. Hence, the interpretation of these results needs careful thought and more examination. Finally, regarding the EEG signal frequency analysis, we found a notable decrease in Delta power in the occipital brain region, an increase in Beta power in the temporal region, and a decrease in Theta power across all regions when participants experiences more cybersickness. Furthermore, we noticed a reduction in both the exponent and offset in aperiodic activities in the most cybersickness inducing condition.

Comparing those prone to sickness with less susceptible individuals, we found increased Alpha in the Frontal and Parietal lobes, increased Beta across all brain regions, increased Delta in the occipital lobe, and heightened Theta in the Frontal, Temporal, and Parietal regions in the more sensitive group. Moreover, a decrease in both offset and exponent was found in more sensitive individuals. Different results in periodic activities between the two comparisons may stem from content variations and individual differences. Acknowledging the complexity of brain signals is crucial. Future research could utilize EGG parameters for identifying sickness instances and exploring brain-gut signal interactions. Additionally, we stress the need to clearly distinguish between results from between-group and within-group analyses in discussions, as our findings indicate differing outcomes. In addition to the aforementioned findings, we found that the 'Roll-dominant' group exhibited decreased Alpha activity, increased Delta and Beta activity in Occipital and Temporal regions, and decreased Theta activity in the Parietal region compared to the 'Pitch-dominant' group. Notably, we obtained medium to large effect size on the comparison of aperiodic activities among Roll-dominant group to Pitch dominant group. This highlights the significant difference with a relatively small sample size. In summary, our findings offer valuable insights into an individual's vulnerability concerning rotational axis factors. Additionally, the identified physiological markers hold promise in predicting both cybersickness severity and susceptibility to its contributing factors.

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