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The Least Increasing Aversion (LIA) Protocol: illustration on identifying individual susceptibility to cybersickness triggers

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Abstract—This paper introduces the Least Increase aversion (LIA) protocol to investigate the relative impact of factors that may trigger cybersickness. The protocol is inspired by the Subjective Matching methodology (SMT) from which it borrows the incremental construction of a richer VR experience, except that the full-blown target experience may cause undesired discomfort. In the first session, the participant briefly encounter all factors at the maximum level. Then in the second session they start with the minimum level of all factors as a Baseline. Subsequently, we expect the participant to minimize their exposure to the most adverse factors. This approach ranks the factors from mildest to worst and helps detect individual susceptibility to cybersickness triggers.To validate the applicability of LIA protocol, we further evaluate it with an experiment to identify individual susceptibility to three rotational axes (Yaw, Pitch, and Roll). The findings not only confirm the protocol's capability to accurately discern individual rankings of various factors to cybersickness but also indicate that individual susceptibility is more intricate and multifaceted than initially anticipated.

Index Terms—Virtual Reality, Cybersickness, Individual susceptibility

1 Introduction

With the increasing use of virtual reality (VR) and other immersive technologies, the issue of cybersickness has become a significant concern for researchers and users alike. Cybersickness, also known as virtual reality sickness or simulator sickness, is a type of visually induced motion sickness that occurs when a person experiences nausea, dizziness, and other symptoms while using VR or other immersive technologies [1].

1.1 Individual susceptibility to cybersickness

Cybersickness is a widely observed phenomenon affecting a significant proportion of the population. However, it has been noted that certain individuals exhibit a heightened susceptibility to this condition. Additionally, the factors contributing to cybersickness may vary across individuals [2]. As of yet, no established theory exists that can account for the observed individual differences [1], [2]. The sensory conflict theory, despite being widely accepted, does not provide an adequate explanation for the variability in individual reactions to the same VR exposure [3]. Meanwhile, The Postural Instability Theory endeavors to link individual susceptibility to cybersickness with their balance ability. Specifically, it posits that variations in postural stability may account for differences in susceptibility to cybersickness across individuals [4]. However, there is currently a debate about whether postural instability is a cause or a result of cybersickness [5]. Experimental evidences indicate that cybersickness could be experienced without or with minimal postural instability [6], [7].

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Uncovering the underlying factors contributing to individual susceptibility to cybersickness has become a pressing need. However, the study of individual susceptibility to cybersickness is currently facing a bottleneck. First of all, with regards to individual susceptibility, research has tended to revolve around demographic factors, such as gender and age, or past experiences, including motion sickness history or previous game/VR experience. Despite the growing number of research papers, the findings remain contradictory [2], [5], [8]. For instance, the influence of gender on cybersickness susceptibility can be categorized into two opposing camps: one which suggests that females are more susceptible to cybersickness than males [5], [9], [10], [11], [12], and another which indicates that there is no significant difference between genders in terms of individual susceptibility [13], [14], [15], [16], [17]. Similarly, conflicting conclusions have been reached when examining the influence of age or past experiences on cybersickness [2], [18]. Recent research papers attribute these inconsistent results to three potential reasons: firstly, differences in experimental settings (such as the use of varying VR stimuli), which could lead to different levels of cybersickness induction, potentially reducing the power of the factor being studied. Secondly, the individual differences of participants selected for the studies could significantly impact the final results due to variations in individual susceptibility. Lastly, the number of participants (i.e., sample size) used in the studies may also play a critical role in determining the accuracy and reliability of the research findings [1], [2], [5]. However, increasing the number of participants itself could increase the chance of finding a difference [19]. Very few papers reported effect size in their studies [2], [12]. Consequently, from a statistical standpoint, validating whether a difference is attributed to an individual factor such as gender, or simply due to the utilization of a large sample size poses

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a challenging task.

Furthermore, an area that has been given inadequate consideration relates to the heterogeneous sensitivities of individuals towards diverse categories of visual stimuli; we summarize it as ”individual susceptibility to cybersickness triggers”. While some individuals may predominantly experience cybersickness as a result of rotation, others may attribute it primarily to the presence of high saturation colors [2]. To the best of our knowledge, despite the existence of numerous papers investigating the various factors that may elicit cybersickness, no prior scholarly publication has specifically concentrated on the identification of individual susceptibility to cybersickness triggers. The identification of the dominant factors or combination of factors that trigger cybersickness in an individual is imperative for three reasons. Firstly, it allows for the categorization of individuals based on physiological characteristics, thereby providing insights into why some people may be more susceptible to such factors. Secondly, these insights further aids in predicting an individual’s sensitivity to such factors by identifying the potentially existing physiological characteristics. Finally, it facilitates the development of personalized solutions that target an individual’s specific triggers rather than relying on a generic approach.

Overall, the phenomenon of individual susceptibility to cybersickness is a multifaceted and intricate matter that is contingent upon various factors. Hence, the objective of the current study is to fill the gap in knowledge by introducing an original protocol that aims to investigate the relative impact of key factors that may trigger cybersickness in each individual. In other words, the study seeks to identify individual susceptibility levels to cybersickness triggers.

1.2 Introducing the Least Increasing Aversion Protocol

The proposed protocol, named as the Least Increasing Aversion (LIA), draws inspiration from the Subjective Matching Technique (SMT) previously employed in Virtual Reality to ascertain the comparative significance of multiple factors for individuals [20], [21], [22], [23]. Given that cybersickness is a negative sensation, the primary objective of our protocol is to identify the worst dominant factor(s) and avoid repetitive exposure to those identified factors. As such, we have intentionally adopted a ”reversed selection” approach to the standard matching experiment. The details are presented in Section 3. In order to better illustrate the practical usage of LIA, we present an experiment that delves into user preference and individual sensitivity concerning three rotational factors (Yaw, Pitch, and Roll axes) which are well-known to induce cybersickness. Participants were initially exposed to the complete configuration of the VR experience in order to discern its distinct factors, specifically the three rotation axes in our study. The second session entailed a ”minimal” configuration without any rotations, serving as a baseline for comparison. This was followed by only two sessions, each introducing a new single factor. The newly added factor is the least sickness-inducing axis based on the subjective ranking of each individual in the initial session. Once a factor is introduced, it remains active in the subsequent session. The specifics of the experiment are elaborated upon in Session 4.

1.3 Contributions

In summary, this paper contributes to the field of individual susceptibility to cybersickness by introducing an original protocol, which consists of two main parts. Firstly, we provide the theoretical background of the LIA protocol, illustrating its conceptual framework and offering a template for future studies. Additionally, we conduct a comprehensive comparison between LIA and the SMT protocol, providing general instructions for applying LIA in future research endeavors. The protocol not only identifies an individual’s susceptibility or immunity to cybersickness but also determines the potential dominant factor causing their discomfort. To the best of our knowledge, this is the first study proposing such a protocol.

In the second half of the paper, we present an experiment focused on evaluating and validating the proposed protocol. We conducted an experiment (n=35), exposing participants to various configurations of rotational axes and asking them to rank these configurations based on discomfort levels while choosing to avoid the most discomforting axis. Our experimental results demonstrate the effectiveness of the proposed protocol in detecting an individual’s susceptibility to cybersickness and identifying the dominant factor responsible for their discomfort. Furthermore, our study provides insights into assessing individual susceptibility to cybersickness.

2 Related Work

2.1 Current methods to detect individual susceptibility

Current ways to detect individual susceptibility include subjective questionnaires like Motion Sickness Susceptibility Questionnaire (MSSQ) and Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ) [24], [25], [26]. Recently, objective measures like postural instability and rod-frame test were frequently adopted to assess individual susceptibility. However, the strong predictability of these measures is yet to be assured.

2.1.1 Questionnaires

The MSSQ developed by Golding et al. is a commonly used subjective questionnaire to assess an individual’s susceptibility to motion sickness [24]. While the MSSQ may provide some insights into an individual’s susceptibility to motion sickness due to similar symptoms and the sensory conflict theory, it does not account for the unique factors that contribute to cybersickness, such as the characteristics of the virtual environment and the unique VR experience. Meanwhile, the VIMSSQ also developed by Golding et al [25], [26] assesses an individual’s susceptibility to visually induced motion sickness by asking questions about the individual’s past experiences with visually induced motion sickness (including 12 categories like TV, smartphone, 3D movies, video games and VR etc.) and their current level of sensitivity to visual stimuli that can induce motion sickness. It is worth mentioning that the MSSQ score does not show a strong correlation with VIMSSQ score in previous paper [26]. Likewise MISSQ score are reported to have a low to moderate correlation with Simulator sickness questionnaire (SSQ) scores in [27], [28], [29], [30].

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2.1.2 Postural instability

Research has shown that individuals who are susceptible to motion sickness or have a history of vestibular disorders may be more prone to experiencing cybersickness. These individuals may also exhibit changes in postural stability [4], as the sensory mismatch caused by the VR environment can affect their ability to maintain balance and stability. Therefore, by conducting a balance test before and after exposure to a virtual environment, it may be possible to identify individuals who are more susceptible to cybersickness based on changes in their postural stability. This information can be used to tailor the VR experience or provide targeted interventions to prevent or mitigate the symptoms of cybersickness in these individuals.

2.1.3 Rod and Frame Test

The Rod and Frame Test (RFT) is a perceptual test used to assess an individual's ability to judge the vertical orientation of an object in the presence of a tilted frame [31]. The test involves presenting a visual stimulus (usually a rod) inside a tilted frame, and the individual is asked to adjust the rod to the perceived vertical position, regardless of the frame orientation. The RFT is designed to measure an individual's ability to use visual cues to orient themselves in space, as well as their ability to suppress misleading information provided by the surrounding environment. There is limited research on the use of the RFT to assess an individual's susceptibility to cybersickness. However, the RFT has been used in studies investigating the relationship between visual perception and motion sickness, which is a similar condition to cybersickness. Research has shown that individuals who are more susceptible to motion sickness tend to exhibit greater variability in their visual perception of the vertical, as measured by the RFT [29]. This suggests that an individual's ability to maintain a stable perception of vertical orientation may be related to their susceptibility to motion sickness. While there is no direct evidence to suggest that the RFT can be used to predict an individual's susceptibility to cybersickness, it is possible that individuals who exhibit greater variability in their perception of vertical orientation on the RFT may be more likely to experience cybersickness [29]. Further research is needed to explore the potential use of the RFT as a predictor of cybersickness susceptibility.

2.2 Subjective Matching Technique

Initially introduced in color science, the Subjective Matching Technique (SMT) has been leveraged in VR to investigate the Sense of Presence [20]. This approach involves finding combinations of factors that produce similar feelings as reference stimuli or experience. Researchers have applied SMT to the study of SoE in avatars [21], [22], [23]. Slater first introduced the technology to study Place Illusion (PI) and Plausibility Illusion (Psi) in 2010 [20]. In this study, participants experienced all possible combinations of four factors (Illumination, Field of View, Display type and Virtual Body) and made transitions until they reached a level of PI or Psi previously obtained in the full configuration. Later, Skarbez et al. utilized the same technology with different coherence factors (Virtual body behavior coherence, Virtual human behavior coherence, Physical coherence, Scenario coherence) towards optimal Plausibility Illusion [21], and Galvan-Debarba et al. studied the impact of different levels of body animation fidelity on plausibility illusion [23].

In Fribourg's study, users were presented with a specific avatar configuration and asked to reproduce the same SoE by manipulating three key factors: Appearance, Control, and Point of View [22]. The combination of these factors led to numerous possible avatar configurations, each with a potential range of SoE. To conduct the subjective matching task, users first experienced an "optimal" configuration of the avatar and remember their SoE in this configuration. They were then asked to combine several levels of factors to recreate the same SoE as the one felt in the optimal configuration. By examining which configurations produced an equivalent SoE to the original one, researchers could identify the most effective factors and their levels for eliciting a high sense of embodiment. Overall this methodology provided valuable insights into the study of subjective experience and offered a useful tool for investigating the impact of different combinations of factors.

Recently, a new research paper by Llobera et al. introduced a combination of SMT and Reinforcement Learning (RL) to help address the challenge of normalizing subjective responses in questionnaires [32]. This approach aimed to reduce the cognitive load associated with using SMT, which was highlighted in a previous study by Fribourg [22]. However, the binary comparison requires much more rounds of selection which may not be ideal for a uncomfortable sensation as cybersickness.

2.3 Rotational axes on cybersickness

The impact of rotation axes on cybersickness has been reported in literature, with Roll being commonly believed to be the most sickness inducing axis due to its infrequency in daily life, Pitch being seen as secondary due to its similarities with seasickness, and Yaw being deemed the least sickness inducing axis due to its regularity [33]. However, the results of a 2001 study by So and Lo revealed no significant difference among the three single-axis rotations [34], although strong evidence of varying susceptibility among participants was found. A more recent comprehensive study by Oh and Son investigated the effect of different VR content factors on cybersickness and found that the overall SSQ score for Roll axis rotation was significantly higher than for the other two axes, although the speed and pattern of rotation were not specified [35]. The combination of Pitch and Roll has been reported to be more cybersickness-inducing than Pitch alone [36], [37]. However, a key limitation of previous studies is the inconsistent rotational speed in multi-axis and single-axis conditions, which undermines the strength of their results.

3 Least Increasing Aversion Protocol

In a typical VR game, a multitude of factors can contribute to the occurrence of cybersickness. These factors are intricately intertwined, making it challenging to isolate the impact of individual elements. To establish a robust and reliable protocol, it is crucial to consider the assumption of individual susceptibility to these factors. This assumption can be

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succinctly formulated as follows: An individual may exhibit heightened sensitivity to a specific factor (or factors), while displaying immunity or reduced sensitivity to other factors (N>=1).

The main goal of the LIA protocol is to determine the order of factors that trigger cybersickness in individuals. As mentioned earlier, cybersickness causes unpleasant feelings that users want to avoid. Therefore, the LIA protocol not only draws on concepts from the SMT but also differs from it in fundamental ways, which we summarized into Table 1:

Outlined below are the conceptual steps of the proposed protocol, known as LIA, which aims to address this issue effectively:

Input:

- N: Total number of factors
- Factors F: List of factors (f_1,f_2... f_n)
- Levels X: Levels of each factor (X_{f_1},X_{f_2}... X_{f_n})
- K: The total number of sessions can be automatically determined by researchers when they assign a value (X_{f_i}) to each factor and follow the specified rules described below.

Output:

- Evaluation of individual factors' impact on cybersickness

Steps:

- Initial Session (S1):
  - Activate all N factors simultaneously
  - In this stage, all N factors are introduced simultaneously to simulate the worst-case scenario at the maximum Level $X_{f_i}max$.
- Baseline (S2):
  - Disable all factors, creating a scene without any of the factors.
- For j = 3 to K Session (Transitions):
  - There are two options available: either introduce a new factor that is deemed to be the least inducing of cybersickness among the non-selected factors, based on individual preferences, or increase the level of an existing factor until its maximum.(Once an individual has selected a higher level of a factor, it is not possible to revert to a lower level.)

  Note: A prerequisite for this protocol is that the researcher must have already determined and defined both the number and order of the various levels for each factor that induce cybersickness.

This protocol allows for a methodical examination of each factor's impact on cybersickness and find the "Most-tolerated" combinations for each individual. Through the gradual introduction of individual factors, researchers can discern their respective influences while considering the potential interactions between them. This approach enhances the reliability and comprehensiveness of the analysis, enabling a more nuanced understanding of cybersickness in VR environments.

TABLE 1
Comparison of SMT and LIA Approaches

Approach	SMT	LIA
Assumption	Having all factors at their maximum level leads to most desired sensation.	Having all factors at their maximum level leads to the most unfavorable sensations.
S1	Familize participants with all levels, factors and the best configuration (risk of overloading cognition because of the underlying memory task [22]).	Having all factors at their maximum level leads to the most unfavorable sensations.
S2	Baseline session with minimum configuration	Baseline session with minimum configuration
Transitions	In the subsequent sessions, participants are asked to choose either a new factor or adjust the level of an existing factor with the intention of enhancing the desired sensation.	In the subsequent sessions, participants were instructed to choose either a new factor or adjust the level of an active factor with the goal of reducing the escalation of the discomfort-inducing sensation.
Final Session	Final session involves full (or sufficient) configuration for the desired sensation.	Experiment stops before reaching maximum levels of all factors or at any time before that last session, if the participant discomfort is too high.

3.1 Example transitions

Imagine we have three factors $\{f_1,f_2,f_3\}$ and each factor has three levels mark as {0,1,2}. Following the conceptual guidelines above, Figure 1 provides an overview of all possible sessions and transitions.

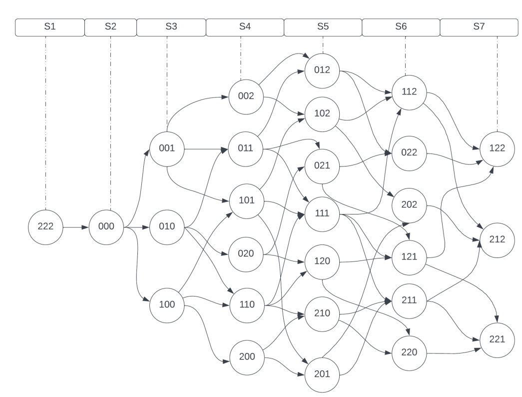

Fig. 1. This graph illustrate possible transitions/paths of LIA selected by an individual's susceptibility towards factors and levels. The first digit represents f_1, second digit represents f_2, third digit represents f_3, number 0-2 presents the three levels.

4 General application of LIA

In this section, we provide an overview of the broad applicability of the LIA protocol. It is crucial to underscore that the LIA protocol is specifically designed for determining the

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susceptibility ranking of multiple factors for each individual, resulting in an experimental framework with a within-subject design. Furthermore, LIA was initially designed for cybersickness; similar discomfort sensations like anxiety could adopt it as well. The LIA protocol is recommended for research purposes under specific conditions: 1) when researchers seek to investigate the ranking of multiple factors (>=3) for each individual, 2) when researchers aim to explore the general ranking of multiple factors, and 3) when each factor exhibits multiple levels. In implementing the LIA protocol, researchers must first define the targeted factors and their associated levels. Subsequently, following the defined protocol steps, researchers illustrate possible transitions, as presented in subsection 3.1. After delineating these transitions, researchers need to develop a suitable design for a virtual reality (VR) application or game capable of presenting all the combinations outlined in the transition graph. The challenge lies in designing a scene that effectively integrates these factors and levels, potentially incorporating simple gaming features. Once researchers finish the implementation and tune the details with pilots, researchers would adapt the experimental procedure by sessions that are outlined by the transitions. It is highly recommended to take gaps/rest (normally at least one day apart) between sessions due to the discomfort feelings.

4.1 Example of application of LIA

The LIA protocol can be further customized to differentiate the effectiveness of various techniques in reducing cybersickness. The goal is to identify the most effective method for minimizing cybersickness, enabling personalized application based on individual preferences. For instance, consider an experiment with three factors: Linear translation (0: Teleportation, 1: Normal linear translation), rotation translation (0: Angular rotation, 1: Snap turn), and field of view (FOV) reduction (0: With FOV reduction, 1: Without FOV reduction). Following the LIA protocol, the first session involves a general game scene with basic features such as coin collection. In the second session, participants experience conditions with teleportation, snap turn, and FOV reduction during linear acceleration. Previous studies suggest that these cybersickness reduction techniques may be less informative and potentially detrimental to the overall gaming experience [2]. Moving on to the third session, participants are given the option to choose the least uncomfortable condition for them. This process helps determine the tolerable conditions for each individual. Subsequently, in the fourth session, participants select an additional factor that is comparatively less sickness inducing. Gradually introducing one factor or an extra level of a factor allows us to discover the most comfortable conditions personalized for each individual while maintaining the highest possible gaming experience.

5 Controlled Experiment

Starting from this section, we present the second part of the paper, focusing on the evaluation of the LIA protocol through a controlled experiment.

5.1 Protocol

The present experiment aimed to evaluate the feasibility and validity of the proposed LIA protocol. To do so, rotational movements along three axes (Roll, Pitch, Yaw) were selected as experimental factors, given that rotation has been identified as a main contributor to cybersickness. Following the protocol described above, we have three factors $\{f_r, f_p, f_y\}$ and each factor has two levels marked as **{0,1}**: **0** is without rotation, **1** is with rotation. The total number of sessions is 4. We describe the four sessions in detail as follows:

A within-subject experiment was conducted, separated by a minimum interval of 1 day between each session (up to 3 days). Participants were first asked to complete a consent form and demographic questionnaire, including the VIMSSQ and MSSQ. As shown in Figure 2, the general experiment flow began with a pre-SSQ assessment to gauge general discomfort before VR exposure. Participants were then equipped with EGG, ECG, and EEG electrodes, and underwent a five-minute baseline recording without the VR headset. Then, the experiment continued with VR rotations for 20 minutes, with participants reporting their discomfort level (with Fast Motion sickness Scale) [38] every minute during both the baseline and VR exposure. Instructions were given to participants to ensure the best quality of recordings: to avoid excessive movements and remain as still as possible; to avoid deep breathing or talking during the EGG recording, except for reporting FMS; and to signal the investigator if they felt too sick to continue the session. To minimize impedance, investigators may shave a small area of hair on the abdominal positions and use a conductive gel to enhance signal transmission. The session concluded with a post-SSQ immediately after VR exposure and an interview to gather subjective experiences.

S1: As aforementioned, the first session involved the presentation of rotational stimuli along all three axes in a worst-case scenario. Participants were initially exposed to a tutorial session, which was designed to familiarize them with the gaze shooting game and the direction of rotational axes, see Figure 3 (A video illustration is attached as supplementary material). 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.

S2: The second session involved a minimal cybersickness configuration with no rotations {0,0,0}, In this session, participants were solely required to engage in the gaze-shooting game, similar to Session 1.

S3: Beginning with the third session, we introduced a new factor; the focus is on choosing the least-sickness inducing axis. This axis is determined based on the subjective susceptibility rankings provided by each participant.

S4: In the 4th session, due to the fact that the highest level of the existing factor was already at 1, the only remaining option was to introduce an additional factor. Consequently, participants were exposed to combinations of the two axes with relatively less sickness, according to their individual preferences.

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5.2 Rotation construction in each session

The rotational movements were generated through a custom python code. Each 5-second period involved a constant speed rotation ranging from -270 to -240 degrees and 240 to 270 degrees, followed by a 4-second pause for evaluating the Fast Motion Sickness Scale (FMS) after every minute. To minimize extraneous factors, the following precautions were taken: First, to eliminate the impact of rotation speed across sessions, the same sequence of rotations was applied to each session except to the second session that has no rotation, ensuring that the magnitude of rotation velocity was consistent across all 5-second intervals in sessions 1, 3, and 4. Second, the direction of rotation was altered every 5 seconds in each session, except for the second session, to induce cybersickness through a fixed pattern of directional changes after a fixed duration.

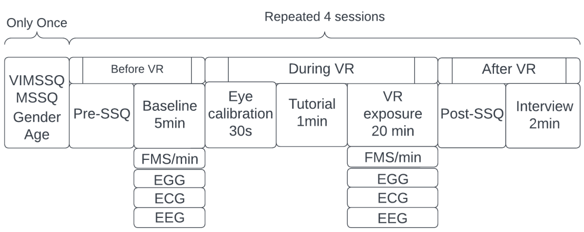

Fig. 2. The sessions commenced with participants filling out a consent form, providing demographic information, and undergoing a pre-SSQ assessment. Following this, they engaged in a 5-minute baseline recording while wearing physiological sensors without VR. Afterward, a one-minute tutorial was provided, and participants played a 20-minute VR game using eye-based interaction. Throughout the VR experience, participants reported their discomfort levels every minute using the FMS. Participants were instructed to limit their movements and promptly inform the staff if they felt unwell. Finally, the sessions ended with a post-SSQ assessment, followed by an interview to capture their experiences.

5.3 Game Design

A VR game set in a futuristic space city environment was employed to provide a rich 3D context for rotational movements. The skybox was configured with a dark blue color and an abundance of stars, and the main camera was positioned inside a spaceship located in the center of a structure consisting of buildings and asteroids (as illustrated in Figure 3). Pilot experiments revealed that pure rotation alone was not sufficiently engaging to maintain participant attention, leading to the integration of an interactive game feature utilizing the head-mounted display's (HMD) embedded eye-tracking capabilities. Feedback from pilot studies also suggested that participants might experience unintended rotations due to active head movements while attempting to destroy asteroids. To address this issue, participants were instructed to keep their heads stationary and to only use their eye gaze to destroy the asteroids. Furthermore, the spawning of asteroids was randomized and limited to specific regions depending on the session (e.g., in the Pitch-only condition, asteroids only spawned in 3D space along the Pitch direction). Please refer to the supplementary video for additional details.

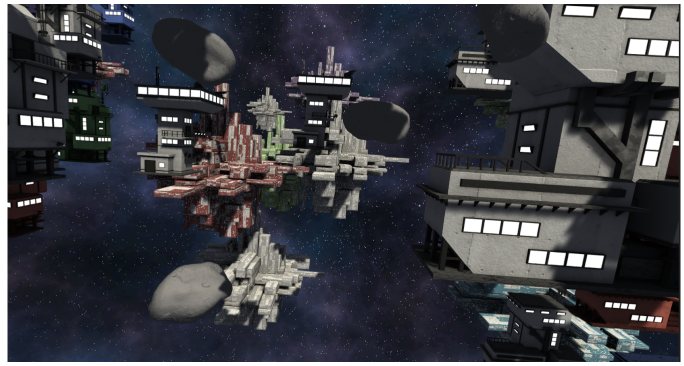

Fig. 3. A Screenshot of the participant viewpoint within a futuristic space city shooting game. We modeled two different kinds of buildings with six different colors. The buildings were randomly and homogeneously generated within a 800 * 800 * 800 cubic space to produce an equivalent optic flow for any rotation axis (or combination of axes). Asteroids were spawned inside a smaller cube within the eye-focus reachable space along the selected axis/axes in each session.

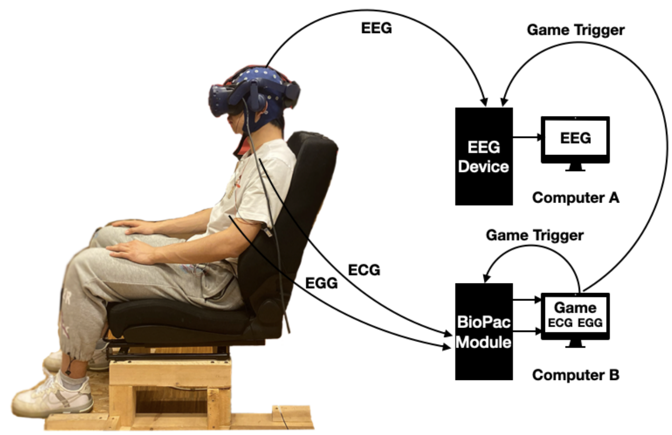

Fig. 4. Setup of the experiment. The full physiological data analysis is presented in another paper [39]

5.3.1 *Material*

The virtual reality (VR) experience in this study was facilitated by the HTC Vive Pro Eye (HTC, 2019). The headset was equipped with Tobii Eye Tracker units, which allowed for precise tracking of eye movements during VR exposure. The eye-tracking data were recorded at a sample rate of 120 Hz, with an accuracy of 0.5 degrees and a latency of 10 milliseconds. The HTC Vive Pro Eye headset has advanced specifications, including dual OLED screens providing a 110-degree diagonal field of view, a combined screen resolution of 2880 x 3200 pixels, and a refresh rate of 90 Hz. The system was powered by a 2.8 GHz Intel Core i9 processor with 32 GB of memory, and an NVIDIA GeForce GTX 2080 graphics card, operating on the Windows 10 operating system. Gastric signals were obtained using the Smart EGG100D Electrogastrogram Amplifier and the MP160 System, both provided by BioPac Inc. The sampling frequency was set at 250 Hz. Two triggers, indicating the beginning and end of rotation, were transmitted through a parallel port from the customized virtual reality (VR) game. The Electrogastrogram (EGG) was acquired by placing three

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electrodes on the participant's stomach, following the recommended standard positions by BioPac (refer to Figure in supplementary materials). The recordings were monitored using the Acknowledge software version 5.0 from BioPac. Additionally, the Electrocardiogram (ECG) signal was collected and utilized to extract the breathing signal, that is required for analyzing the EGG data (however the physiological data analysis is beyond the scope of the present paper [39]).

5.4 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, and the data from the participants who discontinued their involvement were also included for specific purposes (as indicated in the results). Participants were recruited from 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.

5.4.1 Ethic clarification

The study was approved by the swiss ethics committee of the Canton Geneva (project CCER 2018-02006) and all participants were remunerated for their time at a rate of 25 swiss francs per hour. Participants who were unable to complete a session due to sickness were still compensated for a full session, and those who chose to end their participation early were respectfully queried about their motivations and availability for future sessions occuring on a different day. Although a recommendation for termination was given to participants experiencing severe symptoms, a few participants chose to continue with the experiment due to their strong dedication to the study purpose. Overall ten participants chose to discontinue the experiment over a total of 45 participants. It is noteworthy that the safety and well-being of the participants were of utmost importance throughout the study, and any participant exhibiting severe symptoms was advised to discontinue their participation.

6 RESULTS

6.1 Summary of Analysis

We analyzed the subjective feedback data from two perspectives. Initially, we conducted a descriptive analysis, drawing inspiration from previous papers [22], [23], to demonstrate the likelihood of users having specific preferences regarding different rotation axes. Subsequently, we employed standard statistics to enhance our comprehension of the changes in cybersickness levels throughout multiple sessions. Again, objective signal processing and data analysis are presented in another full paper [39].

6.1.1 methods

All analyses were carried out using custom Python code. Descriptive analysis was made through Markov chain plots and lineplots. Shapiro–Wilk test were applied to determine whether the sample data have been drawn from a normal distribution. Paired t-test was used for parametric data in normal distribution and wilcoxon-signed rank test was used for the non-parametric data. For comparisons among groups with different sample size, we used permutation test. Also, we used Pearson correlation to measure the strength of the linear relationship between two variables (e.g. Correlation between MSSQ and SSQ). We present the preliminary results in detail below. Finally, we must highlight that all the partipants who force quit in the first session were only considered in the descriptive analysis in Figures 5, 6, 11, 12, 13, 14. We excluded them for the rest of the data analysis.

To process the SSQ data, we strictly followed the methods described in [40]. We computed :

- SSQ total score (Delta TS)
- SSQ-Nausea score (Delta N)
- SSQ-Oculomotor discomfort score (Delta O)
- SSQ-Disorientation score (Delta D)

Our computations for MSSQ and VIMSSQ were done following the methods described in [24], [41].

6.2 Individual susceptibility to rotation axes triggers

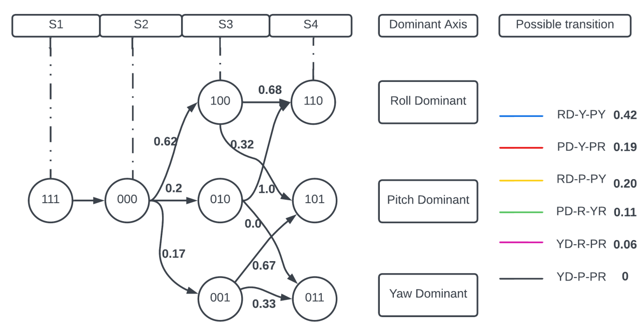

Fig. 5. The path chosen by the participants, each color indicates a selected path during the experiment and the number represents the probability of the selected path by participants. 111 represents the worst configuration of three axes rotation in Yaw Pitch Roll, 000 represents the rotation-free configuration , 100 represents Yaw-Only rotation, 010 represents Pitch-Only rotation, 001 represents Roll-Only rotation, 110 represents rotation configuration along Yaw_Pitch-Only, 101 represents rotation configuration along Yaw_Roll-Only, and 011 represents rotation configuration along Roll_Pitch-Only. The black numbers above the black circle and colored lines are the probability of participants who enrolled in this path. The graph on the right side summarizes the probability of the path is chosen.

A majority of participants (N = 22) rated Roll axis as their dominant axis. Among which, we identified 14 participants who have Yaw as their least dominant axis and 7 participants who have Pitch as their least sick axis. Similarly, we have 11 participants who rated Pitch as their dominant axis. Among which, 7 of them chose Yaw as their least dominant axis and 4 chose Roll as their least dominant axis. Finally, we also have 2 participants who chose Yaw as their dominant axis and both of them rated Roll as their least dominant axis.

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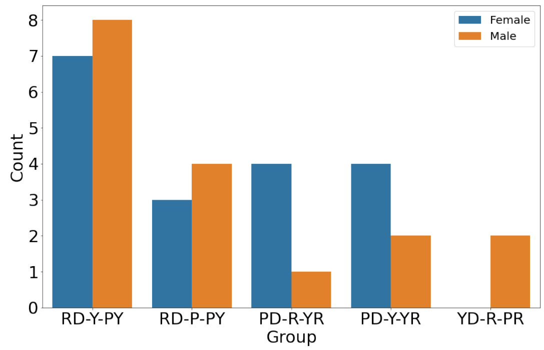

Fig. 6. Gender distribution across selected paths.

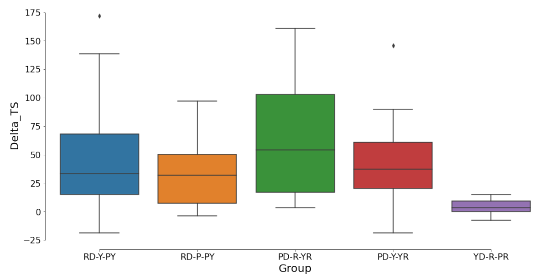

Fig. 7. Variations of the SSQ total scores across the five paths, named as follows: The first two letter represents dominance, for example: RD means Roll Dominant, The letter in the middle represents the least sickness inducing axis choice in S3. The final two letter represents the choice of the two less sickness inducing axes in S4. Statistical test was performed with permutation test due to the different size in each group. No significant difference was found among the first four paths (Roll and Pitch dominant). Given the small number of participants (only 2) who were Yaw-dominant, we don't compare the associated results with other paths' results.

6.2.1 Transitions

All participants were given instructions to avoid the axis that caused them the most discomfort. The selection process for participants enabled us to calculate the probability distribution of the given options. The results are presented using a Markov chain, following the approach used in previous paper [22]. The first two sessions were the same for all participants, but starting from S3, participants made their own choices, leading to divergence among them. Across all selections, the results indicate that a significant majority of participants preferred to select the Yaw axis and avoid the Pitch and Roll axes in S3. As for the second decision in S4, participants primarily chose to avoid Roll, resulting in the RD-Y-PY path being the most frequently selected. Among the participants who chose Pitch as their least uncomfortable axis (which accounted for 20% of the total), all of them selected Roll as the axis they wanted to avoid the most. In contrast, a minority of participants who chose Roll as their least uncomfortable axis showed a tendency to avoid Pitch more than Yaw in Session 4.

6.2.2 Plackett Luce Model

To further examine the validity/effectiveness of our ranking population distribution, we used a probabilistic model of ranking data named Plackett Luce Model [42] [43]. The Plackett-Luce model is a statistical model used to analyze rankings or preferences [44]. It is commonly applied in fields such as psychology, marketing, and decision-making analysis. It helps to understand and quantify the preferences people have when ranking or choosing between different options. In our study, we applied the Plackett-Luce model to our ranking data to assess its efficacy in capturing the true population distribution of preferences. The results of our analysis indicated that the probability of ranking for Roll as the most severe axis was 0.52, for Pitch was 0.35, and for Yaw was 0.12. These probabilities provide valuable insights into the dominance of particular attributes in the ranking process.

6.3 Individual susceptibility with SSQ score variations

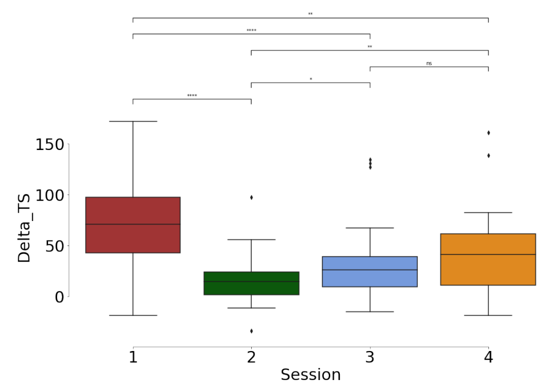

Fig. 8. Δ TS distribution over Sessions, error bars represent the standard deviation.

6.3.1 Gender

In the present study, we conducted a comprehensive statistical analysis to investigate the influence of gender on the dependent variable, considering its potential interaction with both session and path groups. To examine the gender effect in relation to sessions, we employed a mixed analysis of variance (ANOVA), treating gender as the between-group factor and session as the within-subject factor. The results revealed a statistically significant gender effect, with a small

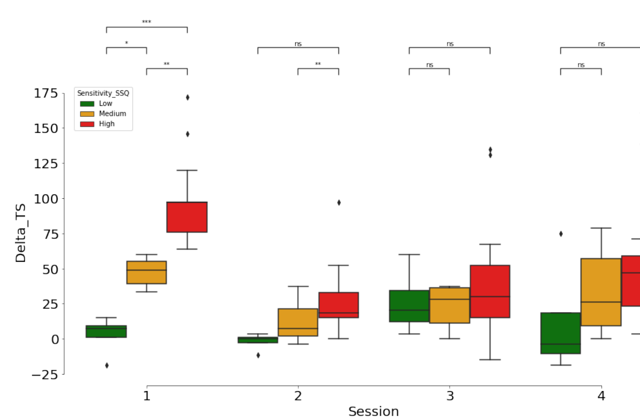

Fig. 9. (left) The individual sensitivity is classified according to the first session ΔTS score [45]; by design of the LIA protocol, the ΔTS scores of sessions 2 to 4 are expected to display less significant differences across susceptibility categories

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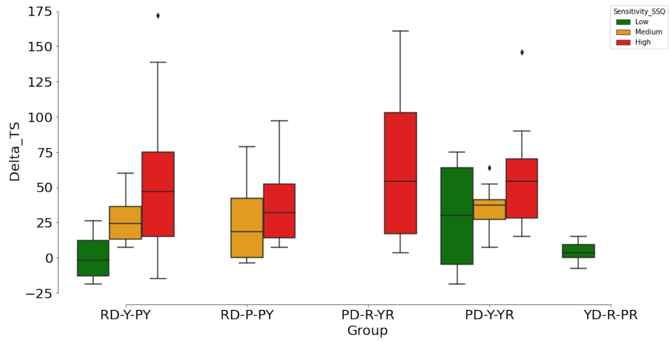

Fig. 10. Individual sensitivity distribution over each path.

effect size (F(1,33) = 7.45, $p < 0.05$, $\eta_p^2 = 0.18$). Furthermore, the main effect of sessions was found to be highly statistically significant (F(3,99) = 23.1, p_corr <0.0001, $\eta_p^2 = 0.41$), indicating a significant variation among sessions. These findings demonstrate that sessions exert a substantial impact on the dependent variable. In terms of the interaction between gender and sessions, our ANOVA results revealed that it was not statistically significant (F = 0.66, $p > 0.05$, $\eta_p^2 = 0.01$). As anticipated, a substantial disparity was observed among the sessions, prompting us to conduct a subsequent post-hoc analysis. The results show that the SSQ data of S1 follows a normal distribution. While the other sessions failed the normality test. The Wilcoxon-signed rank test indicates that there is a significant difference between S1 and S2 with a p-value $< .001$. Likewise, we also found significant differences between the pairs of (S1,S3) and (S1,S4) with p-values p$< .001$ and $p < .01$. Interestingly, there is no significance between the pairs of (S3, S4) with a p-value of 0.17. The p values reported was corrected with Bonferroni correction. The overall delta SSQ score distributions are presented in Figure 8.

Moreover, we extended our investigation by examining the interaction between gender and different paths using a two-way ANOVA. The results indicated a lack of significant interaction (F = 0.90, $p > 0.05$, $\eta_p^2 = 0.01$).

6.4 Individual susceptibility with FMS

Fast motion sickness questionnaire (FMS) was used to assess overall discomfort levels per minute during the VR exposure in every session. We computed longitudinal trajectories of each participant in each session. Figures 11, 12, 13, 14 are organized by grouping the selected path with participant ID on top of each sub-figure, from which we identified seven highly-sensitive participants with low tolerance to cybersickness. We employed different colors to distinguish the sessions based on their potential to induce cybersickness. Specifically, we assigned the color red to Session 1 (S1), blue to Session 2 (S2), green to Session 3 (S3), and orange to Session 4 (S4), Simply put, these participants could not finish all the 20 minutes of rotations in S1 (ID 7, 8, 16, 18, 22, 24, 27, four are female, three are male). The FMS of these high sensitive individuals quickly rose intensively with a bigger slope. Unsurprisingly, we could also identify four participants with high resistance or tolerance to cybersickness (ID 10, 23, 36, 54). In contrast to the highly sensitive individuals, they developed minimal discomfort feelings with a flat slope. Generally, the mean FMS cores present an increasing trend with minutes in all sessions but differ in incremental speed.

Upon closer examination of the graph (see Figures 11, 12, 13, 14), the results reveal the intricacy of individual susceptibility. As anticipated, we were able to categorize participants into four distinct types:

- T1: The first group comprises participants who are immune to all factors. These individuals, identified by the IDs 36, 54, 10, and 23, exhibit a lack of sensitivity to the factors being studied.
- T2: The second group consists of participants who exhibit strong sensitivity to only one factor. This pattern is observed in 13 participants, specifically with the following IDs: 22, 51, 18, 15, 14, 59, 31, 7, 8, 12, 28, 53, 35, 55 and 57.
- T3: we identified a group of participants who are sensitive to more than one factors. The IDs of these individuals are 16, 30, 24, 58, 27, 9, 19, 20, 25, 34, and 13, 32 .
- T4: Lastly, there exists a set of participants who display equal sensitivity to all factors. Their IDs are 26, 52, 11, and 29.

6.5 Correlation analysis

Interestingly, we found a correlation profile of SSQ total scores and subscale scores (Delta N $>$ Delta TS $>$ Delta D $>$ Delta O) with FMS. Specifically, Pearson correlation indicates a high positive correlation between the 20th minute FMS with the Delta_TS (coefficient = 0.59, $p < 0.001$), an even stronger correlation with Delta_N (coefficient = 0.64, $p < 0.001$). Similarly, the correlation coefficient between Delta_D and FMS is (coefficient = 0.57, $p < 0.001$). The correlation between SSQ oculomotor subscore and FMS is the lowest (coefficient = 0.38, $p < 0.001$).
Concerning the correlation between MSSQ and Delta_TS, surprisingly, we found that there is little chance that MSSQ and Delta_TS are correlated (coefficient = 0.04, p = 0.80). We also found that there is a weak positive correlation between VIMSSQ and Delta_TS (coefficient = 0.20, p = 0.24). The questionnaires and calculations are documented in the supplementary material.

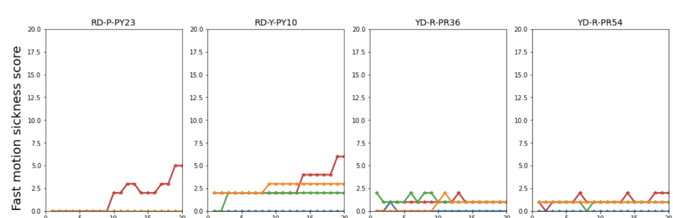

Fig. 11. T1 participants longitudinal trajectories ; these participants are sensitive to no factor, each star is an FMS answer queried every minute (Session colors: S1=red, S2=blue, S3=green, S4=orange).

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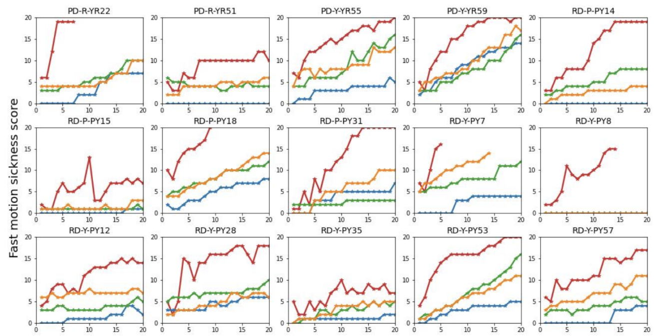

Fig. 12. T2 participants longitudinal trajectories; these Participants are sensitive to one dominant factor, each star is an FMS answer queried every minute (Session colors: S1=red, S2=blue, S3=green, S4=orange).

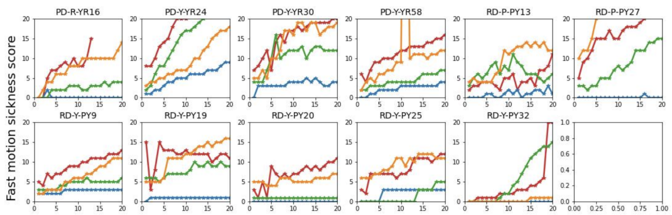

Fig. 13. T3 participants longitudinal trajectories; these Participants are sensitive to one dominant factor, each star is an FMS answer queried every minute (Session colors: S1=red, S2=blue, S3=green, S4=orange).

7 Discussion

7.1 Individual susceptibility towards cybersickness triggers

The analysis of the Markov chain plot reveals a clear pattern: the majority of individuals show a tendency to refrain from rotating around the Roll axis. Furthermore, a smaller segment of individuals also exhibit a preference for avoiding Pitch rotation, while an even smaller subset opts to avoid rotation along the Yaw axis. This finding supports the initial hypothesis that individuals may have varying sensitivities to specific factors. However, it is worth noting that the susceptibility of individuals turned out to be more intricate and multifaceted than originally anticipated. By closely analyzing the graph (See Figures 11, 12, 13, 14), we discovered four distinct participant groups with varying susceptibilities considering both cybersickness triggers and severity levels. The first group, intriguingly, displayed immunity to all rotation factors, indicating the presence of individuals who are resilient to rotations. Understanding the mechanisms behind this immunity could inform strategies to mitigate cybersickness for a broader population. The second group consisted of individuals highly sensitive to a specific factor, suggesting that certain triggers can significantly affect their susceptibility to cybersickness. This finding raises the possibility of identifying these triggers and developing personalized interventions to minimize cybersickness in this subgroup. The third group consisted of individuals who were sensitive to multiple factors, illustrating the intricate nature of individual susceptibility. These individuals may experience cybersickness as a result of a combination of triggers, underscoring the significance of detecting susceptibility to cybersickness triggers for each individual. The final group exhibited equal sensitivity to all rotation axes, suggesting some individuals may be highly susceptible to cybersickness regardless of the specific triggers involved. Recognizing this group is crucial for targeting interventions and designing virtual experiences that cater to their needs.

7.2 Individual susceptibility in traditional understanding

7.2.1 Gender

In our introduction, we highlighted that previous research on individual susceptibility mainly focused on factors such as gender and age. In order to delve deeper, we specifically examined the gender factor and its influence on individual susceptibility, drawing upon established understandings. Upon analyzing the data, we found that there is a significant difference between the genders if we combine all data. These findings align with existing literature that has explored the impact of gender on cybersickness [5], [9], [10]. However, we should emphasize the small effect size, meaning that the difference is highly due to the large sample size of the data (Because we combined data from all four sessions). Upon closer examination, we discovered that there were no notable differences between genders in the first and second sessions. However, in the third and fourth sessions, both male and female participants experienced a decrease in sickness scores. Additionally, we noticed that males exhibited an even greater decrease on sickness score upon their choices compared to females. Furthermore, when we categorized participants based on their chosen paths (e.g., RD-Y-PY), there was no significant gender effect observed. This lack of gender-related disparities in susceptibility to cybersickness within our study is not surprising, as the LIA protocol aims to minimize cybersickness based on individual preferences. Therefore, it is expected that gender would not be a significant differentiating factor in this context.

7.2.2 Individual sensitivity classification

The three sensitivity groups (Low, medium, and high) identified based on the scoring system outlined in [45] exhibited a notable difference in S1 but converged with no significant difference in S3 and S4, shown in Figure 9. This indicates that the LIA protocol effectively avoids triggering cybersickness, even for individuals with high sensitivity. Additionally, we examined the sensitivity levels across five different path groups, see figure Figure 10. The results revealed that the PD-R-YR group displayed the highest sensitivity, while the YD-R-PR group exhibited the lowest

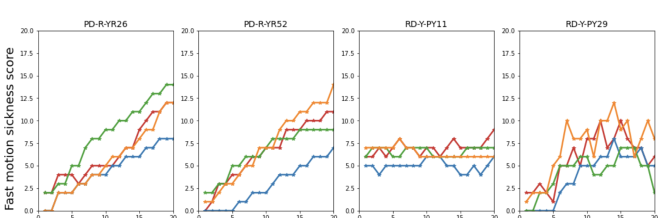

Fig. 14. T4 participants longitudinal trajectories; these Participants are sensitive to one dominant factor, each star is an FMS answer queried every minute (Session colors: S1=red, S2=blue, S3=green, S4=orange).

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sensitivity. However, it is important to note that the YD-R-PR group had a limited sample size, leading us to exercise caution in drawing definitive conclusions about their sensitivity level. These findings demonstrate the validity of LIA in avoiding cybersickness for individuals across varying sensitivity levels. Furthermore, they highlight the different sensitivities exhibited by participants following different paths, with the PD-R-YR group being particularly sensitive. Nonetheless, further research with larger sample sizes is needed to confirm these observations.

7.3 MSSQ and VISSQ

Surprisingly, the MSSQ and VISSQ results were not shown to be as promising predictor of cybersickness as in previous literature [14], [46], [47], [48], [49], [50], [51]. In contrast, our results are aligned with the no-correlation findings from previous papers [52], [53], [54]. The correlation analysis revealed a low positive correlation between MSSQ and SSQ ($r= 0.04$, $p > 0.05$), also VISSQ and SSQ ($r = 0.20$, $p > 0.05$) This might be explained by the fact that the three axes rotational experience is unusual in daily life. Although the Pitch axis rotation is claimed to be similar to the one eliciting sea sickness [1], the magnitude of rotation is much larger than what can be experienced on a boat. Thus, the prediction power of MSSQ may significantly decrease in our paper due to the distinction of cybersickness from motion sickness [55]. With VISSQ, we were able to assess the past game experience and past individual susceptibility to VR. The reasons for a low correlation are unclear but may have something to do with the limited past VR experience of participants. Most of them rarely or never experienced VR before (Only one of them often experienced VR but this participant had to force-quit due to high sensitivity; more details in supplementary material). Another potential explanation could be that the predictive power of VR experiences might have been diluted by previous experiences. To elaborate, the VIMSSQ questionnaire included a total of eleven different devices (contents), with only two of them being related to VR. Furthermore, there is no weighting applied to the calculation of the final score.

7.4 Application of the LIA protocol

Our validation experiment effectively demonstrates the efficacy of the LIA protocol in assessing individual susceptibility. We must emphasize that there is no previous paper aiming directly to investigate the individual susceptibility to cybersickness triggers. Frequently adopted experiment protocols are within-subject design, between-subject design, mixed factorial design (Having both within-subject and between subject factors). When comparing these traditional experimental protocols, both LIA and within-subject factorial design prove capable of identifying the ranking of cybersickness factors for individuals. However, the LIA protocol surpasses the within-subject factorial design by requiring fewer sessions and minimizing the duration of discomfort. To illustrate this difference, a similar investigation conducted by Tian et al. [56] delved into three common factors in VR games—longitudinal translation, lateral translation, and Yaw axis rotation—utilizing a full factorial design. In this study, participants underwent a total of eight sessions, and the ranking of each condition was determined through SSQ scores after completing all sessions. In contrast, our findings highlight the distinct advantages of the LIA protocol in terms of practical time reduction and experiment efficiency. While between-subject studies are also commonly employed [36], they lack the capability to ascertain the ranking of individual susceptibility to multiple cybersickness triggers.

8 Limitations and Future Work

8.1 The LIA protocol

It is noteworthy to mention that the duration of the experiment in the LIA protocol description was not explicitly specified. In terms of future endeavors, our aim is to delve into the scientific validity of a shorter version of LIA. If each session could be condensed to a much shorter duration than the one we used, it would render the standardization and practical implementation of LIA considerably more convenient prior to conducting any substantial experiments. This investigation into a truncated version of LIA holds the potential to yield advancements in the field. By reducing the time required for each session, we would be able to streamline the assessment process and enhance its efficiency, paving the way for greater utilization and exploration of LIA's capabilities. However, one significant limitation could be that the shorter duration would not be sufficient for subjective measures like EGG. Therefore, achieving a balance in duration and other experimental settings is dependent upon the specific requirements of each experiment.

Another limitation of the LIA protocol arises as it is exclusively applicable to the study of multiple triggers within the scope of a single investigation. Due to the within-subject design nature, challenges also emerge in LIA particularly when factors exhibit more than two levels. Therefore, it is essential to note that the application of this protocol is most suitable for scenarios involving the study of multiple factors in situations where researchers have access to participants able to engage across multiple days and sessions. However, normal VR game settings often involve multiple factors, hence, LIA aims to provide an easier way to assess as many factors as possible at once to help find out the dominant factor(s) for individuals.

8.2 Validation experiment

We did not fully take advantage of participants who had to force quit (Only for descriptive analysis). Their data are also precious for analyzing individual susceptibility and predicting highly sensitive individuals. In fact, none of the previous studies included the analysis of those highly sensitive individuals before. However, force quitting raises the inevitable missing value problem. Here, the potential solutions envisioned could be filling the rest of the time with their last-minute data (possible repetition needed) or potentially fitting the ”incomplete” data to a model to predict the missing data. The limited number of levels presented in this experiment was primarily dictated by the constraints imposed by the experimental settings, particularly the time-consuming EEG setup process. However, there is potential to expand the current findings by exploring additional levels within the experiment. Increasing the number of levels could provide a broader understanding of the phenomenon under investigation.

Also, the validation experiment is confined to the design of an eye-based shooting game, limiting its generalizability to other types of interactions and game genres. We encourage further research on employing the LIA protocol with a broader range of VR game designs for a more comprehensive understanding. Additionally, The identification of the "least-sickness inducing axis" relies on participants' subjective susceptibility rankings but not taken the objective measures for reference. For future studies, a more robust approach would involve integrating objective results with subjective selections to mitigate potential bias.

Furthermore, it is worth noting that our study predominantly focused on one specific class of factors, namely rotation axis. However, it would be highly valuable to design experiments that incorporate other factors such as translational locomotion, field of view (FOV), scene complexity, and others. It could enrich the experimental design and yield valuable insights into the interplay between these factors and cybersickness [2]. By broadening the scope of factors considered in future experiments, we can enhance our understanding of cybersickness and its underlying mechanisms.

9 Conclusion

In this paper, we presented an innovative protocol named "Least Increasing Aversion" based on the Subjective Matching Technique but adapted to the assessment of factors potentially inducing negative side effects to a Virtual Reality experience. We illustrated its use with the evaluation of the individual susceptibility to three rotational axes (Yaw, Pitch, and Roll) to identify the individual aversion towards different rotational axis. Our results show that most participants are Roll-dominant as Roll axis rotation is the most infrequent in daily life [33], [34]. It is also evident that Yaw dominant participants are the minority since Yaw rotation is the most commonly used daily. Furthermore, there might be a particular population distribution of individual susceptibility to dominant factors (in our case, rotational axes).

The findings also indicate that individuals have varying sensitivities to specific rotation axis, with some showing a tendency to avoid certain types of rotational movements. The complexity of individual susceptibility is highlighted by the identification of distinct participant groups with different responses to cybersickness triggers and severity levels. This understanding has practical implications for designing personalized interventions, identifying triggers, and developing strategies to minimize cybersickness. Additionally, the presence of individuals who are resilient to all factors and those who are universally susceptible emphasizes the need for tailored approaches and considerations of multiple factors when designing virtual experiences. Overall, this research contributes to a deeper understanding of individual responses to cybersickness.

Finally, the present study provides validation for the effectiveness of the LIA protocol, which offers a promising template for future investigations involving more complex experiments related to cybersickness. The LIA protocol demonstrates its ability to accurately assess individual susceptibilities to cybersickness triggers while requiring fewer experimental sessions compared to traditional factorial designs. In other words, the LIA protocol demonstrates potential for enabling the manipulation of multiple levels and factors within a single experiment. Importantly, this protocol also minimizes the likelihood of participants experiencing discomfort during the experimental process. As such, the LIA protocol represents a valuable contribution to the methodological repertoire available for studying cybersickness and has the potential to advance our understanding of individual susceptibility in this domain.

Acknowledgments

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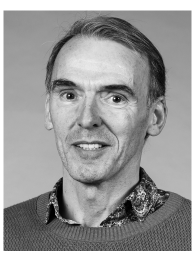

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