Exploring the effect of cognitive load on Cybersickness

Abstract

This study examines the impact of cognitive load on cybersickness within Virtual Reality (VR) environments, focusing on how varying levels of cognitive engagement can influence symptoms such as nausea and dizziness. Utilizing N-back tests to create high and low cognitive load conditions, and employing the HP Omnicept Cognitive Load Database (HPO-CLD) for objective measurement, the study investigates whether increased cognitive demands can mitigate cybersickness symptoms. Results indicate that high cognitive load significantly reduces symptoms of nausea and vestibular, suggesting a threshold effect where sufficient cognitive engagement can alleviate some adverse effects of VR immersion. However, no significant linear relationship between cognitive load and cybersickness was found, indicating that the alleviation may be mediated by factors such as attention allocation rather than direct cognitive load effects. We suggest that future research should investigate real-time changes in cognitive load and explore how does attention mediates the relationship between cognitive load and cybersickness in VR environments.

Introduction

Virtual Reality (VR) utilizes computer-generated simulations to deliver a lifelike sensory experience, offering benefits that traditional media cannot match. In education, VR enhances the illustration of abstract concepts and supports interaction in three dimensions (Kavanagh et al., 2017; Logeswaran et al., 2021; Pottle, 2019). In the research realm, VR is valued for its ability to improve external validity by providing 3D stimuli that more accurately reflect real-world environments compared to 2D objects (de la Rosa & Breidt, 2018). Its applications extend into the entertainment industry, including video games and films, further showcasing its versatility.

Despite these advantages, many users struggle to fully benefit from VR due to cybersickness—a type of motion sickness induced by immersive Extended Reality (XR) environments, such as VR and augmented reality (AR) applications (Lawson & Stanney, 2021). Symptoms can include nausea, dizziness, discomfort, and eye strain, with 73% of participants in some studies experiencing varying degrees of cybersickness (Laessoe et al., 2023). These symptoms can detract from the VR experience, reducing user engagement and posing safety risks, particularly in dynamic.

Understanding the underlying causes of cybersickness is crucial for developing effective mitigations. Two primary theories address motion sickness: Postural Instability Theory (PIT) and Sensory Conflict Theory (SCT). PIT posits that motion sickness arises from a loss of postural control (Riccio & Stoffregen, 1991). while SCT focuses on the mismatch between perceived and expected sensory signals (Reason, 1969). Research has largely supported SCT over PIT (Bos, 2011; Irmak et al., 2023; Riccio & Stoffregen, 1991), particularly in VR-induced contexts (Oh & Son, 2022; Zhou et al., 2019).

One promising approach to alleviating cybersickness involves introducing alternative stimuli to distract from the sickness-inducing ones. For instance, Bos (2015) demonstrated that motion sickness caused by specific frequencies could be mitigated by introducing a distinguishable vibration at a different frequency. Similarly, Kourtesis et al. (2023) found that music served as an effective distraction to reduce cybersickness in VR environments. In another VR experiment, Pöhlmann et al. (2023) explored the impact of cognitive load on cybersickness and observed that participants reported fewer symptoms when engaged in a Rapid Serial Visual Presentation (RSVP) task compared to just experiencing the VR environment.

However, Pöhlmann et al.'s (2023) study only considered a single level of cognitive load, leaving the effects of varying cognitive load levels unexplored. In the real-world environment, VR users are often exposed to a variety of tasks of different difficulties and hence require more than one level of cognitive load. A more detailed account of how different levels of cognitive load affect cybersickness would provide crucial information to VR developers to design applications that help alleviate users' cybersickness symptoms. At the same time, users can also leverage this knowledge to accommodate themselves in VR usage.

Current Study

To address this gap, the current study builds on Pöhlmann et al.'s (2023) findings by investigating the relationship between cybersickness and cognitive load in greater detail. Specifically, this study differentiates between high and low cognitive load conditions using N-back tests of varying difficulty. We hypothesize that participants will experience significantly fewer cybersickness symptoms under both cognitive load conditions compared to a control condition. According to cognitive load theory, more demanding tasks should lead to reduced attention resources allocated to cybersickness-inducing stimuli

(Lavie et al., 2004; Pöhlmann et al., 2023), suggesting that participants will experience fewer symptoms under high cognitive load compared to low cognitive load. Additionally, we anticipate a general negative correlation between cybersickness and cognitive load.

Method

Participants

To determine our sample size, we conducted a power analysis using data from a previous study on cybersickness (Li, 2024). Since no prior research has examined multiple levels of cognitive load, we performed a paired t-test to compare cybersickness between cognitive load and no cognitive load conditions. The analysis indicated that a sample size greater than 20 would provide a power exceeding 70% (Figure 1).

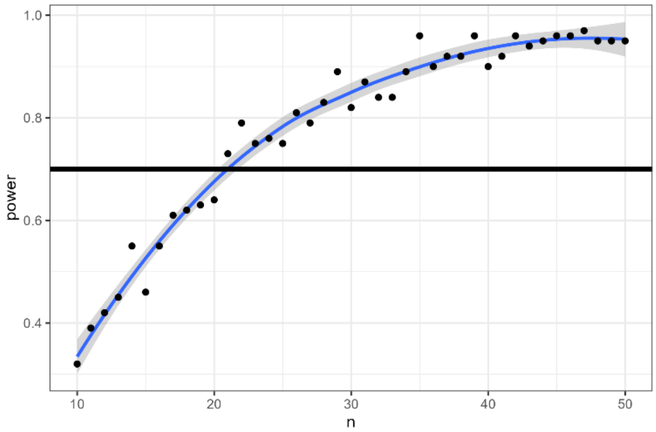

Figure 1

We recruited 28 participants via a university participants pool. Participants were informed about the risks of the experiment before taking part and were compensated £7 for their time. Participants who has experienced severe sickness or no sickness at all were excluded in Pöhlmann et al.'s (2023) study, we filtered participants the same way. Specifically, two participants who experienced severe cybersickness and four who reported no symptoms across all conditions were removed from the study. This left a final sample of 22 participants for analysis.

Apparatus

In this study, we used the N-back test to manipulate cognitive load. Although the N-back test is less precise than the Reading Span Task for measuring working memory capacity, it is effective for assessing general cognitive load and adjusting task difficulty (Jaeggi et al., 2010). In our experiment, participants engaged in 1-back, 2-back, and 3-back tests. The 1-back test served as a practice round to familiarize participants with the VR environment and controls. The 2-back and 3-back tests were used to represent low and high cognitive load conditions, respectively.

To measure cognitive load in the VR environment, previous studies have often relied on questionnaires such as the NASA Task Load Index (Pöhlmann et al., 2023). However, questionnaires can be influenced by individual biases and may not accurately reflect real-time cognitive load. While brain imaging techniques like Electroencephalography (EEG) provide objective cognitive load measurements, they are cumbersome to set up and may cause discomfort (Hanzal et al., 2023; Heo & Yoon, 2020; Li et al., 2022). To avoid these limitations, our study utilized the HP Omnicept Cognitive Load Database (HPO-CLD). This machine-learning model predicts cognitive load based on data from pupillometry, eye-tracking, and pulse plethysmography (PPG), using sensors integrated into the HP Reverb G2 headset (Siegel, E.H. et al., 2021). In their report (2021), the model reached a 79.08% accuracy rate across 700 participants. The HPO-CLD uses sensors that are already built-in HP Reverb G2, allowing us to record cognitive load without any extra brain imaging equipment. The HPO-CLD model produces cognitive load readings once every frame (we set our refresh rate at 30 frames per second). We recorded these readings and calculated the mean cognitive load score for each condition.

Cybersickness was measured using the Simulator Sickness Questionnaire (SSQ), a widely accepted tool in VR research (Jang et al., 2022; Kim et al., 2018). The SSQ assesses three main components of simulator sickness: nausea, oculomotor and disorientation. Although other tools like the Cybersickness Questionnaire (CSQ) and Virtual Reality Sickness Questionnaire (VRSQ) claim to be more reliable for VR-specific environments, they are derivatives of the SSQ and share the same question sets with different scoring methods (Kim et al., 2018; Sevinc & Berkman, 2020). In our study, the SSQ was administered before and after the VR session to capture changes in cybersickness induced by the stimuli.

The SSQ used in this study was identical to the version developed by Kennedy et al. (1993). The questionnaire measured 16 items on a 4-point scale from 0-3: General Discomfort; Fatigue; Headache; Eyestrain; Difficulty Focusing; Increased Salivation; Sweating; Nausea; Difficulty Concentrating; Fullness of Head; Blurred Vision; Dizziness (Eyes Open); Dizziness (Eyes Close); Vertigo; Stomach Awareness; Burping. A score of 0 indicates no symptoms, while a score of 3 reflects intense symptoms.

We used the HP Reverb G2 headset, integrated with the Omnicept SDK, to collect cognitive load data (*HP Developers Portal | Omnicept,* n.d.). The VR environment was constructed using Unity (Version 2022.3.12f1) with a frame rate of 30 frames per second. To induce cybersickness, we adopted a tunnel-traveling scenario from Li et al.'s (2022) study, which has been proven effective in previous research.

The N-back tests deployed in the current study were developed based on the N-back tests from Jaeggi et al.'s study (Jaeggi et al., 2010). Each cognitive load condition involved 60 stimuli, with 20 correct responses. Letters were displayed for one second each, with a two-second interstimulus interval (See Figure 2 for an example of a set of 2-back test stimuli). Participants have a total of three seconds to react to the stimulus. After 180 seconds, the n-back tests and the tunnel-traveling session concluded. In the control condition, no letters were presented, and participants were instructed to focus solely on the tunnel without performing any tasks.

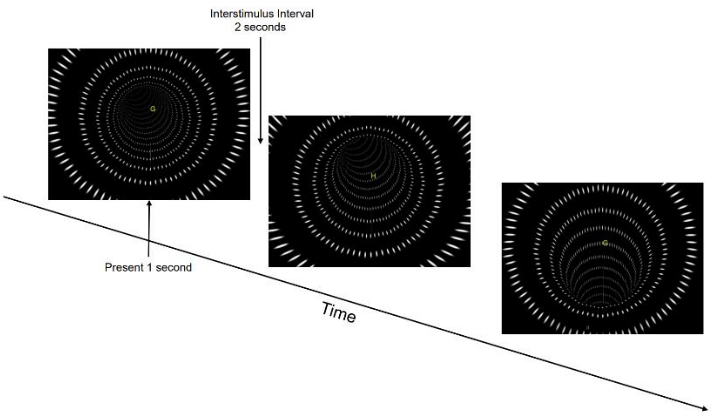

Figure 2

Procedure

This study employed a within-subject design, where participants completed four rounds: a practice round, a no cognitive load round, a low cognitive load round, and a high cognitive load round (Figure 3). Before beginning the experiment, participants were briefed on the study's procedures and provided informed consent.

In each round, participants first completed a set of SSQ before entering the cybersickness-inducing environment. They then spent three minutes in the environment, followed by another SSQ assessment. A two-minute break was provided between each round.

During the practice round, participants performed a series of 1-back tests within the VR environment to familiarize themselves with the task and the control. In the low cognitive load condition, they completed 2-back tests, while in the high cognitive load condition, they completed 3-back tests. The accuracy rate was calculated as the percentage of correct responses, and the skip rate was calculated as the percentage of times participants failed to respond when a corresponding letter was presented. In the control condition, no N-back tests were administered, allowing participants to focus solely on the VR environment.

The pace and conditions of the cybersickness-inducing environment were consistent across all rounds. The order of the three main conditions (no cognitive load, low cognitive load, and high cognitive load) was counterbalanced to control for order effects, except for the practice round, which was always conducted first. After completing all rounds, participants were debriefed and compensated for their participation.

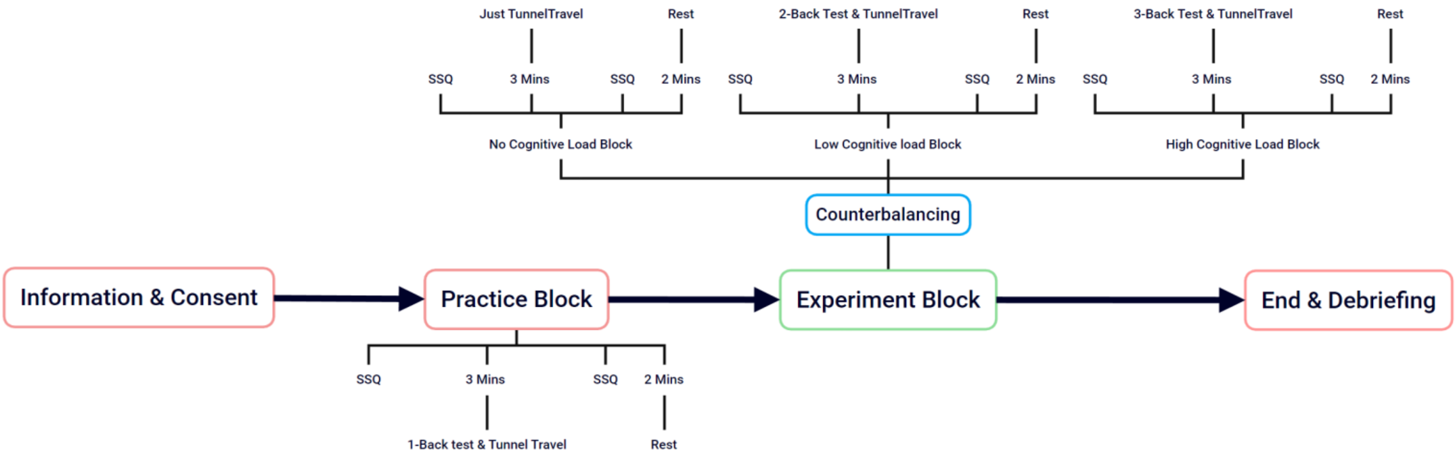

Figure 3

Result

While the SSQ is widely used to measure motion sickness, it may not be fully valid when used alongside cognitive-load-inducing stimuli. Cognitive load can exacerbate symptoms like difficulty focusing, difficulty concentrating, and a sense of fullness in the head, which is less likely to be induced by cybersickness but are still being measured in the SSQ. Therefore, inspired by Kourtesis et al.'s (2023) Cybersickness Questionnaire in Virtual Reality (CSQ-VR), we modified the SSQ by retaining five key items and excluding the rest. The revised questionnaire included two items for nausea (nausea and dizziness), one for vestibular symptoms (vertigo), and two for oculomotor symptoms (general discomfort and fatigue). To align the data with this scale, we adjusted the scores by adding 1 to each data point, dividing by 4, and then multiplying by 7.

We calculated the change in cybersickness by deducting the cybersickness score before the cybersickness stimuli from the cybersickness after experiencing stimuli:

$$Cybersickness\ change = sickness\ after\ the\ stimuli - sickness\ before\ the\ stimuli$$

Normality Check

The cognitive load data and the CSQ-VR data are fairly normally distributed (Figure 4). Additionally, changes in cognitive load in both the high and low cognitive load conditions also showed normal distribution (Figure 5).

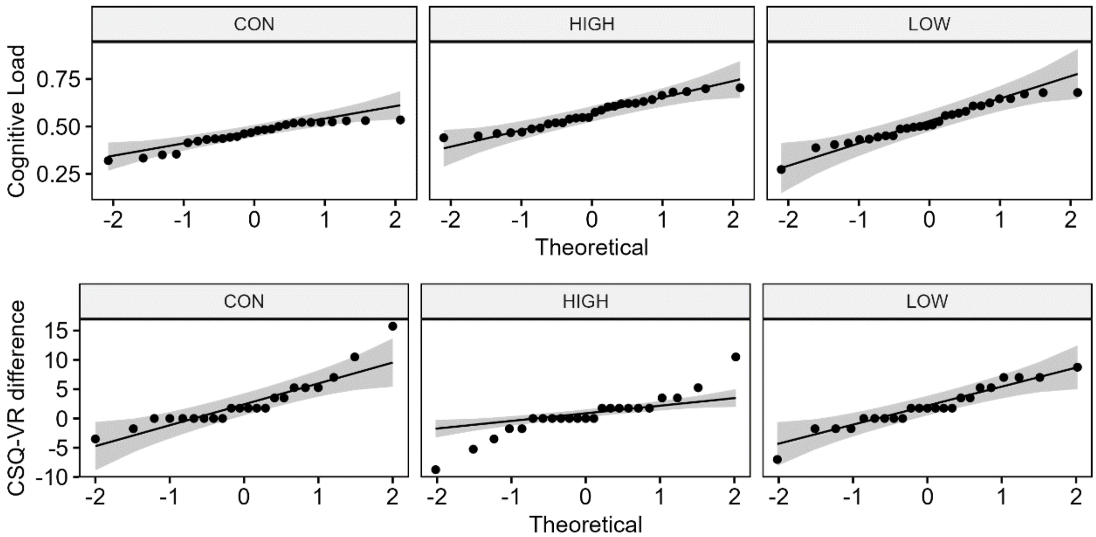

Figure 4

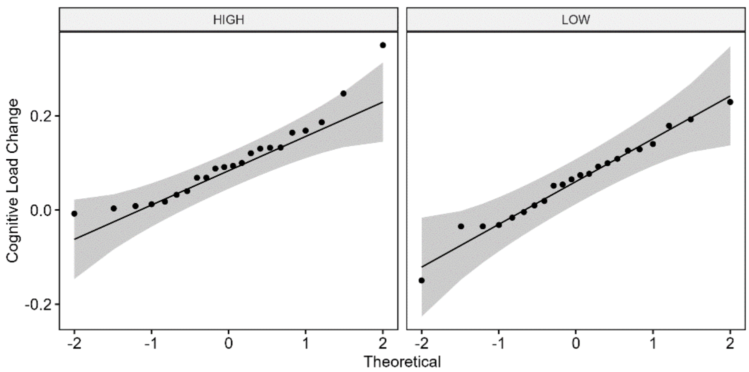

Figure 5

Cognitive Load manipulation check

A one-way repeated measures ANOVA confirmed that the N-back tests successfully induced varying levels of cognitive load. The low cognitive load condition ($M = 0.515$, $SD = 0.100$) and high cognitive load condition ($M = 0.555$, $SD = 0.081$) both produced significantly higher cognitive load scores compared to the control condition ($M = 0.453$, $SD = 0.066$), $F (2, 42) = 12.193$, $p < 0.001$ (Figure 6). Furthermore, the 3-back tests were significantly more challenging than the 2-back tests, as indicated by a higher correct response rate, $t (21) = 10.392$, $p < 0.001$, and a lower skip rate, $t (21) = -5.770$, $p < 0.001$ (Figure 7).

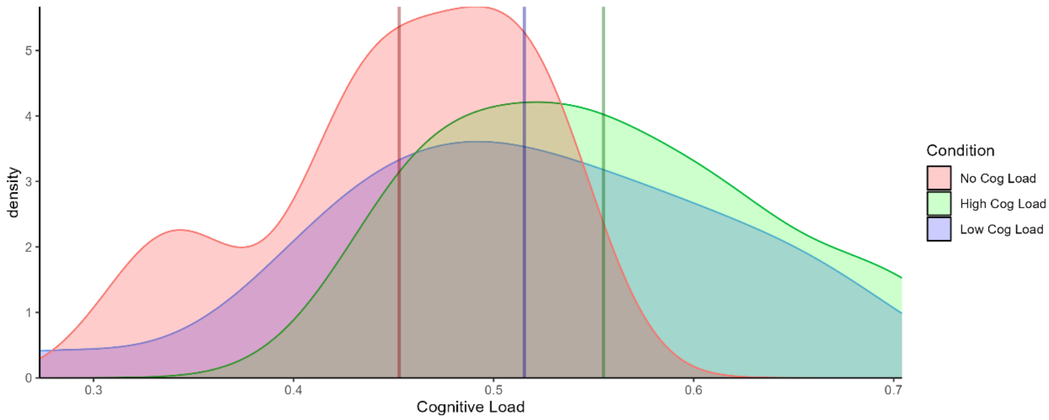

Figure 6

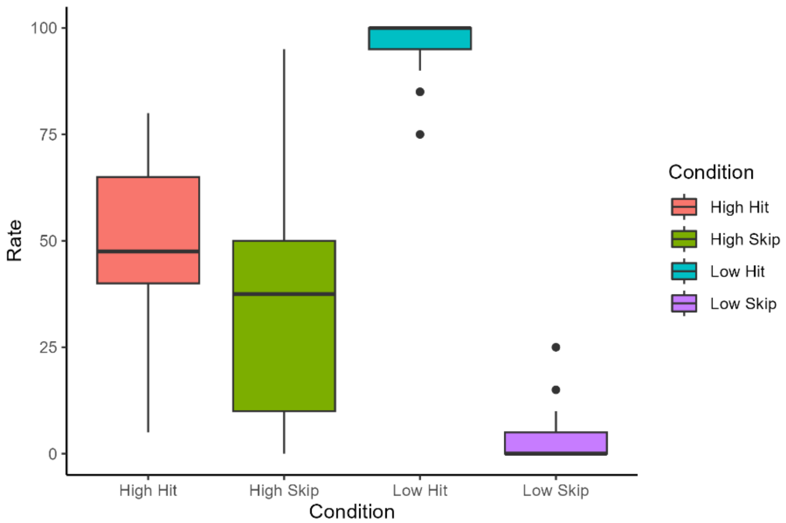

Figure 7

Data Analysis

A one-way repeated measures ANOVA revealed no significant effect of cognitive load on the overall CSQ-VR score difference, $F(2, 42) = 2.467$, $p = 0.097$. However, when the CSQ-VR scores were broken down into sub-scales, cognitive load had a significant effect on nausea symptoms, $F(2, 42) = 3.459$, $p = 0.041$, and on vestibular symptoms, $F(2, 42) = 3.824$, $p = 0.03$ (Figure 8). There was no significant effect on oculomotor symptoms, $F(2, 42) = 0.086$, $p = 0.918$.

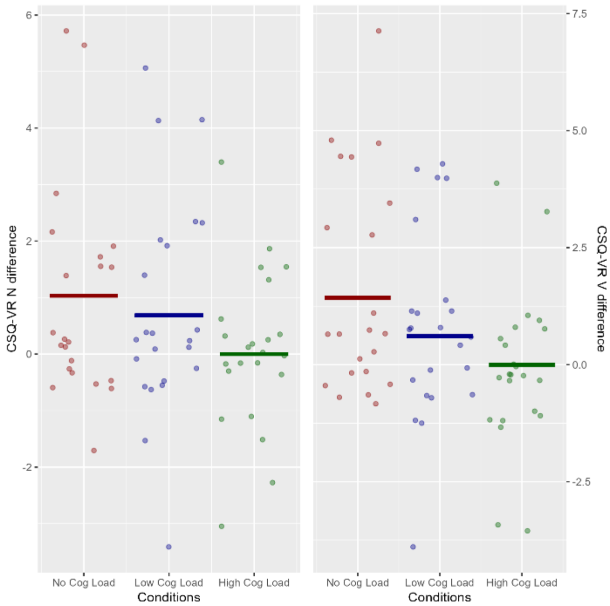

Figure 8

Post-Hoc Analysis

To further explore the impact of cognitive load on nausea and vestibular symptoms, we conducted post-hoc tests using the Bonferroni adjustment method. No significant difference in nausea was found between the high cognitive load and control conditions, t (21) = 2.324, p.adj = 0.091. However, a significant difference was observed in vestibular symptoms between the high cognitive load and control conditions, t (21) = 2.614, p.adj = 0.049. No significant differences were found between the high and low cognitive load conditions or between the low cognitive load and control conditions.

Explorative analysis

To further investigate the relationship between nausea/vestibular symptoms and cognitive load, we applied a Linear Mixed Effects model. To account for individual differences, we subtract the cognitive load score of the control condition from the high and low cognitive load condition. We input cognitive load as the fixed effect and the intercept for participants as a random effect. As the current study implemented a within-subject design, we also included the intercept for condition as another random effect.

$$lmer(formul = \ Nausea/Vestibular\ change \sim Cognitive\ Load\ change + (1|condition) \ + \ (1|P))$$

The analysis showed that cognitive load was not a significant predictor of nausea symptoms, β = -2.338, SE = 2.301, p = 0.317, or vestibular symptoms, β = -4.155, SE = 2.663, p = 0.127.

We partially confirmed our hypothesis. The effect of cognitive load on cybersickness was only significant in the high cognitive load condition. Neither did we find supporting evidence to predict cybersickness using cognitive load.

Discussion

Our findings indicate that cognitive load can reduce cybersickness, but only when the load is sufficiently demanding, as evidenced by the results from the 3-back tests. This suggests that cognitive tasks vary in difficulty, and only those that reach a certain level of complexity are effective in mitigating cybersickness symptoms. Specifically, our high cognitive load condition, with an average score of 0.555, falls within the medium-hard difficulty range, as categorized by Siegel et al. (2021). This observation is consistent with Pöhlmann et al.'s (2023) study, where a high cognitive workload, as measured by the NASA Task Load Index, also resulted in reduced cybersickness (Prabaswari et al., 2019). These results suggest a threshold effect, where alleviation of cybersickness symptoms requires a certain level of cognitive engagement.

This threshold effect might be further explained by Csikszentmihalyi's concept of the flow state, where individuals experience optimal performance and reduced distraction when engaged in tasks that are neither too easy nor too difficult (Csikszentmihalyi, 1990). In our study, the 2-back tests were relatively easy, with an average accuracy rate of 95.89% and 54% of participants achieving a 100% accuracy rate. Conversely, the 3-back tests were more challenging, with an accuracy rate of 50.36% and no participants achieving a 100% accuracy rate. It is possible that participants entered a flow state more readily during the 3-back tests, allowing them to focus more on the task and less on the sickness-inducing stimuli, thereby reducing their experience of cybersickness.

Coupling this with the fact that we failed to establish a significant linear relationship between cognitive load and cybersickness, these findings suggest that cognitive load does not directly alleviate cybersickness. Instead, the alleviation effect appears to be mediated by other factors, such as attention allocation. It is not merely the presence of cognitive load that mitigates cybersickness, but rather the extent to which the cognitive task engages the participant's attention to a degree that fosters a flow state.

Limitations and Future Research

In our study, we modified the Simulator Sickness Questionnaire (SSQ) to a 7-point scale based on the framework of the CSQ-VR by Kourtesis et al. (2023). While this adjustment was necessary for our study, it may have affected the validity and reliability of the measure in accurately capturing cybersickness symptoms. Future research should implement the full CSQ-VR scale to ensure comprehensive and precise assessment.

Although we calculated the mean cognitive load for each condition following the guidelines of the HPOCLD guidelines (2021), the model is capable of providing real-time cognitive load data on a per-frame basis. This capability would allow for a more detailed analysis of how cognitive load evolves throughout the experiment. Previous studies have used real-time measures such as the Fast Motion Sickness Scale and brain-imaging techniques to capture moment-to-moment changes in cybersickness (Li et al., 2022; Li & Chung, 2022). Combining both techniques, future research can explore the dynamic relationship between cognitive load and cybersickness over smaller timeframes to gain deeper insights into their relationship.

Further investigation is also needed into the role of attention in alleviating cybersickness. Our study did not include eye-tracking data, which could have provided valuable information on where participants were allocating their visual attention within the VR environment (Adhanom et al., 2023). Eye-tracking data, available on most VR headsets, could help clarify how visual attention is distributed between sickness-inducing stimuli and other elements of the environment.

Moreover, while our study focused on visual cognitive tasks, real-world VR applications often involve multiple sensory modalities, including both visual and auditory stimuli. Previous research has shown that people can process visual and auditory information simultaneously with minimal interference, although this dual-modal processing may become more challenging as task difficulty increases (Allport et al., 1972; He et al., 2023; Wickens, 2002). Incorporating auditory cognitive tasks in future studies could provide a more comprehensive understanding of how cognitive load across different modalities influences cybersickness, thereby enhancing the external validity of the findings.

Finally, exploring how the flow state affects attention allocation during VR experiences could offer further insights into the mechanisms that alleviate cybersickness. Since the flow state is associated with deep concentration and immersion in a task, future research could investigate the optimal task difficulty levels that induce flow and how these levels correlate with reduced cybersickness. This could involve varying the complexity of tasks across different sensory modalities and measuring both subjective experiences of flow and objective indicators of cognitive load and attention distribution.

Conclusion

The current study explored the relationship between cognitive load and cybersickness in VR environments, expanding on previous research by examining different levels of cognitive load through N-back tests. We found that high cognitive load can significantly alleviate cybersickness symptoms, particularly nausea and vestibular symptoms. Our findings suggest that the alleviation effect of cognitive load is not linear but rather contingent upon reaching a certain threshold of cognitive engagement. While this study provides valuable insights, it also highlights the need for further research into the role of attention and multimodal cognitive tasks in managing cybersickness. Understanding these dynamics could help optimize VR experiences, enhancing user comfort and engagement.

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