Attention Drives Cybersickness in Augmented Reality

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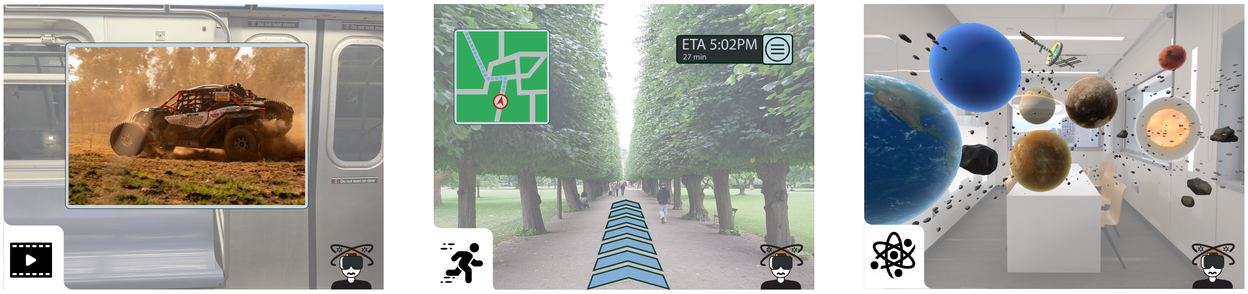

Figure 1: Augmented reality (AR) introduces many different applications that display some form of motion. In scenarios where this motion is diverging from the physical world, the visual-vestibular conflict can induce cybersickness. Common examples include watching movies in AR (left), observing static UIs while walking (middle), and exploring educational simulations (right). In this paper, we identify the parameters that affect this visual-vestibular conflict in AR. Through comprehensive experiments, AR-induced cybersickness is quantified in terms of its dependence on virtual content extent, motion properties, and spatial distribution. We found that in AR, significant cybersickness can occur; however, this occurrence is driven by the user's attention as a primary factor. Our insights highlight concrete design constraints for future AR systems.

Abstract— Cybersickness, a phenomenon of negative symptoms arising from visual motion, remains an obstacle to prolonged use of immersive displays. While cybersickness in virtual reality (VR) has been extensively studied, its mechanisms and mitigation remain underexplored in optical see-through augmented reality (AR). Unlike VR, AR preserves a direct view of the physical world while overlaying virtual content. This stable visual context fundamentally alters the visual–vestibular conflicts that contribute to cybersickness. In this paper, we investigate the causes of cybersickness in optical see-through AR and examine whether mitigation techniques developed for VR transfer to this setting. Specifically, we analyze how attention to virtual and physical content influences cybersickness under visual–vestibular conflict and whether reducing the virtual field of view (FOV) lowers sickness when users do attend to the virtual layer. Our results show that optical see-through AR can induce severe cybersickness when users attend to dynamic virtual content despite the presence of a grounding physical environment. In contrast, sickness levels are attenuated when attention is allocated towards the physical environment. We further find that reducing the global motion cues by a reduced FOV does not reliably mitigate AR cybersickness, suggesting that established cybersickness mitigation strategies from VR may not directly transfer to AR. Together, these findings demonstrate that AR cybersickness is an attention-dependent phenomenon with significant implications for AR interface design.

Index Terms—Cybersickness, augmented reality, motion perception, attention.

1 Introduction

Cybersickness remains one of the main obstacles to the widespread adoption of immersive displays. Symptoms such as nausea, oculomotor strain, and disorientation can reduce usability and limit the kinds of applications that can be deployed. While these effects have been extensively studied in virtual reality (VR), the nature of cybersickness in augmented reality (AR) is less clear, particularly in optical see-through (OST) displays, which present virtual imagery over the user's direct view of the physical world. OST AR is increasingly used for education, navigation, productivity, and entertainment, all of which can expose users to dynamic motion for extended periods of time, so it is important that we gain a better understanding of the factors that influence cybersickness in AR.

In contrast to VR, in OST AR the virtual content is rendered as an overlay onto the physical world, allowing users to perceive both the physical environment and the virtual content. As a result, the perceptual factors that contribute to visual discomfort in AR may differ from those in VR (e.g., the mechanics of vergence-accommodation conflict are fundamentally different in AR and VR [54]). Therefore, it is likely that the factors that contribute to and alleviate cybersickness symptoms in AR may differ from those in VR. The observation that cybersickness is less common and typically less severe in AR than in VR is consistent with this possibility, although the evidence is limited [56].

To improve our understanding of the perceptual factors that contribute to cybersickness in AR (and how they differ from those in VR), we conducted two experiments. Our first study isolates attention as an experimental parameter under controlled visual-vestibular conflict, manipulating the task so that participants either attend to the virtual content or the physical content. This design lets us attribute differences in sickness to attentional allocation rather than changes to the rendered stimulus. Our second study examines whether a common VR mitigation technique (field of view reduction) transfers to AR, as we alter the field of view covered by virtual content while users continue attending to the virtual layer. Together, these studies let us ask both when AR induces cybersickness and whether reducing visible virtual motion is sufficient to mitigate it.

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We find that OST AR can elicit significant cybersickness. Under the tested conditions, sickness increased when attention was directed to the virtual stimuli and decreased when attention was directed to the physical environment. The mere visibility of the real world, therefore, does not necessarily attenuate cybersickness symptoms. Instead, cybersickness severity appears to depend on the allocation of visual attention. Furthermore, reducing the field of view of the virtual content did not reliably decrease cybersickness when attention remained directed to the virtual layer. These results indicate that cybersickness mechanisms in optical see-through AR differ from those typically described for VR and may not be fully explained or mitigated by existing VR-based models.

2 Background & Related Work

In this section, we describe how cybersickness is caused by visual motion and explore previous research that considers cybersickness in OST AR environments. In this work, we use OST AR and AR interchangeably. While other forms of AR, such as video see-through (VST) AR, also exist, our focus is limited to OST AR.

2.1 Theory and Causes of Cybersickness

Motion sickness is a well-known phenomenon in everyday life that can occur in many scenarios, such as on a wavy cruise ship, while reading in a moving car, or while watching an immersive video [17]. The symptoms are diverse and include nausea, dizziness, and oculomotor strain. Despite the familiarity of the phenomenon, its causes remain controversial, and several theories attempt to explain its origin [9].

Most theories base their explanations on a conflict between sensory modalities (e.g., vision vs. vestibular system) that are expected to be congruent as the foundation of the symptoms [49, 50, 58]. In the well-accepted sensory conflict theory, symptoms are attributed to sensory rearrangement, in which the relationships among sensory inputs differ from those the observer has come to expect [50]. These conflicts are not restricted to mismatches between modalities, such as vision and the vestibular system, but can also occur within a single modality, such as between the semicircular canals and the otoliths. Critically, a conflict within the present pattern of sensory inputs is by itself insufficient to provoke sickness. Consequently, methods that desensitize one sensory system have been shown to effectively reduce cybersickness [24]. The neural mismatch theory instead attributes sickness to a discrepancy between perceived and expected input rather than between percepts. Repeated mismatches are stored and reduce sensitivity, which explains why symptoms subside as one adapts to a persistent conflict [49]. Alternative theories focus on conflicts in spatial orientation systems and their evolutionary interpretation as neurotoxin poisoning [58], or they identify prolonged postural instability as the source of sickness symptoms [51].

Cybersickness is a subcategory of motion sickness in which the conflict arises from visual motion on a virtual display, which is incongruent with the physical movement [40]. This visually driven component is more precisely termed visually induced motion sickness (VIMS). The broader construct of cybersickness additionally includes contributors specific to the hardware rather than to visual motion, such as the vergence–accommodation mismatch, headset weight, and imperfect interpupillary distance (IPD) fit [5]. Throughout this work, we therefore use VIMS when referring specifically to the visually induced component and cybersickness for the broader phenomenon. For the visually induced component, visual information typically conveys stronger motion than the vestibular system. Importantly, the symptoms and physiological correlates of physically induced motion sickness and VIMS are identical [40].

Because vision dominates the perception of reality [4], virtual content in a head-mounted display (HMD) can create a strong sense of presence in a simulated world. When that world moves in opposition to the user's physical state, a visual-vestibular mismatch arises and cybersickness can emerge [43].

Common techniques to counteract VIMS while still enabling independent virtual movement typically aim to reduce optical flow in the visual presentation. These methods include imperceptible image deformations [19], peripheral blurring [20, 25], perceptual camera control [27], and the inclusion of rest frames [7, 42]. Perceiving extensive motion by optical flow, even if not real, induces a perception of self-motion referred to as vection [12]. Vection is considered a primary contributor to cybersickness [33], and its reduction is consequently a major objective.

For AR, cybersickness due to sensory mismatches is more ambiguous, as both real and virtual elements coexist in the scene. Sensory conflicts can be weaker or more context-dependent, and additional variables may modulate vection [56].

Research suggests that attention shapes the strength of sensory conflict: fixations or central-focus tasks attenuate symptoms [65], while a stable reference or horizon helps to avoid cybersickness [23]. The picture is not entirely consistent, however. Wei et al. found that allocating less attention to central vision during vection was associated with reduced motion sickness [63], and subsequent work has reported conflicting results on the relative contributions of central and peripheral stimulation. Vision science more broadly links attention to the intensity of vection itself [53]. Vection induction further requires that motion is perceived as background motion rather than discrete object movement [52]. Further related evidence comes from secondary-task and distraction paradigms: auditory, visual, and cognitive distractions [60], as well as secondary-task demands during active exploration [59], have both been shown to modulate cybersickness. The relevance of field of view (FOV) has not yet been systematically quantified for AR, but numerous VR studies demonstrate that reducing the rendered FOV mitigates cybersickness, indicating the importance of virtual extent [2, 20, 21]. Motion speed is another strong predictor, with higher speeds [18, 19, 22, 27] and higher frequency content [45] being more likely to provoke severe symptoms. Recently, researchers have also shown that the complexity of users' head and eye movements may be linked to cybersickness severity [8, 57].

2.2 Cybersickness in Augmented Reality

Cybersickness has been studied extensively in VR, for both prediction and mitigation, yet few works consider it in AR, and fewer still quantify its intensity or its dependence on relevant parameters. One reason for this significant research gap might be the belief that optical see-through AR is not able to induce considerable cybersickness. The argument is that the visible physical world provides a stable point of reference that avoids any visual-vestibular conflict from the beginning, similar to how rest frames are used in VR cybersickness mitigation [7]. However, this might not be the case when the focus of the user shifts towards the virtual content. The following works address cybersickness in AR and give an indication that it might be an underestimated problem in the research community.

Kaufeld et al. evaluate cybersickness in optical see-through AR in a pilot-training context [30]. For seated participants with static UI annotations, they show negligible symptoms, as expected for low-motion content. In a dynamic universe simulation, a subset of participants ($\sim$10%) experiences severe sickness with disorientation as the dominant factor. While the study remains exploratory and does not isolate parameter effects, it provides a strong indication that optical see-through AR is indeed able to cause cybersickness in users.

Zhang et al. further support this view in an optical see-through AR reading task, studying how text color and motion patterns affect both reading performance and cybersickness [66]. They report that participants experienced cybersickness symptoms. At the same time, their use of the CSQ-VR questionnaire may limit sensitivity to higher-intensity sickness, suggesting that the reported effects could be conservative.

In video see-through AR, the "real world" appears via camera images, which directly introduces visual problems. Mismatched expectations regarding the eye–camera viewpoint offset, mis-scaled depth, disocclusions, and exaggerated motion parallax can directly induce cybersickness. El Chemaly et al. propose a geometry-aware passthrough that reprojects camera images into eye views [13]. In a user study, this method was able to reduce cybersickness severity compared to direct passthrough. However, even with geometry-aware passthrough, the additional sickness caused by the video representation could not be fully eliminated, giving a natural advantage to optical see-through AR.

Hughes et al. investigated cybersickness in AR long-duration military training, comparing HMD-based and tablet-based augmentation [28]. They observed oculomotor strain and more persistent aftereffects for head-worn AR devices, while sickness values from the tablet remained generally low. Importantly, even in the most demanding head-mounted condition, the Kennedy-Lane Simulator Sickness Questionnaire (SSQ) [31] scores only slightly exceeded 20, a value often used as an approximate threshold for the onset of VR cybersickness [22].

Vovk et al. assessed cybersickness in HoloLens-based AR training across aviation, medical, and space contexts (n=142) but found negligible sickness symptoms overall [61]. Slightly higher scores during interaction with more virtual elements gave indications for dominant eyestrain effects. However, the scenarios emphasized step-by-step procedural guidance with low optical flow. Our work mostly focuses on dynamic scenarios that have the potential to induce vection and, therefore, VIMS.

Other user studies that compare VR and AR in tasks like naval engagement, cultural heritage, and ball sorting report small performance differences and generally low cybersickness under low optical flow [46, 47]. In an AR science-literacy activity with in-situ visualizations and inquiry tasks, for example, the reported cybersickness was minimal, while the technology was well accepted [62]. Work on video see-through HMDs identifies apparent latency as a primary sickness driver and shows that predictive compensation reduces symptoms [6].

The study of Wolf et al. investigates the effects of different XR displays on the perception and plausibility of personalized virtual humans, comparing VR, video see-through AR, and optical see-through AR [64]. Cybersickness was uniformly low across conditions, including VR, with the task involving little motion and third-person observation.

3 Motivation

In this work, we investigate perceptual factors that influence cybersickness in AR. Unlike VR, where the user's visual field consists solely of virtual content, optical see-through AR renders transparent virtual content that is overlaid over a real-world background. This allows users to continuously allocate their visual attention to either the virtual overlay or the physical surroundings. This added degree of freedom may change how cybersickness is manifested in AR, since the physical world provides a stable reference that users can attend to at any time [48] and the virtual overlay on top of the physical environment introduces a unique vergence-accommodation conflict [54]. We aim to gain a better understanding of which conditions induce cybersickness in OST AR, with a focus on the effects of visual attention and field of view. In the following, we formalize the assumptions that motivate our design and define the research questions that guide our investigations.

Theoretical Assumptions Although AR is used in many application domains, the present work focuses on a common perceptual situation that recurs across them: users view a stable physical environment while dynamic virtual content is rendered simultaneously, and they may direct attention to either layer. In our investigation, we focus on application-agnostic factors that inform general design guidelines. We consider an experimental framework in which the real world remains continuously visible, participants remain stationary, and visual-vestibular conflict is introduced in a controlled manner through motion in the virtual content. The design of this framework is based on the following assumptions from prior cybersickness research:

- `A1` The severity of cybersickness for users is characterized by the absolute amount of visual-vestibular conflict [49, 50, 58]. This means that AR will be able to induce cybersickness as soon as the virtual content is dynamic (displays visual motion).
- `A2` For any relative motion between the observer and the scene, the resulting vestibular conflict is similar whether the head moves while the visual scene remains still (physically driven motion) or the scene moves at the same speed while the head stays still (visually driven motion) [40, 43].

Based on `A1` and `A2`, motion within the virtual scene can induce cybersickness independent of physical movement, since visually- and physically-induced conflicts are assumed to be equivalent in their effect. Consequently, all physically-induced conflict can be replaced with visually-induced conflict. For the purpose of the experiment, this implies that testing one motion scenario is sufficient. We chose to keep users stationary to induce visual motion conflict. This not only allows for explicit control over environmental variables, but also provides a safer experimental protocol. However, even stationary users can induce physical conflicts through head rotation. Therefore, our experimental framework must consider another assumption:

- `A3` Content that is head-locked introduces an increased retinal slip, thereby inducing more sickness than objects that move appropriately with head motion (head-contingent) [16].

If the content is head-contingent, then movements added by head rotation have no meaningful effect on cybersickness. For the purpose of our experiments, we lock the viewport to the head but make the content within the viewport head-contingent, mitigating physically induced motion conflict from head movements.

This approach offers multiple advantages. First, it produces sensory conflicts comparable to those arising during real-world AR use. Second, it ensures participant safety by minimizing physical movement demands. Third, it provides a controlled environment to evaluate cybersickness responses to dynamic virtual overlays.

Given these three assumptions, the findings from our experiment are expected to generalize to a broad range of AR scenarios in which users navigate physical environments with static or dynamic digital augmentations.

Research Questions Building on these assumptions, we examine the conditions under which AR induces cybersickness. Our goal is to clarify the magnitude of these effects and the circumstances in which they occur. Specifically, we ask:

- `RQ1` Is overt attention on the virtual content necessary for cybersickness symptoms to occur?
- `RQ2` Can AR induce considerable cybersickness when users attend to dynamic virtual content, despite the presence of a stable physical reference frame?
- `RQ3` When users attend to the virtual content, how do the extent of virtual content coverage (FOV) and exposure time influence sickness severity?

By answering these questions, we aim to show that AR cybersickness severity depends not only on the magnitude of visual-vestibular conflict, but also on how users allocate their attention between the virtual and physical world. Furthermore, these questions allow us to evaluate whether mitigation strategies motivated by VR, such as reducing the amount of visible virtual motion via field of view reduction, can be directly transferred to OST AR.

4 Experiment 1: Attention Allocation

We conducted a within-subjects experiment to isolate attention in AR cybersickness under controlled visual-vestibular conflict. The visual stimulus was identical across conditions, but the task required participants to attend either to the virtual content (*planet* condition) or to the physical environment (*room* condition). We test the following hypotheses:

- `H1` AR can induce considerable cybersickness when users attend to dynamic virtual content under strong visual-vestibular conflict.
- `H2` Shifting attention away from the virtual content toward the physical environment significantly attenuates cybersickness symptoms.

These hypotheses are formulated to answer `RQ1`.

Sessions were counterbalanced and separated by at least 24 hours to avoid carry-over effects. For the experiment, we used a Magic Leap 2 optical see-through HMD (45° horizontal FOV; 55° vertical FOV; 120Hz refresh rate; 1440 × 1760 pixels per eye).

Figure 2: A screenshot of the visual stimulus participants were exposed to in Experiment 1. Planets and other space objects were spread across the entire field of view afforded by the HMD, where users were tasked to either attend to the physical or virtual stimuli.

4.1 Stimuli

AR can help learners explore and understand both microscopic and macroscopic natural science phenomena. In the experiment, we simulate such an educational setting. The scene showed a virtual universe simulation populated with planets, asteroids, and spaceships (see Figure 2). To enhance realism, planets were animated with self-rotation around their local upward axes and assigned randomized initial orientations. Segmented dimming in the AR glasses was used to render the virtual content fully opaque while keeping the background transparent [39]. We used segmented dimming because transparent virtual content may act as a confounding factor by altering depth, contrast, and color cues of the virtual content that are relevant to perceptual scission [41]. Virtual objects were rotated by a yaw with a predefined, constant velocity that increases with each trial. During pilot tests, an angular velocity of $10^{\circ/s}$ was empirically found to reliably induce mild cybersickness symptoms in most participants and was therefore chosen as the slowest camera rotation velocity used across the 20 trials in our experiment. The maximum velocity was set to $40^{\circ/s}$, the maximum angular velocity before eye gaze smooth pursuit movements become unstable [15]. Additionally, small sinusoidal perturbations were applied globally to the virtual camera along the pitch axis and ran continuously throughout each trial, increasing sensory conflict and reducing the predictability of the scene motion. The amplitude was fixed at 10°, and the frequency was drawn from the range 0.1–0.5 Hz, with a new frequency regenerated after each complete sinusoidal phase. These values were self-calibrated during piloting to be perceptible without dominating the primary yaw rotation.

Sessions were conducted in a well-lit conference room (∼4 m wide, ∼9 m deep, ∼3 m tall). Physical objects, including tables and chairs, were present in the room.

4.2 Measurements

We used the Kennedy-Lane Simulator Sickness Questionnaire (SSQ) [31] and the Fast Motion Sickness scale (FMS) [32] for participants' feedback on cybersickness. Both questionnaires require self-assessment of the participants based on how they feel. Following common procedures, the SSQ was administered twice per session (pre- and post-exposure) to counteract a bias from natural day-to-day variations in cybersickness symptoms. The SSQ included the common 16 elements, and scores were computed according to the original procedure of Kennedy et al. [31]. For the FMS, participants were asked to rate their self-assessed sickness severity level on a scale from 0 (no sickness) to 20 (frank sickness). The FMS was reported verbally after each trial and allows us to analyze the temporal progression of overall sickness. Head motion was recorded throughout the experiment.

4.3 Participants

A total of 20 participants (*8* female, *12* male; aged *20–33* years, $\mu = 24.1$, $\sigma = 2.88$) completed both sessions. This sample size is consistent with comparable within-subjects cybersickness studies [27] and provides equal counterbalancing of the two attention conditions, with 10 participants assigned to each presentation order. To ensure the safety of our participants and to avoid any external factors that might influence participants' feelings of cybersickness, participants were required to be at least 18 years old, not pregnant, have normal or corrected to normal vision, and have no acute illness or significant medication use within 24 hours. This study protocol was approved by the university's ethics committee and human research protection program. Participants gave written consent before the experiment and were compensated with a $20 Amazon gift card.

4.4 Procedure

The session began with participants completing the pre-exposure SSQ and the adjustment of the HMD. Each session consisted of a maximum of 20 trials, each of which had 45 seconds of active exposure to the motion stimulus (15 minutes of total exposure time). During the trials, the virtual camera rotated at a constant angular velocity, which was uniformly increased between trials from $10^{\circ/s}$ on the first trial to $40^{\circ/s}$ on the twentieth. Between consecutive trials, there was a brief pause during which the virtual camera was held stationary and the participant gave their verbal FMS rating before the next trial began. In the *room* condition, participants were instructed to focus on the physical space and ignore the rotating virtual objects (the planets). Their task was to spot any anomaly they could find in the physical room, despite there not being any, to keep them occupied. In the *planet* condition, we encouraged active engagement with the virtual scene, drawing attention to the virtual content. Participants were instructed to freely look around the scene while keeping their foveal gaze within the display viewport and were informed beforehand that questions about specific virtual objects would be asked at the end of the session.

Participants who reported an FMS score above 15 were asked whether they wished to stop. However, they could withdraw the sessions at any time. Immediately after all trials, participants completed the post-exposure SSQ.

5 Experiment 1: Analysis & Results

In this section, we detail the results of our experiment and provide evidence that optical see-through AR can cause cybersickness under conditions of strong visual-vestibular conflict. Crucially, because both conditions presented identical visual stimuli, any differences in sickness can be attributed to the instructed region of attention.

We investigate the SSQ and FMS results to provide insights into `RQ1`. The temporal progression of FMS scores assesses `RQ2`. Overall, the SSQ scores for both the physical and virtual attention conditions increased significantly after participants completed the experiment, corroborating prior results from the literature showing that AR can induce cybersickness [28, 66].

5.1 Kennedy-Lane Simulator Sickness Scores

Normality of pre–post difference SSQ scores was assessed using the Shapiro–Wilk test prior to each comparison. Parametric paired t-tests were used when the assumption was met, and Wilcoxon signed-rank tests were used otherwise. Effect sizes are reported as Cohen's d

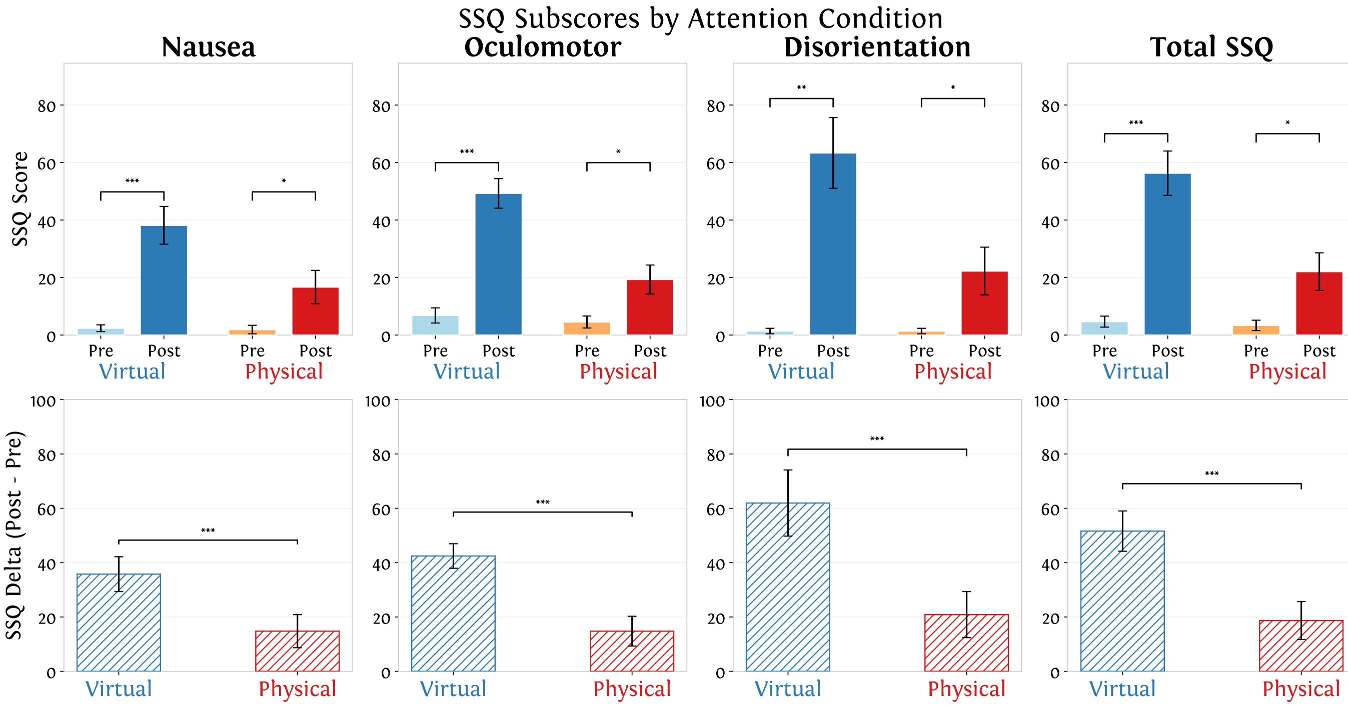

Figure 3: Simulator Sickness Questionnaire (SSQ) subscale scores by attention condition. The top row shows mean pre- and post-exposure scores for Nausea, Oculomotor, Disorientation, and Total SSQ in the Virtual and Physical conditions, and the bottom row shows the corresponding change scores. Across all measures, SSQ scores increased after exposure in both conditions, with consistently larger increases in the Virtual condition than in the Physical condition. Error bars indicate standard error of the mean across participants, and brackets/asterisks denote statistically significant comparisons.

throughout ($n = 20$ per condition). A summary of the results is shown in Figure 3. Effect sizes are reported as Cohen's d_z, the standardized mean of the paired differences [37] ($n = 20$ per condition). To control the family-wise error rate across multiple pairwise comparisons, all p-values in this section are Holm-Bonferroni adjusted [26] and significance is judged on the adjusted p-value against $\alpha = 0.05$; this convention is used throughout the paper. In this section, corrections were applied within two families: the eight within-condition pre-to-post comparisons, and the four between-condition comparisons of change scores.

Nausea In the virtual attention condition, nausea scores increased significantly from pre- ($\mu = 2.385$) to post-exposure ($\mu = 38.160$; $t(19) = -5.578$, $p < .001$, $d = -1.247$). In the physical attention condition, the pre-to-post increase (pre: $\mu = 1.91$, post: $\mu = 16.70$) was likewise significant ($W = 7.00$, $p = .015$, $d = -0.54$). The pre-to-post nausea delta was significantly greater in the virtual attention condition ($\mu = 35.78$) than in the physical attention condition ($\mu = 14.79$; $t(19) = 4.263$, $p < .001$, $d = 0.95$).

Oculomotor Oculomotor scores increased significantly from pre- to post-exposure in the virtual attention condition (pre: $\mu = 6.822$, post: $\mu = 49.270$; $t(19) = -9.402$, $p < .001$, $d = -2.102$) and in the physical attention condition (pre: $\mu = 4.548$, post: $\mu = 19.329$; $W = 14.000$, $p = .015$, $d = -0.603$). The delta was significantly larger in the virtual attention condition ($\mu = 42.448$) than in the physical attention condition ($\mu = 14.781$; paired $t(19) = 5.838$, $p < .001$, $d = 1.305$).

Disorientation Disorientation scores increased significantly from pre- to post-exposure in both the virtual attention (pre: $\mu = 1.392$, post: $\mu = 63.336$; $W = 0.000$, $p = .001$, $d = -1.137$) and physical attention (pre: $\mu = 1.392$, post: $\mu = 22.272$; $W = 2.500$, $p = .015$, $d = -0.551$) conditions. The delta was significantly greater in the virtual attention condition ($\mu = 61.944$) than in the physical attention condition ($\mu = 20.880$; $W = 4.000$, $p < .001$, $d = 0.865$).

Total SSQ The total SSQ scores increased significantly from pre- to post-exposure in the virtual attention condition (pre: $\mu = 4.675$, post: $\mu = 56.287$; $t(19) = -6.962$, $p < .001$, $d = -1.557$) and in the physical attention condition (pre: $\mu = 3.366$, post: $\mu = 22.066$; $W = 12.000$, $p = .015$, $d = -0.599$). The total SSQ delta was significantly larger in the virtual attention condition ($\mu = 51.612$) than in the physical attention condition ($\mu = 18.700$; paired $t(19) = 5.427$, $p < .001$, $d = 1.214$).

5.2 Fast Motion Sickness Scores

In addition to the SSQ scores that we measured before and after each session, participants also reported their level of discomfort on the FMS scale after each trial in both sessions, providing insight into the time course of participants' cybersickness symptoms during our experiment. A summary of the FMS scores over the course of the experiment is shown in Figure 4.

In the virtual attention condition, mean FMS scores increased steadily across the session, rising from $\mu = 0.750$ ($\sigma = 1.118$) after Trial 1 to $\mu = 9.300$ ($\sigma = 4.51$) after Trial 20. In the physical attention condition, the trajectory was substantially flatter, with scores rising from $\mu = 0.300$ ($\sigma = 0.733$, $N = 20$) after Trial 1 to just $\mu = 3.714$ ($\sigma = 3.891$, $N = 14$) after Trial 20.

To compare overall FMS levels between conditions, a Wilcoxon signed-rank test was conducted on participants' average FMS scores for each session (virtual vs physical attention), as normality was violated in both conditions (Shapiro–Wilk $W = 0.847$, $p < .005$). Mean FMS was significantly higher in the virtual attention condition ($\mu = 4.998$) than in the physical attention condition ($\mu = 1.697$; $W = 2.000$, $p < .001$, $d_z = 1.144$).

In summary, the results of Experiment 1 show that participants consistently scored higher on the SSQ and FMS scales after completing our experiment when their attention was directed toward the virtual content, providing evidence that users can feel high levels of cybersickness from exposure to AR. We turn to the extent of virtual content and exposure time in Experiment 2. In contrast, when participants were instructed to

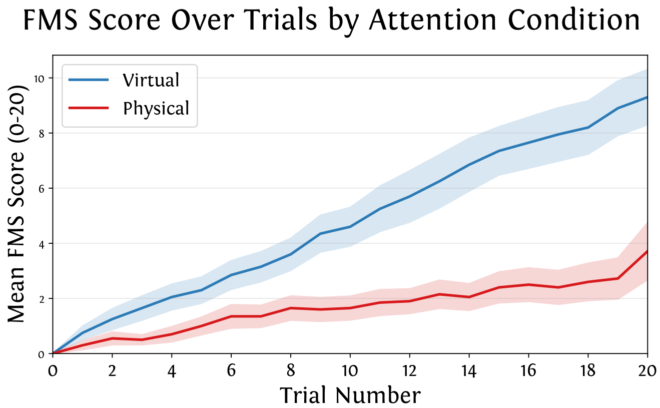

Figure 4: A line plot showing how participants' FMS scores varied across trials in Experiment 1. The trend shows a consistently higher FMS score for the "Virtual" attention condition compared to the "Physical" condition, indicating that participants felt more cybersickness when the task required them to focus on the virtual content rather than the physical surroundings. The shaded regions are the standard error of the mean.

focus on the physical room and ignore the virtual motion, cybersickness symptoms were strongly attenuated.

6 Experiment 2: FOV Reduction

In this second study, we investigate whether a common VR mitigation strategy, reducing visually perceived motion by restricting the effective field of view (FOV) of virtual content, also reduces cybersickness in OST AR when users *do* attend to the virtual layer. In doing so, this experiment addresses RQ3, examining how the extent of virtual content (FOV) and exposure time influence sickness severity under sustained attention to virtual motion.

We conducted a within-subjects experiment with four sessions per participant, exploring how restricting the virtual content FOV (between-session variable) affects cybersickness under increasing visual-vestibular conflict (within-session variable). We hypothesize:

- H3 The virtual scene will induce substantial cybersickness in both the full FOV occlusion condition and the AR conditions.
- H4 Reducing the virtual-content FOV in AR mitigates cybersickness when users attend to the virtual content.

Full FOV (45°) is the AR simulation closest to a conventional VR scenario. In this condition, the physical world is fully invisible within the field of view that is covered by the device. The only fundamental difference between full occlusion in AR and conventional VR is that the physical world that is visible around the device is not purposefully covered as in VR and that the FOV in VR is typically wider. Sessions were fully counterbalanced and separated by at least 24 hours to avoid carry-over effects. The in-session procedure and hardware setup were identical to the first experiment; only the stimulus and the task were altered. Consequently, participants also completed 20 trials of 45 seconds each, with a short FMS verbal rating between trials.

6.1 Stimuli

We altered the viewport size to examine how the extent of virtual content impacts cybersickness and behavior in augmented reality (see Figure 5). The viewport was head-locked to the center of the display and we utilized the spatial dimming feature of the Magic Leap 2 to ensure that no physical world information was visible in this region. The viewport's width and height were adjusted per session to alter the FOV of the virtual content, with four predefined settings: 45°, 33°, 21°, and 10° horizontally. The vertical size was set accordingly to match the display's aspect ratio of 9:11. We chose the smallest region to have a 10° FOV to represent a stimulus at a comparable size to the parafoveal region of vision, where much of central vision lies [55]. The maximum

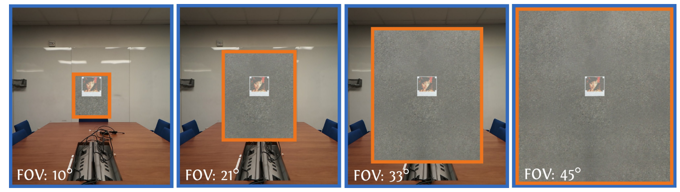

Figure 5: AR headset screenshots from Experiment 2 showing the four field-of-view (FOV) conditions. The blue rectangles visualize the extent to which the physical environment was visible, while the orange rectangle visualizes the windowed virtual content. Like in the images, the virtual content was fully opaque.

viewport size (45°) represents the full FOV of the display. The other values were chosen in uniform steps. Outside the viewport, the physical world was fully visible, and no virtual content was displayed.

Inside the viewport, a virtual scene of a rectangular room (5 meters per side) with detailed, concrete-textured walls was shown as the visual stimulus. Red and blue paintings were randomly distributed across the walls with changing positions per trial. The virtual camera displayed a rotational movement while participants remained stationary to create strong visual-vestibular conflicts, i.e. the user perceived the virtual room as rotating around them while they remained stationary. One wall of the room contained a white painting as a frame of reference for the virtual camera's orientation in the virtual room. Camera motion parameters were the same as the main experiment (cf. section 4) to ensure comparability.

6.2 Participants and Procedure

Similar to Experiment 1, the session began with participants completing the pre-exposure SSQ and adjusting the HMD. Each session had the same exposure time and camera rotation speed. Participants were instructed to keep their foveal gaze within the viewport and to count the number of red and blue paintings in the room. The placement of the paintings were limited to an area that could accommodate all conditions with minimal head movement. Paintings were generated at locations relative to the size of the FOV. Participants were allowed to move their heads freely. We chose this task as it requires active attention and a moderate level of cognitive load, making sure that participants' attention stayed on the virtual content.

After each trial, participants reported the number of red and blue paintings and an FMS rating of their current discomfort level. During this short time, the camera remained stationary in order to encourage participants to focus on their answers. As in Experiment 1, participants who reported an FMS score above 15 were asked whether they wished to end the session early. Participants also completed the post-exposure SSQ after all trials. A total of 24 participants (*9* female, *15* male; aged *19–32* years, $\mu = 23.58$, $\sigma = 2.67$) completed all four sessions. All 20 participants of Experiment 1 also took part in Experiment 2, while the remaining 4 were newly recruited. We chose this number so that each of the $4! = 24$ possible presentation orders of the four FOV conditions could be assigned to exactly one participant, yielding complete counterbalancing of order effects.

7 Experiment 2: Analysis & Results

We investigate both the SSQ and FMS results to validate whether restricting virtual content coverage mitigates cybersickness under sustained attention to the virtual stimulus. The counting accuracy data were also tracked, and while the data suggest a possible trend of improved accuracy with increasing field of view, this measure falls outside the scope of our primary research questions on cybersickness and was therefore not examined further.

7.1 Kennedy-Lane Simulator Sickness Scores

We tested for significant increases in pre- to post-exposure cybersickness between field of view conditions (FOV: 10°, 21°, 33°, 45°) using paired t-tests. Wilcoxon signed-rank tests were used as fallback where differences were non-normal (Shapiro–Wilk). We then tested for an omnibus effect of FOV on total SSQ delta scores using a one-way repeated-measures ANOVA, falling back to a Friedman test where any FOV level violated normality. Post-hoc pairwise comparisons used Wilcoxon signed-rank tests with Holm-Bonferroni correction, with significance judged on the adjusted p-value, as in Experiment 1. Effect sizes are Cohen's d_z.

Nausea For the Nausea subscale, all four FOV levels showed significant pre-to-post increases (all adjusted $p \leq .001$). Mean deltas for each FOV were: $10^\circ = 29.812(\sigma = 21.666)$, $21^\circ = 25.837(\sigma = 19.179)$, $33^\circ = 33.390(\sigma = 30.037)$, $45^\circ = 42.930(\sigma = 32.443)$. Three of four delta distributions were non-normal, so a Friedman test was used. The Friedman test revealed no significant effect of FOV on Nausea score deltas ($\chi^2(3) = 3.729, p = .292$), so no post-hoc tests were conducted.

Oculomotor All four FOV levels of oculumotor SSQ subscale displayed significant pre-to-post increases (all adjusted $p \leq .001$). The mean deltas for each of the four FOV levels were: $10^\circ = 35.689(\sigma = 35.936)$, $21^\circ = 28.425(\sigma = 18.466)$, $33^\circ = 30.636(\sigma = 26.208)$, $45^\circ = 45.796(\sigma = 30.112)$. Due to non-normal distributions of oculomotor score deltas, we conducted a Friedman's omnibus test to test for an effect of FOV on oculomotor scores, but found no significant effect ($\chi^2(3) = 6.537, p = .088$). No post-hoc tests were conducted because the omnibus test was not significant.

Disorientation For the disorientation SSQ subscale, all four FOV levels also showed significant pre-to-post increases (all adjusted $p \leq .001$). The mean deltas across FOVs were: $10^\circ = 48.720(\sigma = 45.153)$, $21^\circ = 48.140(\sigma = 46.437)$, $33^\circ = 46.980(\sigma = 50.074)$, $45^\circ = 71.920(\sigma = 55.781)$. Due to non-normal distributions for the disorientation score deltas, a non-parametric Friedman's test was conducted, but it also revealed no significant effect of FOV on disorientation scores $\chi^2(3) = 6.822, p = .078$, so no post-hoc tests were conducted.

Total SSQ Pre- to post-exposure total SSQ scores increased significantly at every FOV level ($n = 24$): 10° ($t(23) = -5.865$, $p < .001$, $d = -1.197$), 21° ($t(23) = -7.428$, $p < .001$, $d = -1.516$), 33° (Wilcoxon $W = 0.000$, $p < .001$, $d = -1.173$), and 45° ($t(23) = -7.284$, $p < .001$, $d = -1.487$). Mean deltas were 42.387 ($\sigma = 35.406$), 37.088 ($\sigma = 24.461$), 40.828 ($\sigma = 34.804$), and 58.749 ($\sigma = 39.511$) respectively. Because the 33° delta distribution was non-normal ($W = 0.904$, $p = .0263$), a Friedman test was used for the omnibus comparison, which was non-significant ($\chi^2(3) = 6.231$, $p = .101$). Figure 6 shows SSQ deltas for each FOV.

7.2 Fast Motion Sickness Scores

Figure 7 shows the pooled results of participants' FMS scores across sessions. There is a consistent trend that as users spend more time in our AR experiment, they exhibit more symptoms of cybersickness and score higher on the FMS scale. The results of the Friedman test revealed a significant effect of FOV on FMS score ($\chi^2(3) = 17.58, p = 0.0005$). Post-hoc pairwise comparisons using Wilcoxon signed-rank tests with Holm correction revealed significant differences between the following FOVs: 10° vs 45° ($p_{\text{Holm}} = 0.023$), 21° vs 45° ($p_{\text{Holm}} = 0.014$), and 33° vs 45° ($p_{\text{Holm}} = 0.003$).

8 Discussion & Limitations

In this section, we discuss the results and give detailed insights into the implications of our findings, as well as their limitations.

Attention as a Parameter of AR Cybersickness The results from Experiment 1 show strong support for our hypotheses (H1 and H2). We demonstrate that optical see-through AR can induce severe cybersickness, but its severity depends on the user's attentional allocation. When users directed their attention towards the virtual content, both their SSQ and FMS scores rose drastically. Conversely, directing attention toward the physical environment was sufficient to eliminate the onset of symptoms, despite the visual-vestibular conflict remaining visually identical.

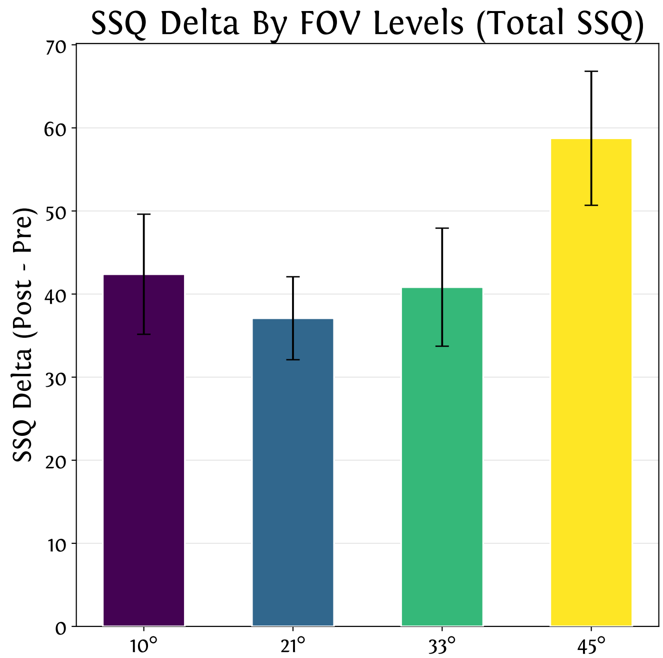

Figure 6: A bar chart showing the total SSQ delta across all participants in Experiment 2, grouped by FOV condition. We found no significant differences in SSQ deltas across any of the reduced FOV conditions ($10^\circ, 21^\circ, 33^\circ$), suggesting that traditional VR sickness mitigation techniques may not be effective for mitigating cybersickness in AR. Error bars indicate standard error of the mean SSQ delta across participants.

This divergence could potentially be explained by how attention modulates spatial reference frames and the perception of vection. When users attended to the virtual content, their cognitive system may have prioritized the dynamic virtual layer as their primary spatial frame of reference. Because this attended layer was in continuous motion, there may have been stronger perceived vection. As a result, there would have been a strong visual-vestibular conflict, which often manifests as spatial disorientation [34]. In both experiments, the disorientation subscale consistently showed the greatest magnitude of SSQ increase, which also coincides with existing VR literature [3]. In contrast, when attention was fixed on the physical room, the static environment served as the dominant spatial anchor, perfectly matching the vestibular system's stationary signal and likely suppressing any visually induced vection. Because dynamic AR content naturally tends to capture and hold attention, the effects observed in our findings are highly relevant for real-world application design. We note that the two attention tasks in Experiment 1 differed not only in where attention was directed but also in cognitive style, since the *room* condition involved an open-ended visual search while the *planet* condition involved free viewing with a later memory test. These tasks may have elicited somewhat different gaze and head-movement patterns, so viewing behavior could have contributed to the observed difference alongside the locus of attention, though given the size of the effect we do not believe it accounts for the result. What remains unclear, however, is how cybersickness develops when attention is constantly divided or shifted between the real and virtual world. While our results point toward a significant attentional effect, more extensive studies are required to deepen our understanding.

Influence of FOV Surprisingly and against our hypothesis (H4), restricting the field of view (FOV) of the virtual content did not proportionally mitigate cybersickness symptoms when attention remained anchored to the virtual layer. Both SSQ and FMS scores indicated that cybersickness severity remains largely constant across 10°, 21°, and 33° FOV conditions. Nevertheless, all conditions produced clear increases in cybersickness, validating our hypothesis (H3).

However, a significant difference in sickness scores emerges when

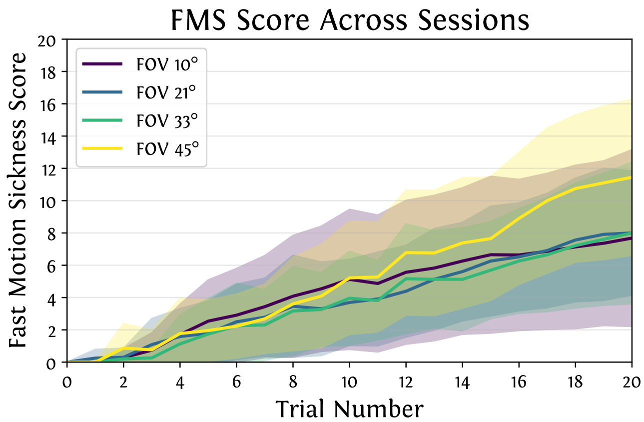

Figure 7: A line plot showing average FMS scores of Experiment 2 as the number of trials increases (N=24). The chart shows a clear and consistent linear trend upward as the number of trials increases. That is, as participants spend more time exposed to our experimental stimulus, they report higher and higher feelings of cybersickness (as measured by the FMS scale). Note the similar trends across all FOVs until around trial #15, after which point the FMS scores from 45° FOV sessions increase more quickly and users feel more cybersickness.

comparing the AR conditions (10°–33° FOV) with the Full-FOV condition (45° FOV) for FMS scores (but not total SSQ scores). Initially, this finding may seem surprising because varying the FOV shows no effect within all AR conditions, but an instant elevation in fully-occluded AR. Multiple factors appear to influence this result.

One possible contributing factor is the interaction between prolonged exposure and peripheral stimulation. Although FMS scores increased over time in all conditions, the full-FOV condition began to diverge from the reduced-FOV AR conditions around trial 15, showing a sharper increase in sickness ratings while the AR conditions gradually converged to a lower FMS value. Because sickness symptoms can accumulate naturally with time spent in the HMD, this pattern cannot be interpreted as evidence of a speed effect alone. Rather, it suggests that extended exposure under full-FOV viewing conditions may increase discomfort more strongly than in the restricted-FOV conditions. This interpretation aligns with prior work showing that peripheral vision is especially sensitive to rapid or large-scale motion, and may therefore play a key role in inducing discomfort [14].

Additionally, the presence of visual references to the real world, which were provided in all conditions except the 45° FOV condition, likely moderated the sickness response. The real-world reference might have provided a visual anchor similar to how rest-frame designs and world-lock content in VR help to reduce cybersickness symptoms by offering stable visual cues [7, 11, 42]. Hence, the mitigating effects of visual stability in AR systems should be considered alongside motion dynamics when evaluating and designing systems for user comfort.

Sickness Questionaires Since we measured participants' cybersickness using both the SSQ (before and immediately after sessions) and FMS (during sessions) scales, we are also able to compare the two scales directly. Figure 8 shows the change in FMS scores at the start and end of each session (abscissa) against the change in SSQ scores before and after each session (ordinate). In Experiment 1, the FMS and SSQ trajectories aligned logically: the virtual attention condition yielded a large, significant correlation between the SSQ and FMS scores ($r = 0.62,\ p = 0.003,\ N = 20$), whereas the physical attention condition yielded a small, non-significant correlation between the sickness scores ($\rho = 0.21,\ p = 0.368,\ N = 20$). For Experiment 2, we observed medium-to-large correlations between total SSQ and FMS delta scores, with all FOV conditions yielding a significant correlation except for FOV 21°, with the strongest per-condition correlation being for the 10° FOV condition ($r = 0.57, p = 0.004$). Accounting for the repeated-measures structure across all four FOV conditions, the FMS change remained correlated with the total SSQ change ($r_{rm} = 0.574, p < .001, N = 24$).

Although these regressions indicate good correlation between SSQ and FMS scores, the omnibus test in Experiment 2 showed a significant effect of FOV on FMS scores but no significant effect on total SSQ scores. This mixed result (good correlations, disagreeing omnibus tests) provides some evidence that cybersickness in AR may not manifest in the same way as it does in VR, which the FMS scale was designed for. However, before attributing the discrepancy to a genuine AR-versus-VR difference, we note that the non-significant SSQ omnibus may instead reflect limited statistical power: with 24 participants and the between-condition variance we observed, the study may have been underpowered to detect FOV-dependent differences in SSQ scores. We therefore treat this as one interpretation among several rather than a firm conclusion. With that caveat, the pattern suggests that the differences between VR- and AR-induced cybersickness may require a new or modified sickness scale to measure OST AR cybersickness accurately.

Movement Type In our study, we deliberately employed virtual movements that are known from prior work to strongly induce cybersickness, in particular, virtual scene rotations. Such rotations have consistently been shown to provoke much higher sickness levels than lateral movements [21, 22], making them a suitable choice for reliably evoking symptoms in our experiments. While these motion patterns can appear in practical AR applications, for example, in educational simulations comparable to our first experiment, these applications may feature lower levels of motion. Nevertheless, any movement that results in visual-vestibular conflict can trigger significant discomfort in sensitive users. Further research could determine how this varying motion intensity influences cybersickness in AR.

Head Movement In both experiments, participants were free to move their heads to explore the virtual environment. The distribution of head movement across different conditions is reported in the supplementary material. To limit systematic differences between conditions, the virtual paintings were placed closer to the wall centers as the FOV decreased. However, each FOV configuration still induced different amounts of head movement as part of the natural viewing behavior. For this reason, head movement was not treated as an independent experimental factor. Instead, the experiment evaluates the end-to-end relationship between interface FOV and cybersickness under natural interaction. The results therefore reflect the combined effect of FOV design and the viewing behavior it induces. The main empirical finding of the study is that reducing the interface FOV did not reliably reduce cybersickness in the tested scenario. The experiment does not determine which specific behavioral or perceptual mechanisms contributed to this outcome. From a design perspective, the results indicate that reducing FOV alone should not be assumed to reduce perceived cybersickness in interactive viewing tasks.

Self-Reported Effects Our observations further highlight several nuanced factors that shape how cybersickness manifests in AR. First, some participants reported experiencing stronger sickness symptoms during periods when they happened to hold their heads relatively still, compared to when they were actively searching for targets. Because head movement was unconstrained in all conditions, this reflects a difference in spontaneous viewing behavior rather than an experimental manipulation. A plausible explanation for this finding lies in the different eye movement patterns that are elicited in both cases: in the static case, prolonged fixations and smooth pursuit made the scene's motion more perceptible, amplifying sensory conflicts, whereas in the head-moving condition, frequent saccades may have introduced saccadic suppression that reduced the perception of visual motion and thus mitigated sickness [1, 38]. Furthermore, participants consistently reported that the randomized pitch movements were more discomforting than consistent yaw rotations, suggesting that unexpected, less predictable motion cues exacerbate sickness more strongly than predictable ones. Consistent with most VR studies, many individuals experienced their strongest symptoms during the first session, regardless of FOV. This

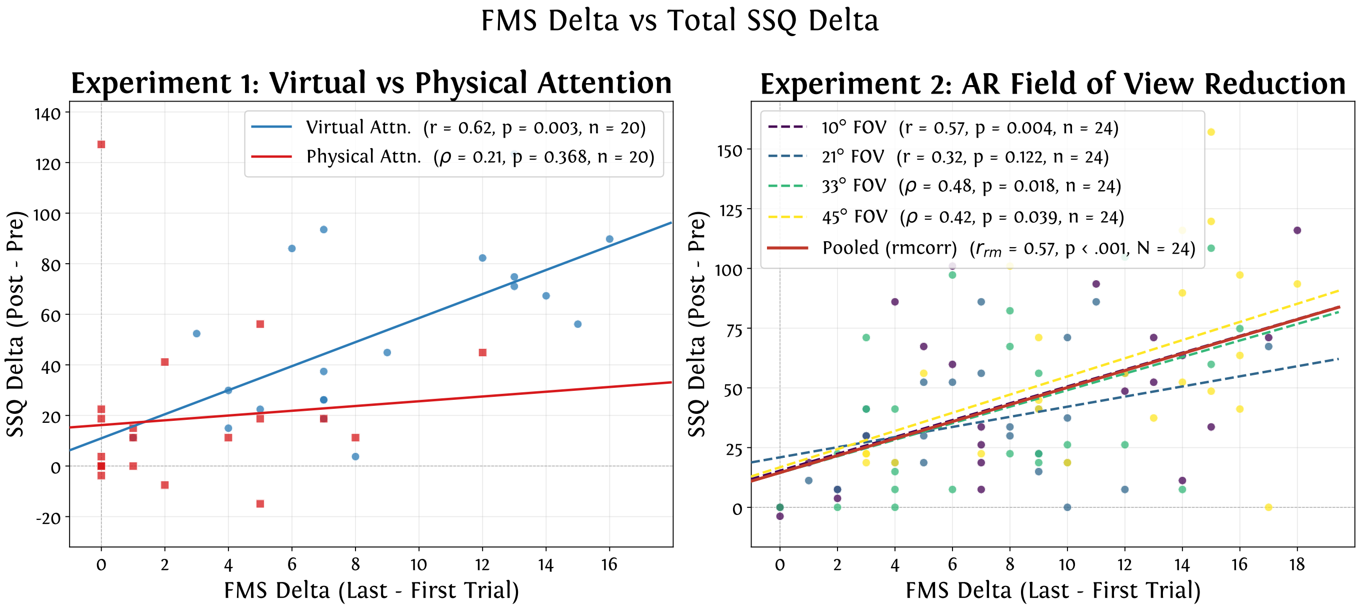

Figure 8: Relationship between change in FMS across trials and change in total Simulator Sickness Questionnaire (SSQ) score from pre- to post-exposure. **Left:** Experiment 1, comparing the virtual attention and physical attention conditions. A significant positive association was observed in the virtual attention condition ($r = 0.62, p = 0.003, n = 20$), whereas the association was weak and not significant in the physical attention condition ($\rho = 0.21, p = 0.368, n = 20$). **Right:** Experiment 2, comparing AR field-of-view (FOV) reduction levels. Positive associations were observed for 10° FOV ($r = 0.57, p = 0.004, n = 24$), 33° FOV ($\rho = 0.48, p = 0.018, n = 24$), and 45° FOV ($\rho = 0.42, p = 0.039, n = 24$), whereas the 21° FOV condition was not significant ($r = 0.32, p = 0.122, n = 24$). Across all Experiment 2 participants, FMS change was positively associated with total SSQ change ($r_{rm} = 0.574, p < .001, n = 24(df = 71)$). Since each participant contributes four observations (one per FOV condition), a repeated-measures correlation is used in place of pooling observations, which would treat non-independent measurements as independent. Points represent individual participants; lines indicate fitted trends.

finding suggests that novelty and increased cognitive load initially amplify cybersickness in AR [10]. To prevent this learning effect from affecting our data, we employed a fully counterbalanced design. Another dedicated analysis of only first-session data further showed that sickness patterns for the initial exposure were similar to those in the full dataset.

Further Considerations While the results are meaningful in informing future design of AR devices and applications, the current work comes with several considerations.

In our study, participants remained stationary to prioritize safety and maintain consistency by minimizing external variables. However, under assumption A2, comparable levels of cybersickness would be expected if the same motion conflict were induced physically while the virtual content remained static. This scenario, involving non-stationary users, has not yet been tested and remains an open question for future research.

We were not able to reliably test for any effects of participant sex on sickness scores since we had an imbalanced split between male and female participants (40% female for Experiment 1, 37.5% for Experiment 2) among those who successfully completed the entire experiment. Higher cybersickness scores among female users are a commonly reported result in the VR literature [44]. However, it is important to note that most of the recent research in VR is biased to underrepresent female participants and that there is evidence to suggest that this leads to systematic bias in the results reported in cybersickness scores [44]. It is important for future research on AR sickness to ensure an even split between female and male participants in order to avoid introducing potential biases.

9 Conclusion and Future Work

Cybersickness has been extensively studied in VR, but is relatively understudied in AR. In this paper, we demonstrated that AR can induce severe cybersickness, but its severity depends on the user's allocation of attention; attending to virtual content induced stronger cybersickness symptoms than attending to the physical world. Furthermore, we showed that reducing the field of view of the virtual content, an established VR cybersickness mitigation technique, failed to reliably reduce sickness severity in AR. We aim for this work to serve as an initial step toward more analytical and comprehensive design guidelines for AR interfaces. To this end, we plan to expand our work by exploring interaction effects between attention allocation, visual presentation, and motion, and we will extend the analysis to dynamic scenarios. Furthermore, investigating the interplay with gaze-guidance [35, 36] and stereoscopic [29] methods is an interesting direction for future work. We hope this work encourages broader investigation of cybersickness in AR systems.

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