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Asymmetric Lateral Field-of-View Restriction to Mitigate Cybersickness During Virtual Turns

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Abstract

Field-of-view (FOV) restriction is a common technique to reduce cybersickness in commercial virtual reality (VR) applications. However, the majority of existing FOV restriction techniques are implemented as symmetric imagery, which occludes users' views during virtual rotation. In this paper, we proposed and evaluated a novel variant of FOV restriction, referred to as a side restrictor. Side restriction uses an asymmetric mask to obscure only one side region of the periphery during virtual rotation and laterally shifts the center of restriction towards the direction of the turn. We conducted a study using a between-subjects design that compared the side restrictor, a traditional symmetric restrictor, and a control condition without FOV restriction. Participants were required to navigate through a complex maze-like environment using a controller using one of three restrictors. Compared to the control condition, the side restrictor was effective in mitigating cybersickness, reducing discomfort, improving subjective visibility, and enabling users to remain immersed for a longer period of time. Additionally, we found no empirical evidence of negative drawbacks when compared to the symmetric restrictor, which suggests that side restriction is an effective cybersickness mitigation technique for virtual environments with frequent turns.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods—User studies;

1 Introduction

Virtual locomotion is an important component in commercial VR games, but it can induce severe cybersickness. Extensive research has been conducted on the causes of cybersickness and techniques to alleviate cybersickness. In particular, virtual turns can cause significant discomfort; during rotation, vection and optokinetic nystagmus are believed to be the main triggers of cybersickness [33]. Vection is the sensation of illusory self-motion in the absence of physical movement. Consequently, many commercial VR games avoid continuous virtual rotation by using "snap turn" techniques.

Dynamic field-of-view (FOV) restriction, also known as "tunneling", shows promise in reducing cybersickness that results from virtual locomotion [6, 16]. This technique partially obscures the user's visual field by displaying a black opaque texture mask in the periphery to mitigate visually-induced motion sickness. In virtual rotational movements, the effect of optokinetic nystagmus is minimal, and so the optical flow of imagery across the visual field is strongly associated with cybersickness. Therefore, a moderate restriction of the FOV during virtual rotation should be an effective intervention to mitigate cybersickness.

FOV restriction is not without its potential drawbacks. Research has shown that a limited FOV can negatively impact distance estimation [53], postural equilibrium [49], and the user's control of orientation [38]. The classical implementation of a dynamic FOV restrictor generally displays a symmetric solid color or static image at the periphery of the user's FOV [16]. However, a symmetric restrictor impedes the user's peripheral vision during locomotion, which becomes more important while executing a virtual rotation. During walking or turning, eye movements and the line of sight will generally be aligned with the end of the desired path [19]. Therefore, during turning, users' sight lines would be aimed in the direction of the turn, but the symmetric restrictor would partially obscure sight lines in this area. An asymmetric restrictor could potentially compensate for this limitation by accommodating the lateral offset in the user's line of sight. However, to the best of our knowledge, no studies have been conducted to evaluate the effectiveness of asymmetric side restriction during virtual turns.

In this paper, we introduce and evaluate a novel variant of FOV restriction, referred to as the *side restrictor*, which preserves perceptual cues in the user's peripheral vision towards the direction of turns. Our primary goal is to explore the effects of left and right peripheral FOV restriction during rotation. We propose that this asymmetric FOV implementation would be more appropriate during virtual turns and could be combined with other forms of asymmetric restriction during translation. To evaluate these technique, we conducted a virtual reality user study with a between-subjects design (N=93) that compared the side restrictor with the traditional symmetric FOV restrictor and an unrestricted FOV as a baseline. Participants completed a navigation task in a complex maze-like virtual environment that required frequent virtual turns using a handheld controller. Our results showed that the side restrictor was effective in mitigating cybersickness and reducing discomfort during virtual locomotion. The proposed technique also provided benefits for subjective visibility and enabled users to remain immersed in the virtual environment for longer periods of time. Furthermore, in our study, we did not observe any negative effects compared to the traditional symmetric restrictor, and we therefore conclude that side restriction appears to be a superior design choice for virtual environments with frequent virtual turns.

2 Related Work

2.1 Cybersickness in Virtual Reality

Cybersickness is a form of motion sickness specific to virtual reality, and the symptoms are similar to those produced by other forms of motion sickness. The most prevalent theory explaining cybersickness is the sensory-conflict theory [40, 42]. Sensory-conflict theory claims that motion sickness is caused by a mismatch between current sensory input patterns about self-motion and expected sensory input patterns based on previous experiences. Within the context of virtual reality, cybersickness is usually associated with virtual images that do not correlate with the body's physical movement [18,25]. The sensation of illusory self-motion in the absence of physical movement, known as vection, has been discussed in many studies on cybersickness [23, 36]. There are also other theories to explain the causes of cybersickness, such as the postural instability theory [41, 45] and the evolutionary hypothesis [44].

The simulator sickness questionnaire (SSQ) is the most common questionnaire to measure cybersickness during virtual experiences. It was developed by Kennedy et al. in 1993 [21], and it measures

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the severity of 15 motion sickness related symptoms on a 4-point scale. However, the SSQ was designed to measure motion sickness induced by flight simulators, and some research indicates that the symptoms of cybersickness do not align with the symptoms from simulator sickness [7, 8, 40]. The Fast Motion Sickness Score (FMS) is the other questionnaire commonly used to monitor participants during a VR experience [22]. The FMS asks users to report their feelings of motion sickness on 20 point scale at various intervals during an experience. Separately, several studies revealed a relationship between postural instability and motion sickness. They suggest that individuals who are more susceptible to cybersickness can be identified based on their spontaneous postural sway [50] [46]. In addition, physiological signals have been used to quantify the severity of cybersickness [13]. The most commonly used signals include electrocardiogram (ECG), electrogastrogram (EGG), electroencephalograms (EEG), and heart rate.

Cybersickness is most commonly associated with virtual locomotion techniques in VR, but it can still occur even when there is a 1:1 mapping between the user's viewpoint and their physical body motion [9, 32]. However, users with virtual locomotion were more likely to experience cybersickness than those without virtual locomotion [29]. One common method to reduce cybersickness is by reducing the perception of virtual locomotion. For example, the incidence of cybersickness can be reduced when a user's virtual locomotion is smoothed while virtually traversing bumpy terrain [14]. Several variations on this theme have been explored, including using static and dynamic rest frames [11], dynamically decreasing the users' FOV by adding blur or opaque masks [12, 16, 27], viewpoint snapping [15, 39, 52], full-screen blurring [10], or selectively detecting and using predefined masks or blurred regions [26, 30].

2.2 Dynamic FOV restriction

Dynamic FOV restriction, also known as "tunneling" or "vignetting," has become one of the most widely used mitigation strategies during virtual locomotion in commercial applications [35]. This technique is based on the hypothesis that peripheral optical flow is an aggravating factor for cybersickness. It aims to dynamically reduce the displayed FOV in a head-mounted display. The size of the FOV is adjusted based on the velocity of virtual movement. Several past studies illustrated that this technique can effectively prevent cybersickness in VR [6, 16, 46]. FOV restriction was shown to be effective in mitigating VR sickness for both sexes [3] [1]. Some studies have also investigated variants of dynamic FOV restriction, such as dynamic blurring in the retina's periphery, rather than using a black background [12, 27, 31].

Recently, some studies have also focused on asymmetric FOV restriction. Varying implementations have been investigated as a way to improve both user comfort and subjective experience. These methods include a FOV restrictor with the horizontal and vertical dimensions adjusted independently [24], displaying a wireframe model of the physical world in the periphery [55], a dynamic restrictor tethering the center of the restrictor to eye motion [2], and a FOV restrictor that preserves visibility of the ground plane [54]. The most similar technique to our proposed method was implemented in Eagle Flight, a video game developed by Ubisoft for the Playstation VR platform. The game implements an asymmetric FOV restrictor that limits the user's FOV in the direction *towards* the turn when flying in open space, which seems counterintuitive. They also restricted the user's FOV symmetrically when flying in a confined space, such as tunnels. In contrast, our method was designed for navigating virtual environments on the ground, which requires turning around corners and avoiding collisions with near-field obstacles. Regardless, to our knowledge, there have not been any empirical studies that have evaluated the efficacy of asymmetric side FOV restriction.

Horizontal FOV plays an important role in providing spatial information and in a user's ability to maneuver [20]. Kim et al. investigated the performance of FOV restriction in both the horizontal and vertical dimension. This research found that horizontal FOV restriction is more noticeable than vertical restriction, and this can consequently reduce immersion [24]. Panlener et al. investigated the impact of a restricted horizontal FOV in subjective median plane judgments and blind reaching tasks, and found it negatively impacted distance judgments [37].

(a) symmetric restrictor (b) side restrictors (left and right turns)

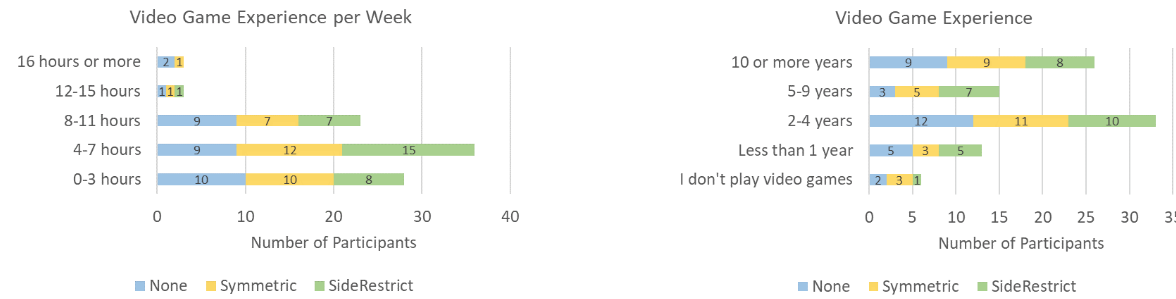
Figure 1: (a) The standard symmetric FOV restriction technique uses a circular black mask to occlude the periphery. (b) When the user turns to the left or right, an asymmetric mask is used to restrict the FOV on the side opposite to the turn, and the center is shifted laterally into the turn.

Some methods of FOV restriction have shown mixed results. Several studies have shown the technique can efficiently and effectively reduce cybersickness [4, 12, 16, 17]. However, improper occlusion of peripheral vision may expose the user to potential adverse effects, leading to more severe cybersickness [28]. Improperly displaying vignetting or increasing and decreasing vignetting too frequently can also lead to an increase in cybersickness symptoms [34]. Previous experimental findings also revealed a relationship between FOV restriction and the subjective sense of presence. A popular finding is that cybersickness has a negative relationship with a user's sense of presence [51]. In this light, FOV restriction should improve the sense of presence, but some experiments have yielded the opposite conclusion [4, 5]. Conversely, some research has found that dynamic FOV restriction did not significantly effect presence compared to an unrestricted FOV [27, 47]. One potential reason for this discrepancy could be that the black mask/vignette added a sense of unreality to the virtual environment [47]. Research has also shown that FOV restriction can come at the cost of users' task performance in spatial learning [5]. These studies confirmed that a certain degree of peripheral vision should be maintained to both reduce the occurrence of cybersickness and to provide a high-quality user experience.

3 Field-of-View Restrictor Design

To implement the FOV restrictors, we extended VR Tunneling Pro, an open-source asset for the Unity game engine. This package provides a computationally lightweight restrictor using a symmetric circular mask that can be customized using a variety of parameters [48]. The mask is defined by an outer radius and an inner radius, as shown in Fig. 1(a). The range beyond the outer radius was completely obscured, while the region between the inner and outer radius provided a smooth transition from transparent to opaque. By default, the shader implemented in VR Tunneling Pro defines the mask radii in screen space. We modified this shader to compute the size of restriction according to the degrees of FOV so that our results could be more easily interpreted and implemented on various headsets.

The FOV restrictor was displayed only when the participant was moving virtually and was not visible when they were physically walking. The restrictor size was dynamically scaled from the maximum FOV to a defined minimum degree. We attempted to select parameters that were similar to those we observed in commercial games and validated their performance in providing a comfortable



(a) (b)

Figure 2: (a) The number of hours per week of video game experience for participants. (b) The number of years of participants' video game experience. Gaming experience was approximately balanced between the three conditions.

experience through internal pilot testing. In this experiment, we set the outer FOV to 60 degrees and the inner FOV to 59 degrees. The size of the fully opaque region was comparable to the parameters used in Wu et al. [54], although the intermediate region was smaller. The dynamic scaling of the FOV mask was applied over a duration of 0.25 seconds when participants started or stopped moving.

Symmetric FOV Restrictor Design. The symmetric FOV restrictor was generated by aligning the angle between the camera's view direction and the vector formed by any point on the edge of the black opaque texture to the center of the camera and, as shown in Fig. 1(a). The symmetric restrictor was activated whenever the user initiated either a virtual turn or a forward/backward translation.

Side FOV Restrictor Design. To create the side FOV restrictor, we modified the shader to separate the horizontal and vertical FOV, and a new variable was added to control the restricted side in the horizontal direction. All the other parameters remained consistent with the symmetric restrictor. The logic was as follows:

- If the user moves virtually forward or backwards, the FOV is restricted symmetrically.
- If the user turns virtually to the left or right, or virtually moves forward/backwards and physically turns left or right, the FOV is restricted only on the side *opposite* to the turn direction. The restrictor in the turning direction is stretched so that the leftmost or rightmost point is positioned at infinity, and the view on the side into the turn remains visible. The center also shifts laterally in the direction of the turn.
- If the user stops moving virtually, the FOV is unrestricted.

The lateral shift of the side restrictor was synchronized with the user's virtual turning. To determine parameters, we conducted internal pilot testing with a Vive Pro Eye. Users navigated through the same virtual environment used in our study without FOV restriction, and we computed the average angular shift of the users' eyes during virtual turns. Based on these data, we set the lateral shift of the side restrictor to ± 17 degrees. Examples of the side restrictor during virtual turns are shown in Fig. 1(b).

4 User Study

4.1 Experiment Design

To evaluate the effectiveness of side restriction during virtual turns, we conducted a between-subjects study with the three conditions:

- No restriction (baseline)
- Symmetric restriction
- Side restriction

In general, we hypothesized that the side restrictor would provide benefits across a range of subjective measures, including cybersickness, discomfort, sense of presence, and visibility of the virtual environment. We also hypothesized that participants would stay immersed in the virtual environment for a longer period of time when using the side restrictor. Our specific measures and scientific hypotheses are described in more detail in sections 5 and 6.

Due to the COVID-19 pandemic, the study was designed for remote deployment over the internet and required explicit recruitment of participants with existing access to consumer virtual reality equipment. All experimental procedures and tutorials were fully automated. To provide a consistent experience, the VR headsets were limited to an Oculus Quest or Quest 2, and the virtual environment was deployed directly to the participant's device. Running in PC-tethered mode using Oculus Link was not supported. The online study protocol was reviewed and approved by our University's Institutional Review Board (IRB).

4.2 Participants

Participants were recruited through online postings on interest groups of Reddit, Facebook, and Linkedin. They were required to have access to an Oculus Quest or Quest 2 and be prepared to sideload an application on the device. Study materials and video tutorials were provided through email along with an APK file of the application. Participants were required to have a normal or corrected-to-normal vision and be able to communicate in spoken and written English. Participants that were pregnant or had a history of epilepsy or severe motion sickness were instructed not to participate due to safety concerns. Each participant was compensated with a $10 Amazon gift card upon submitting the post-questionnaire and uploading a log file recorded by the headset.

A total of 93 participants completed the study, of whom 60 identified themselves as male and 33 identified themselves as female. We managed the distribution of VR application during the study so that the biological sex was evenly balanced across the three conditions. Participant ages ranged from 18 to 55 years old ($M = 23.30$, $SD = 5.95$). A total of 84 participants used an Oculus Quest 2. Only 9 participants used a Oculus Quest 1 and were divided among the three conditions. Upon review of the automatically captured logs in the questionnaire submission system, we discovered that 69 of the participants completed the study from the same IP address. However, thorough review of the data files and quantitative and qualitative questionnaires responses indicated that all the submissions were authentic data from different people. We were able to determine that these participants had completed the study at a large supermall with a VR arcade. Therefore, it appears that approximately two-thirds of our participants were sampled from a more general population than VR headset owners. This diversity is also reflected in the self-reports of video game experience. As shown in the Fig. 2, participants had a wide variety of video game experience, including novice and infre-

(a) (b)

Figure 3: (a) A partial overhead view of the virtual maze, which contains complex pathways and frequent turns. The waypoints that defined a linear path are indicated in gold. (b) To complete the task, participants collected the gold coins by traveling over them.

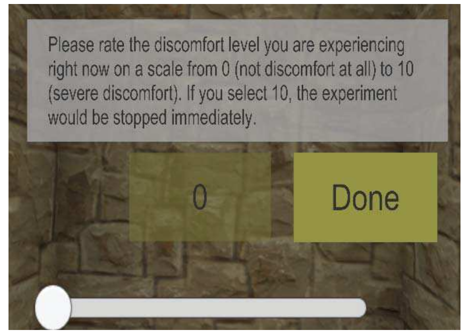


Figure 4: Participants used a spatial menu to rate their discomfort on a 0-10 scale at checkpoints throughout the experimental task.

quent gamers. Furthermore, the distribution of gaming experience across the three conditions was approximately balanced.

4.3 Virtual Environment

The virtual environment was procedurally generated using QMaze, an open-source Unity asset [43]. The 10x10 meter maze contained frequent turns so that we could explore the performance of side FOV restriction during virtual rotations (see Fig. 3(a)). The width of each passageway was approximately 1.5 meters. The virtual environment was consistent for all participants. Gold coins were placed in a linear path throughout the maze, and participants were instructed to collect them by walking over them (see Fig. 3(b)). These waypoints guided participants through the virtual environment so that they followed a consistent path.

Participants were instructed to stand during the virtual reality experience and only turn virtually without physically rotating their bodies. Locomotion was implemented using view-directed steering, which was controlled via the thumbstick on an Oculus Touch controller. The parameters for velocity and acceleration were determined through extensive pilot testing to determine a good balance between comfort and responsiveness. The maximum translational velocity was 2.5 meters per second, and the maximum rotational velocity was 45 degrees per second. When participants moved the thumbstick forward or backwards, translation would accelerate or decelerate smoothly over 0.25 seconds until the maximum was reached. Rotational acceleration was implemented similarly over a time window of 0.5 seconds. If the participant became lost or disoriented, they could press the grip button on the controller to open a spatial menu and teleport back to the last waypoint.

The virtual environment was implemented in Unity 2019.4.29f1. To ensure good performance on the Oculus Quest, the assets used to create the maze comprised computationally lightweight, low-poly models. During pilot testing, we measured the framerate on the Quest and observed that it was able to stay approximately equal to the device's maximum refresh rate of 72hz. We also the data files from each participant and verified that the virtual experience was rendered at the appropriate framerate.

4.4 Procedure

Upon viewing the advertisement, participants registered for the study online. The instructions and study materials were then distributed to each participant via email. Participants reviewed the information sheet and watched an instructional video that explained the task and controls. After watching the tutorial, the instructions walked them through the steps of sideloading the application on the Oculus Quest. The participants then could put on the headset and follow the in-game instructions to start the study.

Once immersed in the virtual environment, participants completed the Kennedy-Lane Simulator Sickness Questionnaire (SSQ) [21] that was displayed on a large spatial menu. They used the controller to point and select responses on the graphical user interface. After completing the SSQ, participants completed a 30-second practice trial to familiarize themselves with moving in the virtual environment. When they were ready to continue, they were prompted to select a button that would begin the experiment. Participants then completed 20 experimental trials that required following a path through the maze defined by the gold coins, as described in Section 4.3. Each trial was a different path that was designed to last approximately two minutes, although the actual time varied between participants. The paths were manually created to be equivalent in length and number of turns, and the path order for each participant was determined pseudo-randomly.

At the end of each trial, participants reached a checkpoint and were instructed to rate their subjective discomfort on a spatial menu using a controller (see Fig. 4). The question "Please rate the discomfort level you are experiencing right now on a scale from 0 (no discomfort at all) to 10 (severe discomfort)" was adapted from the original FOV restrictor study by Fernandes and Feiner [16], which has also been used in Wu et al. [54]. Participants were instructed at the beginning that the navigation task would be stopped without penalty if they reported a discomfort score of 10. Participants were also able to quit immediately via a spatial menu that was opened using the controllers grip button. The written and video materials both instructed participants to discontinue the study if they felt motion sick, and they would still be compensated for participating. Otherwise, the navigation task ended upon reaching the final checkpoint. The experiment lasted approximately 40 minutes.

Upon completing or terminating the navigation task, participants filled out the SSQ post-test in the virtual environment. They were then instructed to remove the headset, connect it to their computer, and retrieve the log file generated by the application. Participants uploaded this data file and completed a feedback post-questionnaire and demographic questionnaire using Qualtrics.

5 Measures

We evaluated the performance of the three FOV restrictors using the following metrics.

Cybersickness. The responses on the Simulator Sickness Questionnaire (SSQ) were used to compute the overall SSQ score before and after completing the navigation task. Because we had no a priority hypotheses about specific symptoms, the SSQ subscales were not analyzed separately. Additionally, it should be noted that the SSQ assesses the magnitude of symptoms related to cybersickness, which is more specific than general discomfort ratings at checkpoints during the study.

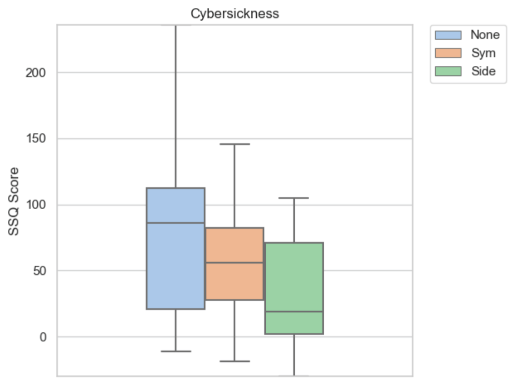


Figure 5: Box plots of the delta SSQ scores for each condition. Users reported significantly lower cybersickness when using the Side restrictor compared to the None condition.

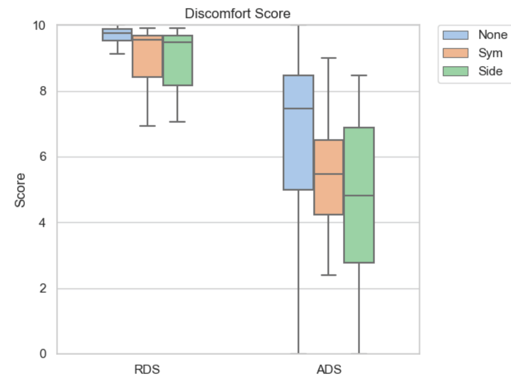


Figure 6: Box plots of average discomfort scores (ADS) and relative discomfort scores (RDS) for each condition. A value of 0 represents "no discomfort at all" and increasing numbers correspond to greater discomfort. Users reported significantly lower ADS and RDS when using the Side restrictor compared to the None condition.

Discomfort Scores. Two dependent variables were calculated from the discomfort scores for each condition following the metrics proposed by Fernandes and Feiner [16]: the participant's time-weighted *Average Discomfort Score (ADS)* and the *Relative Discomfort Score (RDS)*. The ADS measured the mean discomfort score from the time participants entered the VE to the time they left. The ADS may be a good way to measure subjective discomfort if participants complete all trials in the experiment. However, due to the duration our experiment, most participants terminated the navigation task early, so it may not be the best way to measure participants' relative performance. For example, two participants may complete the experiment with the same ADS, but one participant may spend more time in the VE before finishing. The RDS takes into account the time spent in the VE and measured the average discomfort score using the following equation:

$$RDS = \frac{\sum\limits_{0 \leq i \leq t_{stop}} DS_i + (t_{max} - t_{stop} + 1) DS_{stop}}{t_{max}} \tag{1}$$

The value t_{max} represents the longest duration of all participants. The duration of each participant was t_{stop}. The discomfort score at t_{stop} was recorded as DS_{stop}. DS_i was the discomfort score at each second i prior to t_{stop}. If a participant terminated before t_{max}, their DS_{stop} was recorded as 10 and repeated each second from the terminated time until t_{max}. If a participant finished early with a discomfort score less than 10, their final score was used as DS_{stop} and repeated.

Objective Measures. Because the navigation task terminated when the participant felt motion sick or entered a discomfort score of 10, the amount of time spent in the virtual environment is also a useful objective measure. The system therefore recorded the time starting from the beginning of the first experiment trial until the participant completed or quit the task, as well as the total number of completed trials for each participant.

Subjective Experience. The feedback post-questionnaire asked participants to rate agreement with the following two statements on a 7-point Likert scale:

1. It was difficult to see the virtual environment while turning.
2. I had a sense of being present in the virtual environment.

The responses for the first question were reversed so that higher ratings are associated with positive outcomes for both variables. In our results, we refer to these two measures as *visibility* and *presence*, respectively. Free-response questions were included to gather qualitative feedback.

6 Hypothesis

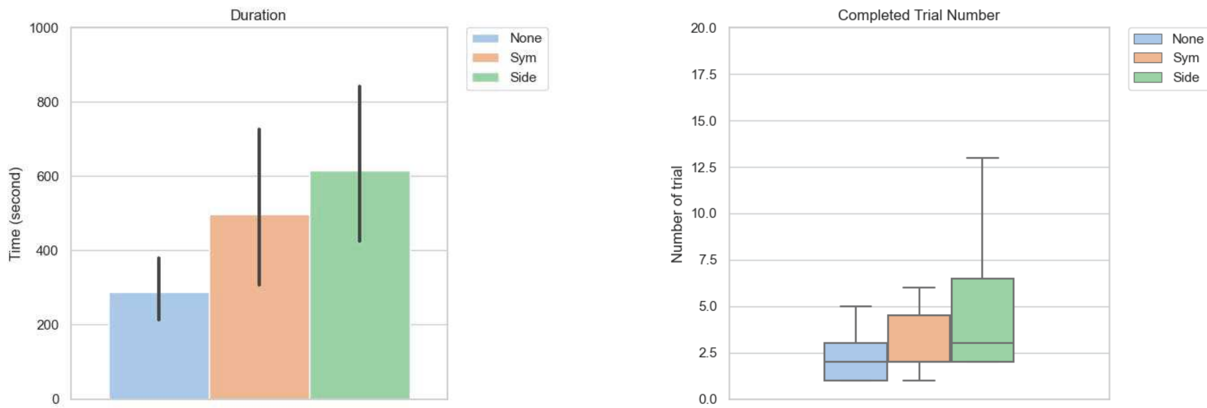
We formulated five scientific hypotheses regarding the dependent variables collected during this experiment:

- H1: Participants would report lower delta SSQ scores with the side restrictor compared to the baseline and symmetric restrictors.
- H2: Participants would report lower discomfort scores with the side restrictor compared to the baseline and symmetric restrictors.
- H3: Participants would be immersed in the navigation task longer with the side restrictor and symmetric restrictor compared to the baseline.
- H4: Participants would report better visibility with the side restrictors and baseline compared to the symmetric restrictor.
- H5: Participants would report a greater sense of presence with the side restrictor and baseline compared to the symmetric restrictor.

7 Results

Shapiro-Wilk Normality tests were conducted for all variables, and the results indicated that only the duration data was normally distributed and rest of these data were not normally distributed. For the non-parametric data, we applied the Kruskal-Wallis H test to analyze differences between the three FOV restrictor conditions (None, Symmetric, and Side) and reported descriptive statistics as median (Mdn) and interquartile range (IQR). All statistical tests used a significance value of $\alpha = 0.05$. When a Kruskal-Wallis H test rejected the null hypothesis, we conducted the post-hoc analysis using pairwise Conover tests with a Holm-Bonferroni correction for multiple comparisons.

Cybersickness. Cybersickness results are shown in Fig. 5. Analysis of deltas between the pre- and post-SSQ scores indicated significant differences among the three conditions, $\chi^2(2) = 9.73$, $p = .008$. Post-hoc comparisons revealed that the Side restrictor ($Mdn = 18.70$, $IQR = 69.19$) had significantly lower SSQ score compared to the None condition ($Mdn = 86.02$, $IQR = 91.63$), $p = .006$. However, the Symmetric restrictor ($Mdn = 56.10$, $IQR = 54.23$) was not significantly different from either the Side restrictor, $p = .07$, or the None condition, $p = .29$. These results partially support hypothesis H1.



(a) (b)

Figure 7: (a) Bar charts showing mean and standard deviation of immersion duration for each condition. (b) Box plots of number of completed trials for each condition. Participants using the Side restrictor persisted significantly longer in the virtual environment and completed a greater number of trials compared to the None condition.

Discomfort Scores. Results for the average and relative discomfort scores are shown in Fig. 6. The analysis for ADS revealed significant differences among the three FOV conditions, $\chi^2(2) = 9.67$, $p = .008$. Post-hoc comparisons found that the Side restrictor ($Mdn = 4.81$, $IQR = 4.11$) was more comfortable than the None condition ($Mdn = 7.46$, $IQR = 3.47$), $p = .006$. ADS ratings for the Symmetric restrictor ($Mdn = 5.46$, $IQR = 2.28$) were also significantly more comfortable than the None condition, $p = .04$. However, the Symmetric and Side restrictors were not significantly different, $p = .42$.

The analysis of RDS was also significant, $\chi^2(2) = 12.92$, $p = .002$. Post-hoc comparisons indicated that the Side restrictor ($Mdn = 9.49$, $IQR = 1.50$) was significantly more comfortable than the None condition ($Mdn = 9.75$, $IQR = 0.35$), $p = .001$. The Symmetric condition ($Mdn = 9.55$, $IQR = 1.25$) was also more comfortable than None condition, $p = .010$. RDS ratings for the Side and Symmetric restrictors were not significantly different, $p = .44$. These results partially support hypothesis H2.

Objective Measures. Results for task duration and number of completed trials are shown in Fig. 7. For the time data, 6 extreme outliers greater than 2 standard deviations from the mean were excluded to avoid biasing the analysis (1 in None, 2 in Side, and 3 in Symmetric). The trimmed data were then analyzed using a between-subjects ANOVA, which revealed significant differences among the three conditions, $F(2) = 3.57$, $p = .03$, $\eta^2 = .08$. Participants in the Side restrictor condition ($M = 615.06$, $SD = 583.21$) remained immersed in the navigation task significantly longer than the None condition ($M = 288.11$, $SD = 243.60$), $p = .03$. However, the Symmetric restrictor ($Mean = 497.92$, $SD = 538.62$) was not significantly different from either the Side restrictor, $p = .62$, or the None condition, $p = .22$.

The analysis of the number of completed trials also revealed significant differences among the three conditions, $\chi^2(2) = 9.53$, $p = .009$. Participants in the Side restrictor condition completed significantly more trials ($Mdn = 3$, $IQR = 4.5$) compared to the None condition ($Mdn = 2$, $IQR = 2$), $p = 0.005$. Similar to above, the Symmetric condition ($Mdn = 2$, $IQR = 2.5$) was not significantly different from either the Side restrictor, $p = .15$, or the None condition, $p = .16$. Taken together, these results partially support hypothesis H3.

Subjective Experience. Results from the feedback questionnaire are shown in Fig. 8. The analysis of visibility ratings revealed a significant difference among the three FOV conditions, $\chi^2(2) = 20.54$, $p < .001$. Post-hoc analysis indicated that the Side restrictor ($Mdn = 6$, $IQR = 4.5$) was given favorable visibility ratings compared to the Symmetric restrictor, $p = .002$. The None condition ($Mdn = 6$, $IQR = 2.5$) was also associated with higher visibility compared to the Symmetric restrictor ($Mdn = 2$, $IQR = 3.5$), $p < .001$. However, there was no significant difference observed between the Side restrictor and the None condition, $p = .62$. These results support hypothesis H4.

The analysis of presence ratings was not significant among the three conditions, $\chi^2(2) = 1.74$, $p = .418$. Participants reported similar sense of presence in the None condition ($Mdn = 5$, $IQR = 3.0$), the Symmetric restrictor ($Mdn = 5$, $IQR = 3.5$), and the Side restrictor ($Mdn = 5$, $IQR = 2.0$). We therefore did not find any empirical support for hypothesis H5.

8 Discussion

8.1 Effects on Cybersickness and Discomfort

The side restrictor was the only technique that significantly reduced the level of cybersickness compared to the unrestricted condition. This is strong evidence supporting the side restrictor as a viable method for mitigating cybersickness during virtual turns.

The non-significant results for the symmetric restrictor are consistent with the original study by Fernandes and Feiner [16]. Their primary findings involved subjective discomfort ratings, and SSQ scores were also not significantly different between restrictor conditions. Responses to our open-ended questions revealed potential explanations for the underperformance of the symmetric restrictor.

Because the virtual environment was a maze with many turns, participants needed to make a lot of virtual rotations during navigation. Some participants reported that when making a turn, the symmetric restrictor occluded their view of the maze in the turning direction. To avoid hitting the maze wall and to correctly follow the path, they had to stop frequently and wait for the restrictor to disappear before continuing. This sporadic turning process, as well as the appearance and fading of the restrictor, was likely to induce strong optical flow. This, in turn, could have increased the level of cybersickness. Conversely, the side restrictor gave participants a

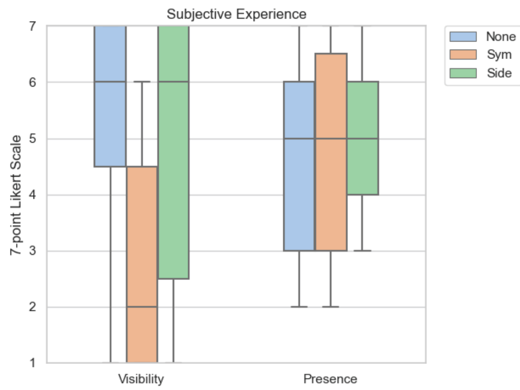


Figure 8: Box plots of visibility and sense of presence ratings for each condition. The direction of the scale was adjusted so that higher values are associated with positive outcomes. Users reported significantly worse visibility when using the Symmetric restrictor compared to the Side and None conditions.

clear view of the path while turning, allowing them to complete the turn smoothly without pausing.

The side restrictor was rated as significantly more comfortable than the unrestricted condition, which provides further support that this implementation improves users' experience during virtual turns. Although there was not a significant difference between the side restrictor and the symmetric restrictor, the side restrictor had the lower median value, which suggests that the lateral shift of the restrictor center did not cause any additional discomfort.

8.2 Effects on Subjective Experience

Visibility when using the side restrictor was rated significantly higher than when using the symmetric restrictor. This confirms that the proposed technique effectively increases visibility for users during turns, and subsequently enhances their awareness of the environment in the direction of the turn. This makes the experience more convenient for the user and can improve safety during virtual turns. Additionally, visibility ratings for the side restrictor were very close to those of the unrestricted control condition; there was no significant difference between the two. This suggests that the side restrictor more effectively compensates for the shortcomings of the traditional symmetric implementation and provides visibility during virtual turns that is comparable to an unrestricted experience.

The ratings for the sense of presence were very close among all three conditions. The results of various previous studies also show a mixed relationship between presence and FOV restriction. Presence has a positive relationship with vection [47], but a negative relationship with cybersickness level [51]. Since the use of a restrictor typically results in a reduction of both vection and cybersickness, it is not surprising that the trade-off between the changes of vection and cybersickness had a minimal effect on presence. A similar phenomenon can also be seen in previous studies [16, 47].

8.3 Effects on Objective Measures

Participants using the side restrictor remained immersed for significantly longer and completed a greater number of trials compared to those in the unrestricted condition. According to some questionnaire responses, being unable to see the surroundings while turning in the symmetric condition induced enough frustration to lead them to stop the experiment. Because participants were explicitly instructed to discontinue if they felt motion sick, and the task ended immediately upon a discomfort score of 10, the longer immersion time provides further evidence that the side restrictor was more effective in mitigating negative effects. Furthermore, the fact that participants also completed more trials when using the side restrictor indicates that the longer duration was not due to navigating the maze more slowly.

8.4 Limitations

This study has some practical limitations that may have influenced its results. All participants were recruited online, and the experiment was conducted remotely due to the COVID-19 pandemic. However, the variety and complexity of the logs captured during the experiment, in addition to the varied responses to the open-ended questions, supports the authenticity of the data. In any remote study, potential differences in the physical environments of the participants could have influenced their performance. However, these outside factors are also generally present for actual users "in the wild" who would also be experiencing VR in different physical environments. Thus, our experimental results should be generalizable to the real-world conditions in which FOV restriction techniques would be used. However, it should be noted that this study tested a specific type of virtual experience, and evaluation of FOV restriction in a wider range of VR experiences remains an open question for future work.

The vast majority of participants used a Quest 2, which has minor differences in field-of-view and resolution compared to the original Quest. Given the very small proportion of Quest 1 participants in each condition, we believe that these differences between devices are unlikely to have any meaningful impact on the results. Additionally, we relied on participants following the headset's built-in instructions for adjusting the interpupillary distance. Additional variability could have been introduced if some participants did not adjust it correctly, which is a limitation of conducting studies remotely.

9 Conclusion

In this paper, we proposed and evaluated asymmetric side FOV restriction, a new variant of a widely used technique for mitigating cybersickness in virtual reality. We conducted a between-subjects user study with three conditions to compare the proposed technique with a traditional symmetric restrictor and a control condition without FOV restriction. Our results showed that the side restrictor maintains similar outstanding benefits for improving user comfort compared to the symmetric restriction, while providing better performance for cybersickness reduction, visibility, and immersion time during virtual times. At the same time, we found no evidence of potential drawbacks to applying side restriction. Therefore, we conclude that this form of asymmetric FOV restriction appears to be superior to symmetric restriction during virtual rotation. It performs particularly well in close environments involving a large number of turns. Although we required participants to have access to the Oculus Quest, based on our information about participants, they were distributed across experience levels, and a large proportion of them had minimal experience with video games. Therefore, our study results are not solely limited to experienced VR users, despite the remote modality.

In the future, we plan to further investigate new variants and parameters for FOV restriction techniques. The combination of different asymmetric restrictors for translation and turns, such as side restriction, foveated restriction [2], and ground-visible restriction [54], has yet to be investigated. Future studies can also investigate FOV restriction techniques in a wider range of virtual environments and tasks to further understand the applicability of these techniques in different types of VR applications.

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