Effects of Field-of-View Restriction and Peripheral Teleportation on Path Integration during Virtual Locomotion

Tongyu Nie, Yuxuan Huang, Ville Cantory, Danhua Zhang, and Evan Suma Rosenberg

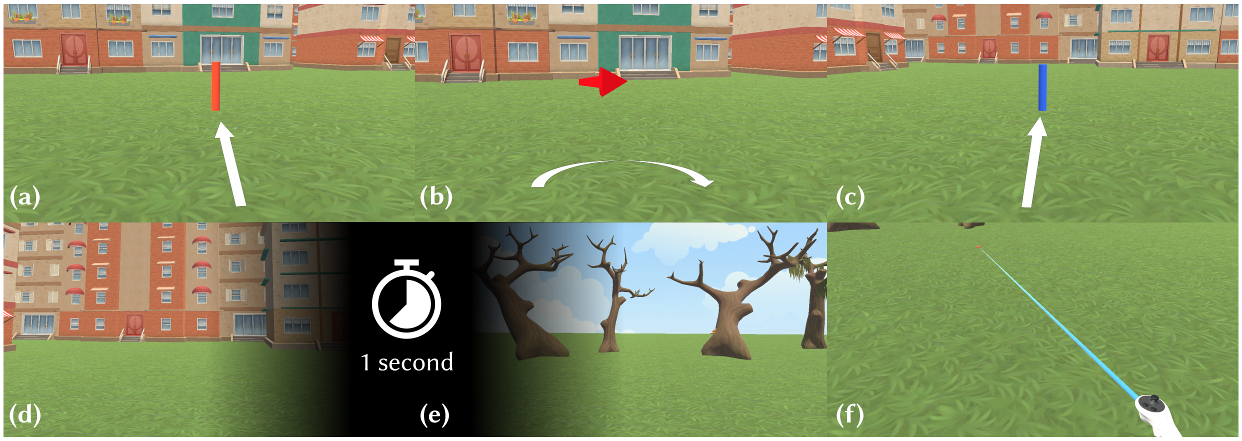

Figure 1: Illustration of the triangle completion task procedure. Participants were instructed to navigate two sides of a triangle and point back to where they started. Participants first navigated from the target position to the red pole (a), where they used the joystick to turn in the direction indicated by a red arrow appearing in front of them (b) until facing the blue pole. They then navigated to the blue pole (c). Upon reaching the blue pole (d), the virtual scene above the ground was replaced with a different set of virtual objects through a one-second fade-in transition (e). After the transition, participants physically turned to face the estimated direction of the target position and used a virtual ray extending from the controller to point to the ground and indicate their estimate (f). A red dot appeared at the intersection of the ray and the ground plane to visualize the pointing location. Participants pressed the controller trigger to confirm their estimate and complete the trial.

Abstract— Most software-based cybersickness mitigation techniques, such as field-of-view (FOV) restrictors and rest frames, alter visual content and peripheral optical flow, often negatively affecting various locomotion quality factors. Path integration, a critical component of spatial updating, relies on optical flow during virtual locomotion and may therefore be particularly affected by these techniques. Despite a substantial body of work evaluating cybersickness mitigation methods, relatively few studies have examined their effects on spatial updating or path integration. Moreover, prior studies on spatial updating have not yielded conclusive results, despite theoretical predictions from the perception literature. In this work, we conducted a preregistered experiment with 48 participants to compare the effects of two mitigation techniques, the dynamic FOV restrictor and peripheral teleportation, on path integration, relative to an unrestricted control condition. By minimizing potential confounding factors identified in previous work, we found that participants made significantly larger homing errors with the FOV restrictor than in the control condition, whereas performance with peripheral teleportation did not differ significantly from either of the other conditions. These findings provide direct evidence that FOV restriction impairs path integration, while the impact of peripheral teleportation remains inconclusive. Our results further highlight the trade-off between mitigation effectiveness and spatial updating, providing VR designers with deeper context for selecting mitigation techniques.

Index Terms—Virtual reality, cybersickness, visual perception, path integration

1 Introduction

Locomotion through virtual environments (VEs) is a fundamental user interface task in virtual reality (VR) [10, 61]. Despite its widespread use, continuous virtual locomotion can induce severe cybersickness, leading to the development of various mitigation techniques, such as dynamic field-of-view (FOV) restrictors, rest frames, peripheral blurring, and image deformation. While the FOV restrictor is the most widely used cybersickness mitigation technique due to its effectiveness and ease of implementation [23], a more recent approach, peripheral teleportation, has been shown to provide stronger mitigation effects than FOV restriction [49]. Most of these techniques mitigate discomfort by altering the peripheral optical flow available to the user to some extent, which is a critical component of motion perception and visual path integration [33, 56, 63]. Path integration is a process by which humans and animals integrate idiothetic cues to track their position in space for spatial updating. This process allows one to navigate unfamiliar region of space and gradually integrate the isolated perspective views encountered into an internal representation suitable for subsequent piloting [25, 44]. Therefore, studying the potential negative effects of these mitigation techniques on spatial updating, particularly on path integration, is necessary to provide a comprehensive evaluation of their effectiveness. To date, there is no conclusive evidence regarding the negative impact of commonly used cybersickness mitigation techniques on path integration or spatial updating. Although many prior studies suggest that a limited field of view negatively affects perception [12, 20, 69], findings specifically examining the impact of FOV restriction

• *Tongyu Nie, Ville Cantory, Danhua Zhang, and Evan Suma Rosenberg are with the Department of Computer Science & Engineering at University of Minnesota. E-mails: nie00035, canto063, zhan5954, suma@umn.edu*
• *Yuxuan Huang is with the Department of Computer Science at North Carolina State University. E-mail: yhuang94@ncsu.edu*

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on spatial updating remain inconclusive [5, 51].

Upon closer examination of the existing literature, we identified two confounding factors that may have contributed to this inconsistency: **cybersickness** and **landmarks**. First, reductions in cybersickness may attenuate the negative effects of FOV restriction on spatial navigation performance. It is reasonable to hypothesize that users perform worse on tasks assessing spatial updating when experiencing cybersickness [75]. However, if a mitigation technique simultaneously reduces cybersickness while impairing spatial updating, these opposing effects may cancel each other out, thereby decreasing the likelihood of detecting a significant effect. Second, with dynamic FOV restriction, participants periodically regain a full view of the virtual environment, allowing them to update their spatial knowledge using landmarks within their FOV. We hypothesize that dynamic FOV restriction and similar techniques primarily affect path integration while having limited impact on landmark-based piloting (see Section 2.1.1 for details on path integration and piloting). Consequently, it is necessary to control the level of cybersickness induced by the task and remove landmark information to isolate the effects on path integration.

In this work, we used a triangle completion task to evaluate the effect that different cybersickness mitigation methods have on path integration. Specifically, we compared the *dynamic FOV restrictor* [23] and *peripheral teleportation* [49], a rest frame design that utilizes content from the current virtual environment, against a *control* condition with a full FOV. In a within-subjects user study with 48 participants, we observed a significant difference between the FOV restrictor and the control condition. Performance in the peripheral teleportation condition was not significantly different from the restrictor and control conditions. These results suggest that trade-offs between mitigation effectiveness and spatial updating should be carefully considered when developing novel cybersickness mitigation techniques.

Beyond our empirical findings, the main methodological contribution of this work is a confound-controlled triangle completion design that isolates path integration from cybersickness and landmark-based piloting. This design enables the first direct evidence that FOV restriction impairs path integration, and it explains why earlier studies that left these confounds uncontrolled were inconclusive.

2 Background and Related Work

2.1 Background

2.1.1 Spatial Updating and Sensory Information

An effective travel technique should help users maintain awareness of their position and orientation within the environment, a process commonly referred to as spatial updating [10, 67]. *Homing* is a commonly used task for studying spatial updating, in which participants explore an unfamiliar environment and then attempt to return to their starting location [33]. Strategies for spatial updating are typically categorized into path integration and piloting [36].

Piloting Piloting relies on external cues, like landmarks, to specify self-location [44]. External information, particularly visual landmarks, is important for accurate spatial updating because it provides orientation and position cues relative to known reference points [14, 74]. Many studies have shown that when landmark information is manipulated, navigators tend to be heavily influenced by it, suggesting that landmarks often dominate the spatial updating process [40, 57, 59].

Path Integration Path integration is the process of integrating a traveler's motion over time [44], first theorized in [21]. It provides distance and directional information between locations [33] and serves as a foundation for piloting and the acquisition of other forms of spatial knowledge [25, 36]. Multiple studies have shown that humans can perform homing tasks using optical flow alone during virtual locomotion in VR [22, 33, 52], supporting the existence of visual path integration. Although bodily sensory cues can dominate optical flow when available [33], visual path integration primarily relies on optical flow derived from self-motion. Optical flow specifies the relative motion between the observer and the environment and plays a central role in locomotion control [26, 62]. Peripheral optical flow is particularly important due to the geometric relationship between field of view and motion [26, 56].

2.1.2 Triangle Completion Task

Task Introduction Although several variants of homing tasks exist, the triangle completion task (see Figure 2) is the simplest task that incorporates both distance and orientation information [33]. As a result, triangle completion tasks, which consist of an encoding phase and a response phase, are widely used to study spatial updating [16, 52, 73]. During the encoding phase, participants start at a home location and move along two fixed legs defined by waypoints. In the response phase, they take the most direct route back to the home location, completing the third leg of the triangle. By manipulating the sensory information available during the response phase, researchers can examine how different sensory systems contribute to spatial updating.

Previous Studies on Virtual Locomotion Compared to physical walking or teleportation, fewer studies have evaluated virtual locomotion using the triangle completion task. Klatzky et al. investigated self-position and orientation updating during real, imagined, and virtual locomotion and found that optical flow alone had a limited effect on heading updating [39]. Subsequently, Riecke et al. demonstrated that participants could reliably perform visual homing without stable or salient landmarks [52]. Weißker et al. compared steering, jumping, and teleportation and found that jumping enabled some users to achieve spatial updating performance comparable to steering [65]. Additional studies have examined the effects of stress [41], movement experience [8], and auditory cues [11] on triangle completion performance.

Previous Studies on FOV Studies examining the impact of field of view on spatial updating have produced mixed results. An early study using a projector display with 10 participants found no significant differences in homing performance across three geometric FOV conditions (40°, 60°, and 80°) [51]. However, the authors noted that the virtual environment lacked visual structure, which limited the use of peripheral vision. Moreover, the display technology and small sample size limit the generalizability of these findings to modern head-mounted displays. Using more recent hardware, a study with 28 participants employing an HTC Vive HMD also reported no significant difference in home position estimation error between a 55° FOV restrictor and a 100° unrestricted condition [5]. This study examined spatial updating as a whole without disentangling the effects of path integration and piloting. Although the reasons for these seemingly counterintuitive results remain unclear, we attribute them to confounding effects related to cybersickness and landmark availability.

2.2 Related Work

2.2.1 Cybersickness Mitigation Techniques

Methods to reduce cybersickness during virtual locomotion have been a long-standing area of research in VR. Vestibular and haptic stimulation, such as galvanic vestibular stimulation [28] and head-mounted air propulsion [43] have recently been explored, but require additional devices to utilize. In contrast, software-based techniques typically focus on reducing peripheral optical flow [46, 70], or in some cases the entire flow field [13, 30, 50], which is known to play a critical role in motion perception and control [56, 64]. The dynamic FOV restrictor, which occludes peripheral vision during virtual locomotion, is the most widely adopted mitigation technique to date [3, 23, 70, 71]. Newer techniques, such as the vision modulator [72], deformation [27, 47], and peripheral teleportation [49], attempt to reduce cybersickness with smaller interference with peripheral vision.

Peripheral Teleportation Proposed as an earth referent rest frame design [7], peripheral teleportation demonstrated stronger mitigation effects than the FOV restrictor, significantly reducing discomfort and extending participants' immersion time [49]. This technique creates a rest frame in the user's peripheral vision by rendering the current virtual environment with additional rest-frame cameras whose motion is influenced only by the user's physical head movements. During locomotion, the technique keeps the peripheral view up to date by repeatedly teleporting these rest-frame cameras to new positions and orientations. Figure 3(b) illustrates the resulting visual appearance of peripheral teleportation.

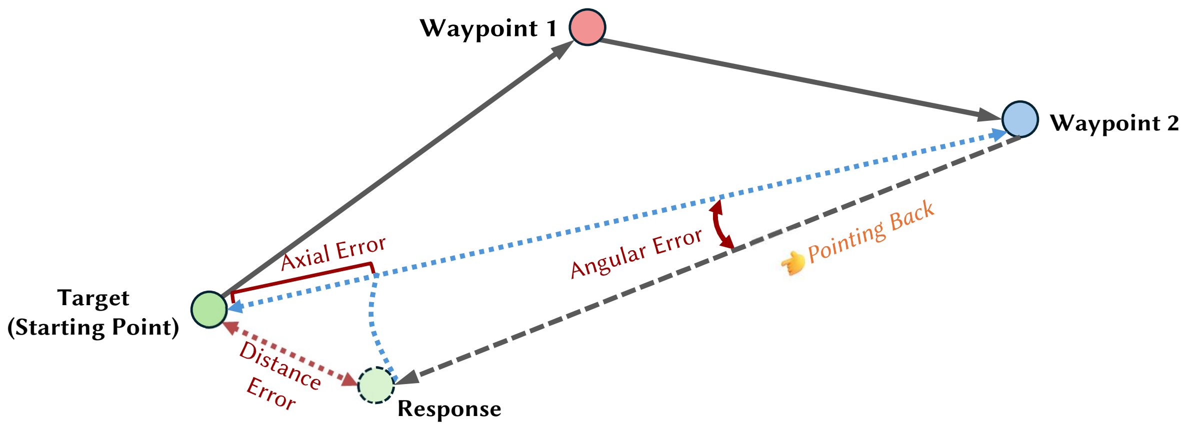

Figure 2: Overview of the triangle completion task. Participants start at the target location (green circle) and navigate the first two legs by following two waypoints (red and blue circles). Upon reaching Waypoint 2, they point back to the starting location using a controller-based ray to complete the third leg. The response location (light green circle) is recorded by the VR application. The dashed black and blue lines indicate the response and target distances, respectively, and distance, angular, and axial errors are illustrated.

2.2.2 Gaps in Mitigation Techniques Evaluation

Cybersickness mitigation techniques are often evaluated primarily based on their ability to reduce discomfort. However, mitigation effectiveness alone does not fully capture their impact on users. Many techniques achieve mitigation by reducing or altering peripheral optical flow, which provides important cues for motion perception (see Section 2.1.1). As a result, these techniques may introduce unintended side effects on user experience, motion perception, and spatial updating processes such as path integration. For example, FOV restrictors reduce visual content in the user's peripheral view, with stronger restrictions generally producing greater mitigation effects [6]. In contrast, techniques such as peripheral blurring preserve a blurred view of the periphery and may better maintain visual context, but they are typically considered less effective than restrictors in reducing discomfort. These examples highlight the need for more comprehensive evaluations that assess not only mitigation effectiveness but also the potential negative impacts of these techniques on perceptual and behavioral outcomes.

2.3 Confounding Variables: Cybersickness and Landmarks

As is discussed in Section 1, cybersickness and landmarks are potential confounding factors for studying the impact of cybersickness mitigation techniques on path integration.

Cybersickness Participants often perform worse on cognitive and perceptual tasks when experiencing cybersickness [75]. As a result, mitigation techniques that impair spatial updating may be harder to evaluate if their reduction of cybersickness simultaneously improves task performance, thereby masking negative effects on spatial updating. Unlike studies using more comfortable locomotion interfaces such as teleportation [18,36] or physical walking [16,34,45], continuous virtual locomotion can induce severe cybersickness. For example, Al Zayer et al. reported no significant difference in spatial navigation performance with or without an FOV restrictor [5], despite observing significantly higher cybersickness in the unrestricted condition. The increased discomfort in the control condition may therefore have counteracted any potential benefit of an unrestricted FOV. To mitigate this confound, we kept overall discomfort low by shortening total navigation duration and adding a five-minute break between sessions.

Landmarks The interaction between landmarks and dynamic FOV masking is also critical. As noted by Al Zayer et al., dynamic mitigation techniques restrict the FOV only during locomotion while preserving a full FOV when stationary [5]. Although FOV restriction reduces optical flow during movement, participants can frequently regain a full view of the environment, allowing them to update spatial knowledge using landmarks. Prior work suggests that landmarks often dominate the homing process [73,74]. Accordingly, dynamic FOV restriction and peripheral teleportation are more likely to affect path integration while having limited impact on landmark-based piloting. To isolate effects on path integration, landmark information must therefore be restricted, for example by scene swapping prior to the response phase [52].

3 User Study

3.1 Hypotheses

We preregistered the following hypotheses on the Open Science Framework[1] to evaluate the effects of cybersickness mitigation techniques on spatial updating.

- **H1**: Participants would have larger errors using peripheral teleportation and the restrictor compared to the control condition.
- **H2**: Participants would have larger errors using the restrictor compared to peripheral teleportation.
- **H3**: Participants would have larger variability using peripheral teleportation and the restrictor compared to the control condition.
- **H4**: Participants would have larger variability using the restrictor compared to peripheral teleportation.
- **H5**: Participants would have larger errors in trials with higher discomfort scores.
- **H6**: Participants would report higher task load using the restrictor compared to peripheral teleportation and the control.

We expected larger error and variability with the restrictor than with peripheral teleportation (H2 and H4) for two reasons. First, peripheral stimulation enhances depth perception [32,38], and peripheral teleportation may similarly improve judgments of traveled distance. Second, discrete peripheral updates may still provide usable input to visual path integration [4,65].

3.2 Study Design

This study (IRB approved) used a within-subjects design with three conditions: Control, Peripheral Teleportation, and Restrictor (see Figure 3), counterbalanced using a Balanced Latin Square. The FOV restrictor was selected as the most widely used mitigation technique, and PT as the most recent technique shown to exceed it in mitigation effectiveness. Together, they represent the current state of the art, with the no restriction control as the baseline to measure participants' natural performance in VR without any visual effect. Between conditions, participants took a mandatory 5-minute break to recover from cybersickness symptoms. Although a short break cannot guarantee full recovery [48], it does not compromise our results because cybersickness is not our primary focus. To monitor cybersickness symptom development, we collected per-trial

[1] https://osf.io/x625k

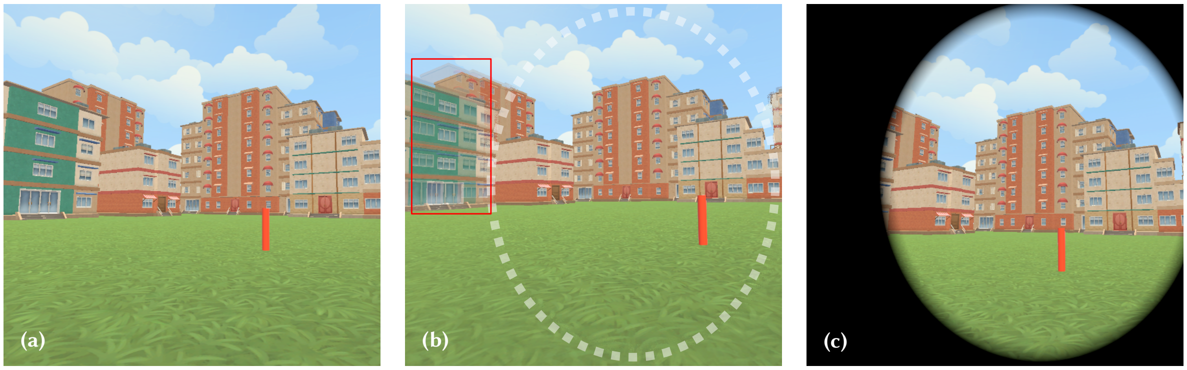

Figure 3: The visual appearance of the three conditions tested in our study, including the control condition (a), which has the standard viewpoint with full FOV, peripheral teleportation (b), and Black FOV restrictor (c). All images were for the left eye. The dashed white circle in (b) marks the boundary of the FOV mask, which is not part of peripheral teleportation's visual effect and is only shown for illustration. As is shown in the area marked by the red box in (b), peripheral teleportation renders the peripheral region by linearly interpolating the outputs from a pair of stationary cameras that are teleported consecutively, which appears like double vision between teleportations.

discomfort ratings and post-session SSQ scores (Section 4.7). Readers can refer to [49] for a between-subjects comparison of these conditions.

Participants performed 12 triangle completion tasks per condition (36 trials in total) [36] while wearing a head-mounted display (HMD). Each trial takes 30 seconds to finish, making each session approximately 6 minutes long. Although more trials per participant would reduce estimated population response variability, it could also increase cybersickness, thereby elevating dropout rates and confounding effects (see Section 2.3) [54].

3.3 Participants

We recruited 48 participants (24 Male, 24 Female) from the university campus using classroom announcements, email lists, and flyers. Participants included 26 aged 18-24, 21 aged 25-34, and 1 aged 35-44. Inclusion criteria required participants to be over 18, able to stand without assistance, have normal or corrected vision, no history of severe motion sickness, and not pregnant. Each participant received a $20 Amazon.com gift card.

3.4 Equipment

The experiment used a Meta Quest 3 headset with Oculus Link (resolution: 2064×2208 pixels per eye, 110° FOV, 72 Hz frame rate). The VR application ran on a PC with an Intel Core i9-9900K CPU, NVIDIA RTX 2080 Ti GPU, and 32 GB RAM.

3.5 Virtual Environment

The Unity builds of this experiment are available online [2].

Scenes The VE was built using Unity 2022.3.23f1 with assets from the Unity asset store[3,4]. To minimize the impact of landmarks, a confounding factor discussed in Section 2.3, we swapped the virtual scene before participants started pointing (see Section 3.7 for details). Figure 4 shows the overhead view of both environments.

Paths We adopted the path design from [36], including the shape of triangles and path leg lengths, for direct comparability with prior work. The VE included 12 triangles, each corresponding to a trial within a condition with a unique turn angle from -135° to 135° in 22.5° increments except for 0°. Path leg length was randomly selected per trial from three values (6.1, 6.7, and 7.3 meters). Paths were marked by vertical poles (1 meter tall, .25 meter diameter, see Figure 1) appearing sequentially along the two outbound path legs (details in Section 3.7.2). Waypoint 1 (first path leg end) was marked by a red pole with a red arrow indicating the blue pole direction; Waypoint 2 (second path leg end) was marked by a blue pole.

Locomotion Interface We implemented view-directed continuous virtual locomotion using XR Interaction Toolkit 2.5.4 in Unity with maximum translational velocity of 3m/s and maximum rotational velocity of 45°/s.

Mitigation Techniques Both FOV restrictor and peripheral teleportation's implementations and parameters were adopted from [49], which was open-sourced on GitHub[5]. Peripheral teleportation creates two sets of cameras, each attached to a stationary parent. The cameras' local transforms are updated based on the user's head motion, while the parents are teleported every second based on current translational and rotational velocities. The peripheral view is linearly interpolated between the two camera sets between teleportations, making it a rest frame stationary relative to the earth. Because the view of peripheral teleportation when it is triggered is the same as the HMD's view, we scale the FOV mask immediately when the user starts or stops moving (i.e., mask onset is triggered by any nonzero locomotion velocity without gradual interpolation). We keep the same design for the restrictor for scientific rigor [49]. For both techniques, the central region continues to render the user's normal view, and the outer and inner radius of the FOV mask were set to 60° and 55° in the user study. The center of the FOV restrictor was shifted 17° towards the turning direction during turning following previous works [49, 71].

3.6 Measures

3.6.1 Triangle Completion

We adopted standard triangle completion measures from prior work [36, 45] to quantify errors in participants' estimates.

Distance Error Distance error was defined as the Euclidean distance between the target and the participant's estimated location (Figure 2) and served as the primary outcome measure, consistent with prior studies (e.g., [33, 36, 45]). To disambiguate directional and distance components of error, we additionally analyzed angular and axial errors.

Angular Error *Signed angular error* was defined as the angular difference (in degrees) between the pointing direction and the direction to the path origin, with errors flipped for counterclockwise triangles so that negative values always indicated under-rotation. *Unsigned angular error* was computed as the absolute value of the signed angular error.

Axial Error *Signed axial error* e_{axial} quantified distance scaling error as the normalized difference between the response distance and the target distance (Figure 2):

$$e_{axial} = \frac{|\mathbf{r} - \mathbf{w_2}| - |\mathbf{t} - \mathbf{w_2}|}{|\mathbf{t} - \mathbf{w_2}|}, \quad (1)$$

[2] https://osf.io/jgx6p

[3] https://assetstore.unity.com/packages/3d/environments/urban/modular-resort-town-91427

[4] https://assetstore.unity.com/packages/3d/environments/fantasy/lowpoly-fantasy-swamp-245240

[5] https://github.com/nietongyu/PeripheralTeleportation

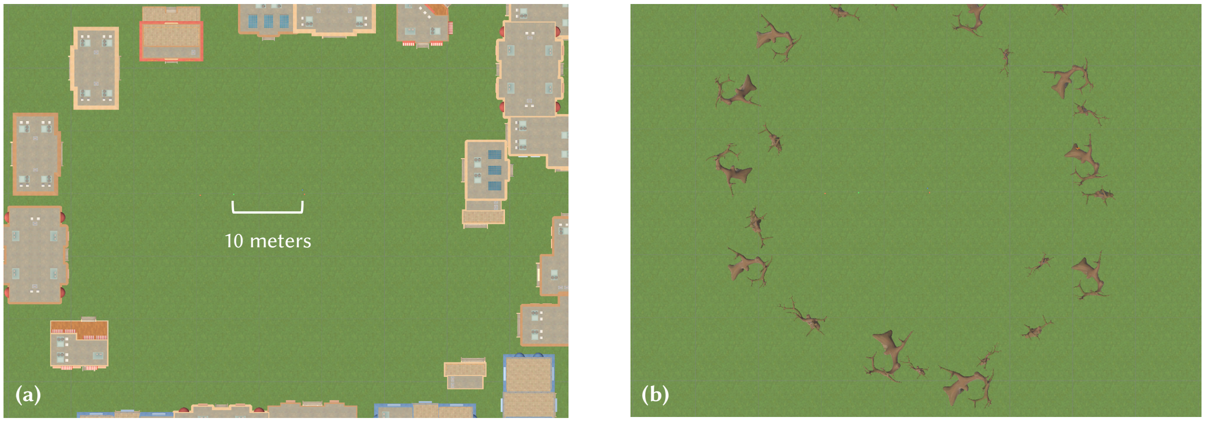

Figure 4: The overhead views of the virtual environments before (a) and after (b) scene swapping. The ground, which was textured with a repeated grass pattern, was kept during the scene swapping.

where $\mathbf{r}$, $\mathbf{w_2}$, and $\mathbf{t}$ denote the positions of the pointing response, waypoint 2, and the target, respectively. *Unsigned axial error* was defined as the absolute value of the signed axial error.

Variability Variability was defined as the standard deviation of distance error across trials from each session, reflecting consistency in spatial memory [45].

3.6.2 Cybersickness

We included the following measures to monitor cybersickness induced by the triangle completion task. These measures were not used for condition comparisons, but to assess whether cybersickness may have compromised task performance.

SSQ The Simulator Sickness Questionnaire (SSQ) measures symptoms of simulator sickness [37]. It was administered immediately before and after each experimental session.

Discomfort Scores Participants reported their discomfort on a 0–10 scale using a VR slider, where 0 indicated no discomfort and 10 indicated severe discomfort, following prior work [23, 70]. For each session, we computed a time-weighted average discomfort score.

3.6.3 Task Load

Task load was measured after each session using the raw NASA Task Load Index (TLX) questionnaire [29].

3.7 Procedure

The whole experiment lasted approximately 50 minutes and was completed in a single laboratory visit.

3.7.1 Pre-Experiment

Introduction At the start of the study, the experimenter verified that participants met all inclusion criteria, explained the task, demonstrated controller usage, and obtained informed consent. Participants also watched a video demonstrating the task procedure.

Practice Session After providing consent, participants completed a practice session consisting of three trials conducted in a different virtual environment and using different triangle configurations than those in the experimental sessions. To provide performance feedback during practice, a green pole indicating the target location and a red dot indicating the participant's response were displayed [5, 11, 24, 52]. Participants completed one practice trial per condition and were allowed to repeat the practice if desired. They were required to locate the target with a distance error of $d < 6.5$m for at least once; otherwise, they repeated the practice session. Informal testing with seven people revealed two distinct performance groups, with mean distance errors of 4.3m and 8.7m, respectively. The performance criterion of 6.5m was set as the midpoint between these two means.

Questionnaires Participants completed the Simulator Sickness Questionnaire (SSQ) before and after each session. After each session, they also completed the NASA Task Load Index (NASA-TLX).

3.7.2 Triangle Completion

The triangle completion task was adapted from prior studies [5, 16, 36, 45, 74]. Figure 1 illustrates the task procedure.

Encoding Phase Participants started directly at the target location rather than from a separate starting point to evaluate path integration in the absence of landmarks, thereby preventing participants from encoding the target's position relative to objects in the environment [74]. The target's location and facing direction in the virtual environment were randomly selected from eight predefined transforms [36]. We placed a red pole (waypoint 1) in front of the user at the beginning. During the encoding phase, participants navigated two sides of a triangle, as shown in Figure 2. They first traveled to the red pole using the joystick. Upon reaching the red pole, a "ding" sound was played, and a blue pole appeared along with a red arrow indicating its direction. Participants then virtually turned and navigated to the blue pole. After they arrived, the virtual scene above the ground plane was replaced with a completely different scene using a one-second fade-in transition, as shown in Figure 1 (d–e). This scene swap removed all landmark information [35, 52], ensuring that performance differences reflected path integration alone.

Response Phase Participants were instructed to point to the path origin as accurately as possible using a ray extending from the controller, as shown in Figure 1(f). Virtual locomotion was disabled during the response phase. A red dot indicated the pointing location at the intersection of the ray and the ground plane. Participants were encouraged to physically rotate their bodies to avoid awkward behind-the-back pointing. Once confident in their estimate, they clicked the trigger to record and confirm their response. While some prior studies asked participants to return to the origin via walking, particularly those involving physical locomotion [5, 16, 45], we used pointing instead, like many others did [17, 36, 65, 68] to reduce cybersickness caused by sharp virtual turns (140.6° on average) at waypoint 2 and extra translations to the target, which could otherwise confound the results. Pointing also ensured that performance differences reflected spatial updating during outbound path travel rather than differences in response execution [36].

Monitoring Cybersickness At the end of each trial, participants rated their discomfort on a 0–10 scale using a slider before proceeding to the next trial. The experiment was terminated if a participant chose to stop using VR or rated a discomfort score of 10, in which case their data were discarded and replaced with data from newly recruited participants. Two participants (both women) terminated the study early due to cybersickness.

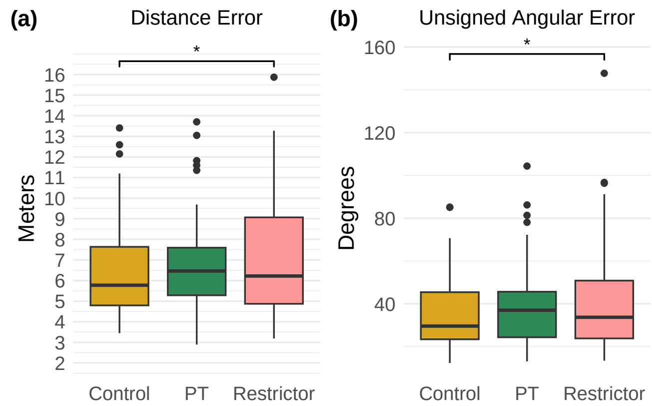

Figure 5: Box plots of distance (a) and unsigned angular (b) errors for each condition. Participants made significantly larger distance errors and unsigned angular errors in triangle completion in the Restrictor condition than in the Control condition. Note: for both figures, significance level is indicated as: * $p < .05$.

3.7.3 Post-Experiment

After completing all three sessions, participants filled out a feedback questionnaire and a demographic questionnaire.

4 Results

Data from one participant (female) were excluded because her mean pointing error exceeded three standard deviations above the group mean in one condition, consistent with our preregistration, leaving 47 participants for analysis.

Shapiro–Wilk tests indicated that most variables violated normality, except for variability, signed angular error, and raw TLX scores. Parametric data were analyzed using repeated-measures ANOVA to compare the three conditions (Control, PT, Restrictor), with results reported as mean (M) and standard deviation (SD). Nonparametric data were analyzed using Friedman tests, with results reported as median (Mdn) and interquartile range (IQR). When a main test was significant, post hoc comparisons were conducted using Conover tests with Holm correction. To evaluate H5, we used a linear mixed-effects model on per-trial data. All statistical tests used a significance threshold of $\alpha = .05$.

4.1 Distance Error

Figure 5 (a) shows the distance error results. The analysis for distance error showed significant differences among the three conditions, $\chi^2(2) = 6.13$, $p = .047$, $W = .07$. Post hoc comparisons found the Restrictor condition's distance error ($Mdn = 6.22$, $IQR = 4.20$) was significantly larger compared with the Control condition ($Mdn = 5.77$, $IQR = 2.84$), $p = .04$. The PT condition's distance error ($Mdn = 6.47$, $IQR = 2.31$) was not significantly different from the Control, $p = .42$, and the Restrictor, $p = .42$. These results partially support hypotheses H1 but not H2.

4.2 Distance Error Variability

The variability (Control: $M = 3.20$, $SD = 1.04$, PT: $M = 3.34$, $SD = 1.15$, Restrictor: $M = 3.24$, $SD = 1.27$) was not significantly different, $F(2) = .54$, $p = .59$, $\eta_p^2 = .01$, which does not support H3 and H4.

4.3 Angular Error

Figure 5 (b) shows the *unsigned angular error* results. The analysis for unsigned angular error showed significant differences among the three conditions, $\chi^2(2) = 6.26$, $p = .04$, $W = .07$. Post hoc comparisons found the Restrictor condition's unsigned angular error ($Mdn = 33.69$, $IQR = 27.02$) was significantly larger compared with the Control condition ($Mdn = 29.57$, $IQR = 22.03$), $p = .04$. The PT condition's unsigned angular error ($Mdn = 36.98$, $IQR = 26.94$) was not significantly different from the Control, $p = .23$, and the Restrictor, $p = .34$.

The *signed angular errors* (Control: $M = 2.30$, $SD = 31.33$, PT: $M = 2.69$, $SD = 33.29$, Restrictor: $M = 3.85$, $SD = 35.66$) were not significantly different, $F(2) = 0.14$, $p = 0.87$, $\eta_p^2 = .003$.

4.4 Axial Error

The main effect for *unsigned axial error* (Control: $Mdn = .31$, $IQR = .09$, PT: $Mdn = .29$, $IQR = .09$, Restrictor: $Mdn = .30$, $IQR = .11$) was not significant, $\chi^2(2) = 3.11$, $p = .21$, $W = .03$, nor was the main effect for signed axial errors (Control: $Mdn = -.05$, $IQR = .24$, PT: $Mdn = -.07$, $IQR = .26$, Restrictor: $Mdn = -.07$, $IQR = .23$), $\chi^2(2) = .04$, $p = .98$, $W = 4.52 \times 10^{-4}$.

4.5 Discomfort Score

We used a linear mixed-effects model (LMM) to evaluate the effect of discomfort on participants' errors. Although the data violated normality assumptions, LMMs are robust to such violations [53] and have been used in similar contexts (e.g., [1, 45]). We specified the model as $DistError \sim Condition + ds + (1|ID)$ using the *lmer* function from the *lme4* package in *R* [9], where *ds* denotes the per-trial discomfort score and *ID* represents participant-level random intercepts to account for individual differences. The model was fitted at the trial level using 1,692 observations from 47 participants. Condition was included as a fixed effect due to its significant impact reported in Section 4.1.

Discomfort scores were not significantly associated with distance error ($B = -0.13$, $SE = 0.10$, $p = .18$), providing no support for H5.

Mitigation technique had a significant overall effect on distance error. The model estimated a baseline distance error of 6.57m in the Control condition. Relative to Control, the Restrictor increased distance error by 0.64m ($SE = 0.21$, $p = .002$), while PT showed a non-significant trend of +0.37m ($SE = 0.21$, $p = .08$). These results support H1 for the Restrictor comparison but do not support H2.

4.6 Raw NASA TLX

The analysis showed no significant difference for raw NASA TLX scores (Control: $M = 5.28$, $SD = 2.79$, PT: $M = 5.61$, $SD = 2.9$, Restrictor: $M = 5.44$, $SD = 3.01$), $F(2) = 1.08$, $p = .34$, $\eta_p^2 = .02$. H6 was not confirmed.

4.7 Cybersickness and Discomfort Scores

Although cybersickness was not the primary focus of this study, we conducted repeated-measures ANOVAs on post-exposure SSQ scores (Control: $M = 18.08$, $SD = 22.68$; PT: $M = 14.88$, $SD = 21.14$; Restrictor: $M = 16.67$, $SD = 21.85$), $F(2) = 1.08$, $p = .34$, deltas between the pre- and post-SSQ scores (Control: $M = 10.21$, $SD = 12.06$; PT: $M = 5.38$, $SD = 13.78$; Restrictor: $M = 8.73$, $SD = 11.35$), $F(2) = 2.82$, $p = .07$, and average discomfort scores (Control: $M = 0.94$, $SD = 1.18$; PT: $M = 0.81$, $SD = 1.09$; Restrictor: $M = 0.90$, $SD = 1.17$), $F(2) = 0.51$, $p = .60$. Neither analysis revealed significant differences between conditions.

4.8 Qualitative Feedback

Participants completed a feedback questionnaire at the end of the experiment. We conducted a thematic analysis of the feedback provided by participants. The first author led the identification and synthesis of the main themes, which were subsequently reviewed by the second author. We resolved disagreements through discussion. Some noted that the Control condition aided their spatial updating, helping them "stay oriented" and "more accurately pinpoint my starting location."

In the FOV restrictor condition, participants described the task as "tricky" and "disconcerting" because "a lot of the environment was hidden/covered in black." One participant specifically reported that "the black vignette felt much more disorienting" and caused "confusion," adding that they "experienced the same negative effects as the tiling vignette (peripheral teleportation) but stronger."

In the peripheral teleportation condition, some participants found the technique "disturbing," "jarring," or even "janky." A few also mentioned that it made the environment "harder to see" or "skewed," although one participant who initially disliked it noted that "after a few rounds of tests it started to grow on me." Most negative feedback focused on subjective experience, with only one participant describing the rest frame as "confusing."

Many participants reported that both the FOV restrictor and peripheral teleportation reduced discomfort compared with the control condition. Several described the control condition as "dizzy," while the other two conditions "reduced the feeling of motion sickness."

Overall, these comments highlight the trade-off between mitigation effectiveness and subjective user experience. Importantly, only participants in the FOV restrictor condition explicitly reported being disoriented, suggesting that peripheral teleportation may better preserve spatial updating.

5 Discussion

5.1 Errors in Triangle Completion

5.1.1 Distance and Angular Errors

FOV Restrictor Results for both distance error and unsigned angular error at the condition and trial levels indicate that dynamic FOV restriction impairs path integration during virtual locomotion. Contrary to prior findings on spatial updating as a whole [5], our results provide direct evidence that dynamic FOV restriction can impair path integration under conditions designed to minimize cybersickness and landmark-based piloting. This isolation also offers an explanation for why earlier work has been inconclusive. With the offsetting influence of cybersickness and the availability of a landmark-based fallback both removed (see Section 2.3), the FOV-specific impact becomes observable, which we suggest is why it emerges here but not in studies where either factor was uncontrolled. This suggests that successfully reducing overall cybersickness (see Section 4.7) mitigated the confounding influence of discomfort on spatial task performance. Previous work on the effects of FOV restriction on spatial learning [2] may also be worth revisiting once the confounding influence of cybersickness is eliminated. Notably, the differences between conditions were small relative to the average error, and their practical significance requires further empirical evaluation.

Peripheral Teleportation Although the peripheral teleportation exhibited numerically higher median distance and unsigned angular errors than the FOV restrictor, the rank-based nonparametric tests did not show a statistically significant difference between peripheral teleportation and either control or restrictor. In other words, the participant-level ordering of errors across these conditions was not consistent enough to distinguish them given the present data, and we cannot draw any definitive conclusions. Because power depends on sample size and standardized effect size, and our sample size is already large for this type of experiment, the non-significant PT result is more easily explained by a small underlying effect than by insufficient sampling. However, another plausible explanation is that discretely updated peripheral information may be helpful for some participants to perform integration while misleading for others. Weißker et al. found that around 25% of their participants' spatial updating was severely affected by teleportations within vista space while the rest of them were not [65]. Moreover, although we based H2 and H4 on the effect of peripheral luminance on depth perception [32], its contribution on motion perception may be limited [66]. Participant errors in this study were substantial. Prior research attributes much of the error in triangle completion tasks to the execution phase [19], indicating that improved task design could reduce noise and enhance sensitivity to detect differences. Finally, parameter settings, such as FOV mask radius, teleportation interval, and path length, may have affected the results. Notably, a smaller FOV mask radius or a longer teleportation interval may further increase error, while a longer path length might make it easier to detect the effect.

Theoretical Implications Our results suggest that visual path integration depends on the completeness of peripheral optical flow. The restrictor's significant impairment shows that suppressing peripheral flow degrades path integration. On the other hand, PT's inconclusive result raises an open question of whether discrete peripheral updates can partially substitute for continuous flow. Further investigation is needed to clarify this question.

Practical Implications In our experiment, we found direct evidence that the FOV restrictor degrades path integration but found no such evidence for PT. Taken together with previous findings that PT is more effective in mitigating cybersickness [49], for navigation-frequent applications, PT is the option with lower overall risks in both cybersickness and spatial updating, while the restrictor warrants more caution.

5.1.2 Axial Errors

No significant effects were observed for either signed or unsigned axial errors. Because the triangle completion task involves turning, which may introduce additional variability, it is difficult to draw firm conclusions regarding the effects of the mitigation techniques on perceived travel distance. A dedicated experiment may therefore be required to further investigate this issue.

5.2 Evaluating Cybersickness Mitigation Techniques

The evaluation of cybersickness mitigation techniques should extend beyond their effectiveness, as there is an inherent trade-off with other factors commonly assessed in locomotion studies, such as user experience, spatial updating, and survey knowledge acquisition (e.g., [4, 10, 58]), which have received less attention. Previous work has focused primarily on FOV restrictors [2, 5] due to their effectiveness, simplicity, and widespread use. To our knowledge, the effects of other techniques, such as blurring [42] and image deformation [27], on these factors, including path integration, remain largely unexplored. This study provides the first evaluation of a rest frame technique on path integration and the first direct comparison between a rest frame and a dynamic FOV restrictor.

Cybersickness mitigation and spatial updating are often evaluated simultaneously; however, these goals impose conflicting experimental requirements. Tasks designed to elicit strong cybersickness are preferred when evaluating mitigation effectiveness, whereas minimizing cybersickness is necessary to reduce confounding effects when evaluating task-based perceptual and cognitive effects.

5.3 Limitations and Future Work

This paper focuses specifically on path integration. Although path integration is an important and widely studied component of human spatial navigation, it is not the only strategy people use. Landmark-based piloting also plays a critical role in spatial updating. However, metric information derived from path integration is often considered necessary for constructing an internal map that supports subsequent piloting [15, 44, 60]. In this experiment, we deliberately removed all landmarks during the response phase to isolate effects on path integration. This approach was chosen not only because we hypothesized that dynamic mitigation techniques would have minimal impact on piloting, but also because path integration is a fundamental process that is frequently studied in isolation (e.g., [52, 55, 73]). Nevertheless, this setup differs from many typical VR experiences, particularly in outdoor environments where landmarks tend to remain stable. In contrast, indoor environments, such as narrow hallways, often involve situations where objects that could serve as landmarks become occluded by walls as users enter a new room, making it difficult or even impossible to track the origin of their paths using those landmarks. Future studies that retain the scene during the response phase, in both indoor and outdoor virtual environments, could provide additional insight.

To keep the overall cybersickness level low, we adopted a point-to-origin response to test participants' homing accuracy. However, this method introduces potential sources of bias that warrant careful consideration. First, motor imprecision when manipulating the controller may add noise to the indicated direction, systematically or randomly shifting responses away from the true perceived heading. Second, VR systems are known to introduce depth perception inaccuracies [31], which could cause participants to misjudge the distance to the origin even when its direction is correctly perceived. Together, these factors likely inflate response noise and reduce statistical power, meaning that significant effects of locomotion interface on homing accuracy may go undetected.

While an alternative response method, such as physically returning to the starting location, might reduce pointing-related error, it risks elevating cybersickness and introducing a different set of confounds, as discussed in Section 2.3. Future work that systematically compares response modalities, ideally while monitoring cybersickness, would help disentangle these sources of bias and provide cleaner estimates of path integration performance across locomotion interfaces.

While our participant pool was relatively large and gender-balanced, it skewed younger than the general population, as recruitment primarily occurred on a university campus. Previous work has shown that young adults tend to make smaller errors in triangle completion tasks with physical walking, suggesting that results may differ for older adults [45, 55].

Finally, this study compared only peripheral teleportation and FOV restrictors. Other techniques, such as the image deformation method proposed by [27], which also preserves the visual appearance of the environment, could yield similar or even better performance.

6 Conclusion

In this paper, we presented the first study to evaluate the effects of dynamic FOV restriction and peripheral teleportation on path integration, a core component of spatial updating. We compared both cybersickness mitigation techniques with an unrestricted control condition using a triangle completion task. We conducted a within-subjects study with 48 participants and mitigated confounds related to cybersickness and landmark use. Dynamic FOV restriction resulted in significantly larger distance and unsigned angular errors in estimates of the starting location, providing direct evidence that this technique impairs path integration. In contrast, peripheral teleportation did not differ significantly from either the control or the FOV restrictor condition. Overall, these findings help clarify the trade-off between cybersickness mitigation and spatial updating performance. While our results demonstrate a clear cost of dynamic FOV restriction, they do not provide conclusive evidence regarding the impact of peripheral teleportation. Future work should examine its effects on other navigation skills, such as landmark-based piloting and spatial memory, to enable a more comprehensive evaluation of this technique.

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