An Evaluation of View Rotation Techniques for Seated Navigation in Virtual Reality

Brett Benda, Shyam Prathish Sargunam, Mahsan Nourani, and Eric D. Ragan

Abstract—Head tracking is commonly used in VR applications to allow users to naturally view 3D content using physical head movement, but many applications also support turning with hand-held controllers. Controller and joystick controls are convenient for practical settings where full 360-degree physical rotation is not possible, such as when the user is sitting at a desk. Though controller-based rotation provides the benefit of convenience, previous research has demonstrated that virtual or joystick-controlled view rotation to have drawbacks of sickness and disorientation compared to physical turning. To combat such issues, researchers have considered various techniques such as speed adjustments or reduced field of view, but data is limited on how different variations for joystick rotation influences sickness and orientation perception. Our studies include different variations of techniques such as joystick rotation, resetting, and field-of-view reduction. We investigate trade-offs among different techniques in terms of sickness and the ability to maintain spatial orientation. In two controlled experiments, participants traveled through a sequence of rooms and were tested on spatial orientation, and we also collected subjective measures of sickness and preference. Our findings indicate a preference by users towards directly-manipulated joystick-based rotations compared to user-initiated resetting and minimal effects of technique on spatial awareness.

Index Terms—virtual reality, human-centered computing, human-computer interaction

1 Introduction

Head tracking is commonly used in virtual reality (VR) applications to allow users to naturally view 3D content using physical head movement. Supporting natural physical interaction is often seen as one of the greatest benefits of VR technology, and prior research has demonstrated that realistic physical forms of travel and view control offer significant benefits for navigation (e.g., [1], [2]), presence (e.g., [3], [4]) and 3D spatial judgment tasks (e.g., [5], [6], [7]).

However, many VR applications do not rely solely on physical interaction for travel and viewing. Many applications support the use of hand-held controllers and joysticks to allow additional virtual turning. Joystick control is convenient for practical settings where full 360-degree physical rotation is not possible or preferred, such as when the user is lying on a couch or sitting at a desk. Though joystick control provides the benefit of convenience, previous research and development projects have demonstrated joystick-controlled view rotation to have drawbacks of sickness (e.g., [8]) and disorientation (e.g. [9]) compared to more natural physical turning. To combat such issues, developers often considered various technique configurations, such as speed adjustments, and have also explored reduced field of view (FOV) [10], [11], but empirical data is limited on how different design variations for virtual rotation controls compare to each other.

While there are many different ways of allowing virtual rotations in conjunction with head tracked rotation, the large variety of available possible rotation implementations makes it difficult to understand the tradeoffs among common approaches. The purpose of our research is to provide a comprehensive study of common approaches of controller-based virtual rotation in VR. This work provides an empirical basis for comparison for both researchers and developers in the VR community. We organized our research into two experiments that cover controller-based rotation control using (a) *discrete* rotational updates, and (b) *continuous* rotation. *Continuous* updates offer the advantage of showing uninterrupted orientation transitions to allow users to easily understand the rotation. However, due to the mismatch between virtual-only turning and real-world physical cues for orientation and motion, continuous rotations sometimes introduce problems with sickness, disorientation, or general discomfort. In contrast, *discrete* rotational methods update the orientation instantaneous in set intervals rather than by continuous transitions, which usually means a more immediate change. This may reduce the duration of experienced mismatches between physical and virtual orientation cues, but at the cost of a sudden interruption to the view of the virtual environment, which may negatively affect spatial understanding or sense of orientation.

With so many variations of controller-based techniques existing, each often developed or evaluated with a singular benefit in mind, it is necessary to conduct an evaluation for their effects on multiple outcomes to understand what tradeoffs they create. We present the results of our experiments evaluating controller rotation techniques. Our studies include different variations of techniques such as: joystick rotation; resetting; field-of-view reduction; and rotational gains. We investigate effects of different controller-based rotation techniques on sickness, the ability to maintain

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spatial orientation in a 3D environment, and entertainment. In a controlled experiment, participants traveled through a sequence of rooms and tested on spatial orientation, and we also collected subjective measures of sickness and preference.

2 Related Work

Many travel and viewing techniques for VR have been studied in terms of effects on outcomes such as speed, accuracy, spatial awareness, and presence. Usoh et al. [3] found that the most natural and believable travel method in virtual reality is physical walking, where the changes in user's movements in the real world are tracked and applied directly to the virtual camera. However, our research focuses on scenarios and real world setups where convenient interactions with virtual environments are expected or are required.

2.1 Stationary Travel Techniques

The main issue with physical walking is that it usually requires large tracking space for the users to walk. Techniques have been explored that try to simulate a walking metaphor, but do not require actual translational movement in the real-world. Coomer et al. propose *arm-cycling* (a technique where users are propelled forward by activating both controllers and pulling them apart) as a less physically-demanding technique than walking in place or redirected walking [12], though still still requires room for arm movement. Researchers have explored many alternative techniques for such situations where full physical motion is not practical or not preferred. Many techniques even allow the user to remain in a mostly stationary position, with examples including *walking in place* (e.g., [3], [13]) or *leaning* (e.g., [14], [15]). In other cases, it may be useful (or necessary) to update the virtual view orientation all at once rather than by gradual control. In a comprehensive evaluation of several seated travel techniques for use in an immersive analytic environment (identifying the shortest path between two vertices in a graph, Zielasko et al. [15] identified that leaning performed the best. However, they did not evaluate these techniques for their impacts on sickness or spatial awareness and where limited to task completion time and errors. The researchers later expanded on this work to consider three directional components for determining travel direction in VR (gaze-directed, real-world torso-directed, and virtual-body-directed) [16]. These were evaluated both with leaning to control movement, and controllers. Overall, torso-directed travel outperformed the other methods, with leaning being rated the most usable among participants.

2.2 Input Remapping Techniques

Other research has explored the techniques that manipulate the mapping between physical and virtual orientation via rotational gains, as is commonly done in *redirected walking* (e.g., [17], [18]). With this approach, developers have explored making the virtual rotation faster or slower than the user's corresponding physical real-world rotation. Also referred to as amplifying rotation, this method allows a user to easily view more of the virtual space while making relatively small physical turns (e.g., [19], [20], [21]). For example, Ngoc et al. [22] studied head rotation amplification in the context of a training simulator to allow a wide view with a single display with the technique being easy to learn by novice users, though options for customization were desired by trainees. A study by Ragan et al. [21] found rotation amplification to work better when a reference frame (a salient object which can be used to orient oneself) was available for spatial orientation in VR, and they found evidence of sickness problems with a high amplification factor. Bölling et al. [23] have demonstrated that users can become less sensitive to rotational amplification after an extended period of exposure. These adjustments to sensitivity can be leveraged to allow even larger rotations than may initially be used.

Due to their reliability only on head movement, amplified head rotations can be applied in applications where body movement is limited (i.e., users sitting at a desk or during travel on an airplane or train). Different methods of applying these amplifications have been explored to maximize comfort and performance. In previous work with goals related to our own, Sargunam et al. [24] presented *guided rotation*, which adopted head rotation amplification in headworn VR with joystick travel along with a redirection adjustment that used gradual rotational adjustments while the user traveled virtually. This technique was used to help orient the user's head direction back to the default physical forward direction so the user was better situated for future turning. Razzaque et al. [13] demonstrated a similar approach for a variation of walking-in-place in CAVE environments. A more active approach utilizes dynamic rotation gains which change as the user rotates their head can allow for better performance than static gains [25].

Detection of automatic head rotations have also been investigated in order to create more natural techniques. Langbehn et al. [26] have leveraged change blindness during blinking to translate users up to 9 centimeters and rotate their view by 2-5 degrees without the transformation being noticeable. Stebbins et al. [27] propose an automatic view resetting technique that rotates a scene after a user has their neck physically turned for a period of time to reset their view back to forward. If the turning speed is sufficiently small, users can reset without being aware the rotations were applied.

Resetting also is a straight forward method used to re-orient users during a virtual experience that has sometimes been used to accommodate cases where a VR user reaches physical bounds of a tracking or display area, and an adjustment to the virtual orientation can provide a correction to allow the user to continue the experience. Whenever physical reorientation is required, discrete rotation is applied to the virtual camera. After the camera rotation, the users try to face the section of virtual environment which was in front of the camera before transition, thereby getting reoriented in real world (e.g., [28], [29]). This is an example of a remapping between physical and virtual view orientations that has often by initiated by the system or manually by a human administrator.

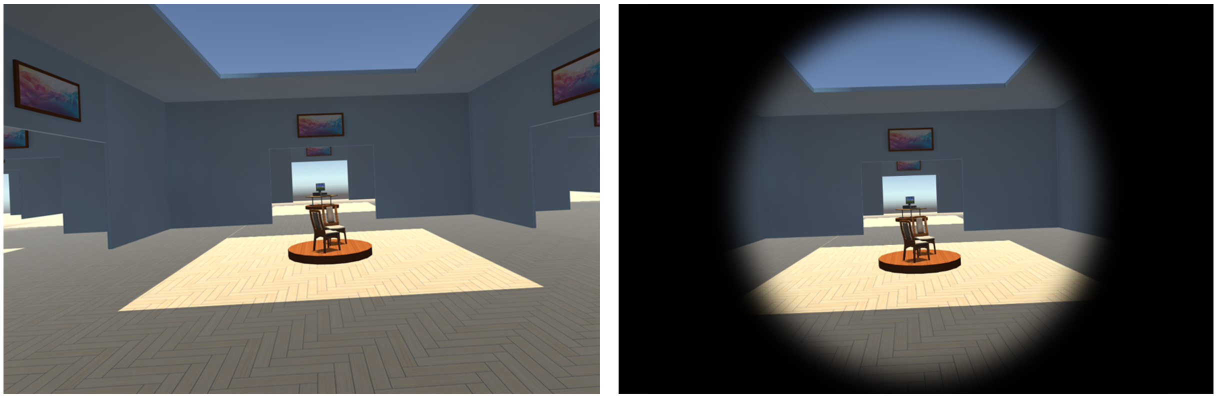

Fig. 1. Screenshots showing perspective views of the virtual environment without FOV reduction on the left and with FOV reduction on the right

2.3 Controller-based Travel Techniques

Generally speaking, the previously discussed techniques attempt to preserve some level of naturalness through physical head or body movement to control rotation. However, perhaps the most common approaches being used in applications for virtual travel involve the use of a simple joystick and hand-held controller to *steer* (or *fly*) (e.g., [9], [30]),*teleport* (e.g., [31], [32]), or *jumping*(e.g., [31], [33], [34]). Studies have found *teleportation* can cause disorientation while jumping from one place to another, as it does not allow users to gather information about the environment while traveling since the positional changes are discrete and instantaneous [9]. However, experiments by Rahimi et al. [35] found sense of spatial understanding to be significantly better with rotational teleportation (i.e., updates to orientation without changes to position) than with teleportation that changes position. Similar to our research, their experiments included different forms of discrete (instant and in multiple iterations) and continuous (smooth continuous transitions) rotations, but their studies focused on understanding scene changes that were not user-initiated, whereas we present studies of user-controlled travel via controllers. On the other hand, jumping metaphors rely on transforming smaller real world movements (e.g., a single step) into an accelerated "jump" in the virtual environment [31]. In work conducted by Weissker et al. [33], jumping and steering were compared for their effects on simulator sickness and spatial awareness (in the form of a point-to-start evaluation). Overall, jumping produced less error in spatial awareness, but steering was more preferred for the exploration task used. The jumping metaphor has also been extended to joystick or head-based navigation rather than real walking, with jumping occurring as the user's speed increases [34]. Different methods of scene interpolation in teleportation and jumping techniques have also been explored, with tradeoffs between sickness and spatial awareness being identified [36]. For example, animated transitions produced more accurate measurements for spatial awareness, but also higher sickness compared to instantaneous transformations to the user's view or rotation.

Many other studies have included controller and joystick rotations as part of their research. For example, Chance et al. [1] studied physical rotation to *visual turning* in which the virtual camera is rotated based on the joystick input. In other work, Riecke et al. [14] compared joystick-controlled travel and rotations with a gaming chair setup where controls are based on the leaning metaphors. Generally, joystick-controlled travel has been found to have problems when compared to more natural or physically-based techniques. Comparisons of joystick-techniques against other techniques, such as leaning or teleportation, revealed little differences on sickness but positive effects of teleportation on movement times [37]. However, effects on spatial awareness were not examined which necessitates the need to investigate if instantaneous view transformations perform differently than continuous ones. In their comparison of eight different locomotion techniques, Bozgeyikli et al. identified redirected walking, teleportation, and joystick travel as optimal techniques regarding user preference in room-scale navigation [38]. These were found to be more efficient in navigation and more enjoyable to users compared to alternative techniques like flying, flapping, or using a physical stepping device. Work conducted by Langbehn et al. also identified positive benefits of redirected walking regarding spatial knowledge and user preferences [39], though this technique cannot be used in seated or stationary VR use. Work by Zielasko et al. compared the effects of body and device (joystick) techniques for direction manipulation and selection in stationary contexts on search time and egocentric orientation error [40]. They considered techniques where a joystick or the users body were used either to gradually apply discrete rotations or select a new forward direction. They found that both selection techniques reduced overall search time, and that body techniques required more time to perform the search. No significant effects on orientation were identified.

2.4 Simulator Sickness During Travel

Important to this work is the consideration of techniques to reduce *simulator sickness* or *cybersickness*. Simulator sickness is a collection of symptoms that may occur with the use of current VR headset technology, including but not limited to: eye strain, nausea, excess sweating, or dizziness [41]. The most popular theory for its cause is the *sensory conflict theory* [42]. Essentially, this theory states that sickness arises when a user's visual system mismatches their vestibular sensing (relating to their sense of balance and motion). The presence and intensity of sickness can be influenced by factors intrinsic to users (e.g., age or gender [43]), as well as technological factors like system lag or headset ergonomics [41]. For seated and stationary VR, this is particularly important to consider as users visually move in a virtual environment, but are not actually moving and lack the vestibular sensing to match.

One approach to reducing sickness is to reduce the field-of-view (FOV) while rotating the user's view (e.g., [10], [44], [45]). By reducing the visible area, it is possible to lessen the mismatch between the visual and vestibular systems to reduce sickness. Field-of-view reduction can also reduce optical flow at the periphery of a user's vision [46] which may reduce sickness. For example, Fernandes et al. [11] studied subtle and dynamic FOV reduction for reducing sickness during virtual travel. Despite the prior research involving travel techniques and joystick control, the body of research specifically focusing on comparisons of different controller-based travel implementations in the VR context is limited. Additionally, work by Farmani et al. [47] has shown that "snapping" can reduce cyber sickness by removing intermediate frames during rotation during mouse-controlled navigation. When users rotated their head above a given threshold speed (25 degrees per second), continuous transitions were replaced with snapping in 22.5 degree increments which reduced SSQ scores by up to 40%. This work was later extended to consider snapping for positional translation [48], which reduced SSQ scores by 47%. In their analysis of discrete and continuous controller-based navigation, Ryge et al. did not find any significant differences towards sickness.

In our own prior work, we presented a preliminary study of joystick-based rotation techniques for VR [49]. This study considered joystick techniques that allowed discrete rotational increments along with continuous joystick rotation with and without reductions to the field of view. The study found some evidence of subjective preferences of discrete rotational adjustments in terms of sickness and preference for many participants, but preferences varied. We note that this was a workshop paper that presented preliminary studies that informed the final studies presented in the current paper, but we note that the study design was modified and the study was conducted with new participants.

2.5 Summary

Our exploration of prior work supports a comparison of many different techniques on sickness, spatial orientation, and entertainment outcomes. We address limitations of previous work (i.e., [33], [50]) that acknowledge the use of including other known sickness-reducing techniques (i.e., reducing the field-of-view) to base techniques like steering and examining other factors other than pure sickness.

3 Research Overview

Our overarching research questions are as follows:

> **RQ1:** What are the tradeoffs between sickness, spatial awareness, and entertainment value for different seated travel techniques?
> **RQ2:** How do users with higher familiarity with 3D environments differ from those with lower familiarity, as it relates to RQ1?

This section provides information about the study design and procedure applicable for both experiments, and later sections provide more details about specific techniques and conditions included in each individual experiment.

3.1 Study Task and Environment

For the purposes of our evaluation, we designed a virtual environment consisting of cubical rooms with identical dimensions of 13.25 meters in length and width. The rooms were arranged in a 10x10 regular grid with doorways connecting to adjacent rooms. We placed 3D objects at the center of every room to serve as navigational reference points. The reference points were 3D models, with examples including a car, a desk, a couch, and a piano. Users could use the orientation of the objects to get an idea of their direction after turning. However, to make the environment more challenging for a navigation task, the models were repeated throughout the rooms. Reference points were chosen such that for any particular room with its four adjacent neighbors, their five reference points were unique. But once the user steps out of these five rooms, one of the five reference points from the previous set of rooms could be seen again.

Using these environments, participants completed a VR navigation task that consisted of three sub-tasks: (1) virtual travel along a path, (2) an egocentric pointing task, and (3) an exocentric plotting task. The virtual travel subtask involved participants moving from one room to another following a path indicated by blue rings that appear over the 3D reference points in the adjacent rooms. Only one ring was visible at a time; once a ring was collected, the next ring would appear in one of the four rooms adjacent to the current location. The last ring was shown as orange instead of blue to indicate the end of the path. The room paths were manually pre-determined based on two simple rules: (1) each path consists of exactly ten rooms including the starting and ending rooms; (2) each path will have one 180-degree virtual turn where the user travels to the center of the room and then immediately returns to the previous room. Following these criteria, each study used 12 unique paths where one was randomly picked for each trial tested by a participant. Being seated, participants moved in the environment by pressing forward on the joystick to steer. Speed was linearly determined by the strength of the press, with a full press resulting in a forward speed of 2 meters per second. While other studies (e.g., [34] and [33]) examined steering at speeds up to 5 and 50 meters per second respectively, these studies used a larger, outdoor environment in their evaluations. In our contained, room-based environment, using a slower max speed allowed for easier and more precise control over navigation.

After following the path and reaching the end point, users were asked to do an egocentric pointing task where they had to turn and face towards the room where the virtual travel started. The error in pointing angle compared to true direction to the starting room was one of the two metrics used to determine the spatial awareness of the users.

Immediately following the egocentric pointing task, the users completed an exocentric plotting task using a 2D grid that represented a top-down view of the environment (see Figure 2). The 2D grid only displayed the reference points

TABLE 1
Sickness and Entertainment Questions.

Entertainment
E1. The overall experience of playing the game was comfortable.
E2. The overall experience of the game was frustrating.
E3. The overall experience of the game was fun.
E4. I am interested in using this technique in home entertainment.
Sickness
S1. I felt symptoms of nausea while playing the game.
S2. I felt symptoms of dizziness while playing the game.
S3. I felt symptoms of headache while playing the game.
S4. I felt tired while playing the game.

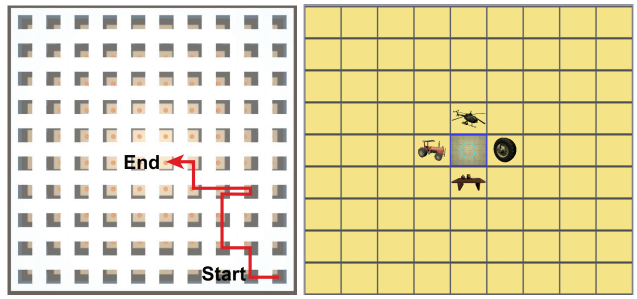

Fig. 2. **Left:** A top-down view of the environment showing an example path the participant may take. **Right:**The exocentric plotting task used a top-down view showing the neighbors of the end room with the cursor initially located at the ending room's position.

for the four neighbors of the end room (where the orange ring was found), and all the other cells were blank. Based on the arrangement of these reference points on the grid, the users were asked to select the cell corresponding to the initial room where the path started. Users made this selection by using a controller to move a cursor to the indicated cell. From this task, an error metric was calculated as the difference in the number of cells in both vertical and horizontal directions from the actual starting point to the selected cell. This task was designed based on other exocentric and allocentric orientation assessment methods. These methods often involve drawing a path taken through a maze (e.g., [51], [52], though given the guided nature of our travel task (following waypoints) and uniform grid-based environment, we chose to simplify the assessment to selecting the starting room.

3.2 Dependent Variables

The dependent variables of this experiment were:

- Egocentric pointing task error (angular error)
- Exocentric plotting task error (positional error)
- SSQ score [53]
- Sickness score (average of Likert scale responses)
- Entertainment score (average of Likert scale responses)

The post-experiment questionnaire consisted of questions based on ease of use, sickness, comfort, and preference for home entertainment (see Table 1) determine sickness and entertainment scores. The goal of these questions was to provide a general insight into perceived entertainment and sickness, and were presented in the form of scales with ratings ranging from 1 to 10 which were averaged for each measure.

3.3 Procedure

The research was approved by our organization's institutional review board (IRB). On arrival, participants were given an overview of the study and asked to provide signed consent before proceeding. They were then asked to complete a brief background questionnaire with questions about age, gender, education, computer knowledge, gaming experience, and VR experience. After this, the participants were asked to complete the SSQ sickness questionnaire [53] based on how they felt before starting the experiments. Next, they were given an explanation of the VR application and experimental tasks.

Next, they started doing the trials with the navigation tasks split into three blocks with four trials in each. In each technique block, the first trial was a practice trial for the participant to gain familiarity with the techniques, then three main trials followed whose data was considered for analysis. Participants were told each technique would use the controller's analog thumbstick to adjust the view whenever needed. Additional instructions specific to each technique were given before each block to allow participants to understand how to control the technique (which was particularly necessary for resetting).

Participants were asked to complete another SSQ after each technique block. After the SSQ at the end of each block, participants took a three-minute break where they were asked to walk casually in the lab space without the headset before starting the next session. This was done to reduce carry-over effects related to any sickness. Because sickness was likely reduced, but a full recovery not guaranteed, we analyze changes in SSQ scores between blocks.

After completing all three technique blocks, participants were asked to complete an experience questionnaire. Finally, there was a semi-structured interview about the overall experience, general preference and thoughts about the techniques, and use of the techniques for spatial navigation. The procedure took approximately 65 minutes for each participant.

3.4 Apparatus

The experiments were run in a lab environment. Since the motivation for this research is studying virtual rotation techniques in cases where full physical rotation is not ideal, participants completed the study seated using a non-swivel chair. An Oculus CV1 headset was used with the system's default positional and orientation head tracking enabled, thus allowing participants to control viewing using a combination of tested controller methods along with physical head movements. An Xbox One controller was used for user inputs during the trials. A Windows PC with a 3.4 GHz Quad Core processor and a 16GB GeForce GTX 1070 graphics card was used to run the experiments. The study application was developed using the Unity game engine. The application ran with the frame rate ranging between 128 and 134 frames per second. 0.8

4 Experiment 1: Discrete Rotational Updates

Experiment 1 focused on comparing discrete rotation techniques. Variations of discrete rotation techniques can provide advantages of instance updates to orientation in an attempt to avoid issues with sickness that are sometimes associated with continuous virtual motion that does not match physical motion. The first experiment tested three discrete rotation techniques—one based on *joystick* control and two based on variations of user-controlled *resetting*. These techniques each update a user's view in a single discrete rotation. Only head orientation was virtually adjusted by these techniques, and full six-degree-of-freedom head tracking was always enabled.

4.1 Techniques

In this experiment, we examine three different techniques for rotating the user's viewpoint:

- *Discrete joystick rotation* : A fixed rotation is applied when a user moves the joystick.
- *Resetting*: The user selects a new forward direction, moves their head to face forward, and then the rotation is applied.
- *Amplified resetting*: The same as *Resetting*, but with additional rotational gains applied to head movement.

We consider these techniques as "discrete" due to the instantaneous view transformation they apply. Discrete joystick rotation instantly applies a fixed rotation upon moving the joystick, while both resetting techniques apply a variable rotation based on the new forward direction selected by the user.

4.1.1 Discrete Joystick Rotation

The first technique we describe is *discrete joystick rotation*, which is a variation of common joystick turning that allowed turning in discrete increments. This technique used the analog joystick, but the magnitude of discrete rotation was constant for each time the user moved the joystick to the left or the right; the user could not control or adjust the angular amount for each discrete rotation. This technique was chosen as a simple variation of discrete updating that makes use of familiar joystick input for turning. With this technique, the users can control a sequence of instant rotational updates to have a new view heading. The implementation for this study controlled the magnitude of discrete rotation at 30 degrees per increment. Other work recommends smaller rotations (e.g., 22.5 degrees [47]), we acknowledge that discrete rotations of 30 degrees may induce a larger amount of cyber sickness. However, we chose this value to reduce the overall number of inputs needed to rotate increments of 90 degrees necessary in our grid-based environment.

4.1.2 Resetting

While many uses of resetting in VR are system-initiated based on the experience and system state, our study evaluates a *user-controlled* variation that can be used for convenience along with head tracking for situations where users would not be expected to easily or comfortably make full physical rotations (e.g., as is often experienced with wired VR headsets or might be expected if on a couch or as a passenger during travel). With this user-controlled resetting, users are able to control which part of the virtual environment will correspond to their physical forward direction. Users can decide when they need resetting in the real world based on comfort or strain experienced in the neck when their head orientation is offset from the physical forward direction.

For the implementation in this study, once a user decides to use this technique, the user presses a button while on the controller while facing the virtual direction to choose the new direction to align with physical forward. When activated, an assistive cursor (a cross-hair) is shown overlaid on the view and moves along with virtual camera until the direction is controlled. Once the button is released, the user's virtual view is blocked completely with a black mask and the indicated rotation is applied to the virtual camera. This rotation brings the section of VE marked by the cursor (cross-hair), in line with the user's physical forward direction. Now, with the view still masked, a green arrow is displayed to guide the user to turn towards the physical forward direction to complete resetting. Once facing the physical forward direction, the view of the virtual environment will return, and the user will be facing the same virtual direction as when the resetting was confirmed. Figure 3 demonstrates this technique with screenshots and pictures from consecutive steps involved in *user-controlled resetting*.

4.1.3 Amplified Resetting

A downside of user-controlled *resetting* is that users may at times need to make additional large physical rotations to update the rotation. Larger rotational resets could cause greater disruption to the experience and potentially make it more difficult to maintain a sense of spatial orientation. For this reason, the experiment also include a secondary implementation of resetting that made use of *amplified head rotation*. Amplified head rotation allows 360-degree viewing of the virtual world using physical head rotations but without requiring full physical rotations. As previously mentioned, this type of technique has been explored and studied by others using various different implementations, displays, and amplification factors (e.g., [19], [21], [22], [54]), so we sought to evaluate the benefits along with discrete rotation updates in this experiment. By using amplified rotations to limit the necessary amount of physical turning to see the environment, it was possible to reduce the amount of resetting rotation needed with user-controlled resetting.

We refer to this combination technique as *amplified resetting*. In this condition, the resetting control worked the same as in our user-controlled *resetting* condition, but additional rotation amplification was applied for tracked head rotations. The differences in rotation angle of the tracked physical head was multiplied by an amplification factor to produce the rotation angle of the virtual viewpoint. This study used a constant amplification factor of 2.0 to allow users to quickly view the entire 360 degree range. So, for example, a 90 degree turn in the real world would result in a 180 degree turn in the virtual world, or a 20 degree turn in

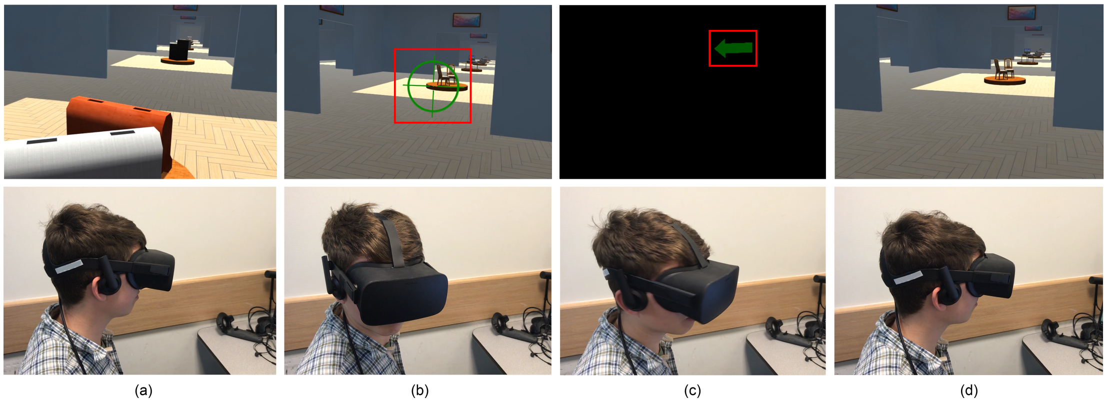

Fig. 3. Screenshots and pictures demonstrating how user-controlled *resetting* works. (a) The user is facing along their physical forward direction. (b) The user turns to look a new direction to make forward, using the cursor (crosshair) via controller input which is highlighted by a red box (not shown to participants). (c) The user releases the controller input and turns along the direction of the green arrow back towards their physical forward direction (shown within the red box). (d) Once the user reorients physically with the forward direction, the mask is removed and selected virtual forward now matches their physical forward.

the real world would result in a 40 degree turn in the virtual world.

We classify the resetting techniques as *discrete* due to the fact that the rotations they apply to the user's view occur as one singular transformation. The users select a new forward direction, which (after turning to forward) instantly becomes a new basis for real head turning.

4.2 Hypotheses

We hypothesized that the *amplified resetting* would reduce the number of the manual resets needed during a virtual experience since users can view a wide range of virtual space with smaller turns. Since frequent resetting could disorient users, we hypothesized that users would make more errors in the spatial tasks with non-amplified *resetting* than with *amplified resetting* since users can rotate more with amplified rotation. Given the spatially demanding task, we expected the need to frequently reset would be considered disruptive with *resetting* without amplification, so we hypothesized that *resetting* would be less preferred over *amplified resetting*.

However, since the *amplified head rotations* have been found to cause sickness problems [21], [24], we hypothesized that *amplified resetting* would cause the worst sickness among the discrete techniques. Since *discrete joystick rotation* does not require users to rotate physically, we hypothesized this technique to have the lowest sickness effects among the three techniques compared.

Finally, regarding entertainment, we hypothesized that due to the simplicity of the discrete technique it would be seen as most suitable for regular use by participants. Amplified resetting would follow, since it reduces the amount of total reset actions required to navigate. Standard resetting would have the lowest entertainment scores.

These experimental hypotheses are summarized as:

- **H1 (Spatial Awareness):** Amplified Resetting > Discrete > Resetting
- **H2 (Sickness):** Amplified Resetting > Resetting > Discrete
- **H3 (Entertainment):** Discrete > Amplified Resetting > Resetting

4.3 Experimental Design

The experiment followed a within-subjects design to compare three rotation techniques: *discrete joystick rotation*, *resetting*, and *amplified resetting*. Each participant completed the navigation task 12 times, split into three sessions corresponding to the three techniques. Participants completed the task four times for each technique, with the first trial being the practice trial. The order of *discrete rotation* and *user-controlled resetting* was counter-balanced across the participants. However, *user-controlled resetting with amplification* was always tested as the last technique by all the participants to avoid confounding effects of sickness, which is a documented problem with amplification (e.g., [21], [24]). As a result of this design, we examined *differences* in SSQ scores induced by using each technique opposed to total SSQ scores.

4.4 Participants

Experiment 1 had 23 participants (15 males and 8 females). All were university students aged between 19 and 36 years (Mdn = 22). Twelve participants reported regularly playing some form of 3D video games for at least one hour weekly and are included in our gamer analysis, with reported hours ranging from 2-30 hours (Mdn = 10 hours).

4.5 Results

We examined the effects of each technique on user performance in the egocentric and exocentric orientation tasks, sickness while using the technique, and overall preference of technique. We analyze all participants and only those classified as gamers (more than one hour of weekly 3D video game play) to see if experience with 3D environments influences our measures. Results from Friedman tests are shown in Table 2.

4.5.1 Spatial Orientation

Spatial orientation results are based on egocentric pointing error and errors from the 2D positional plotting measure (Figure 4). No significant effects of technique were found

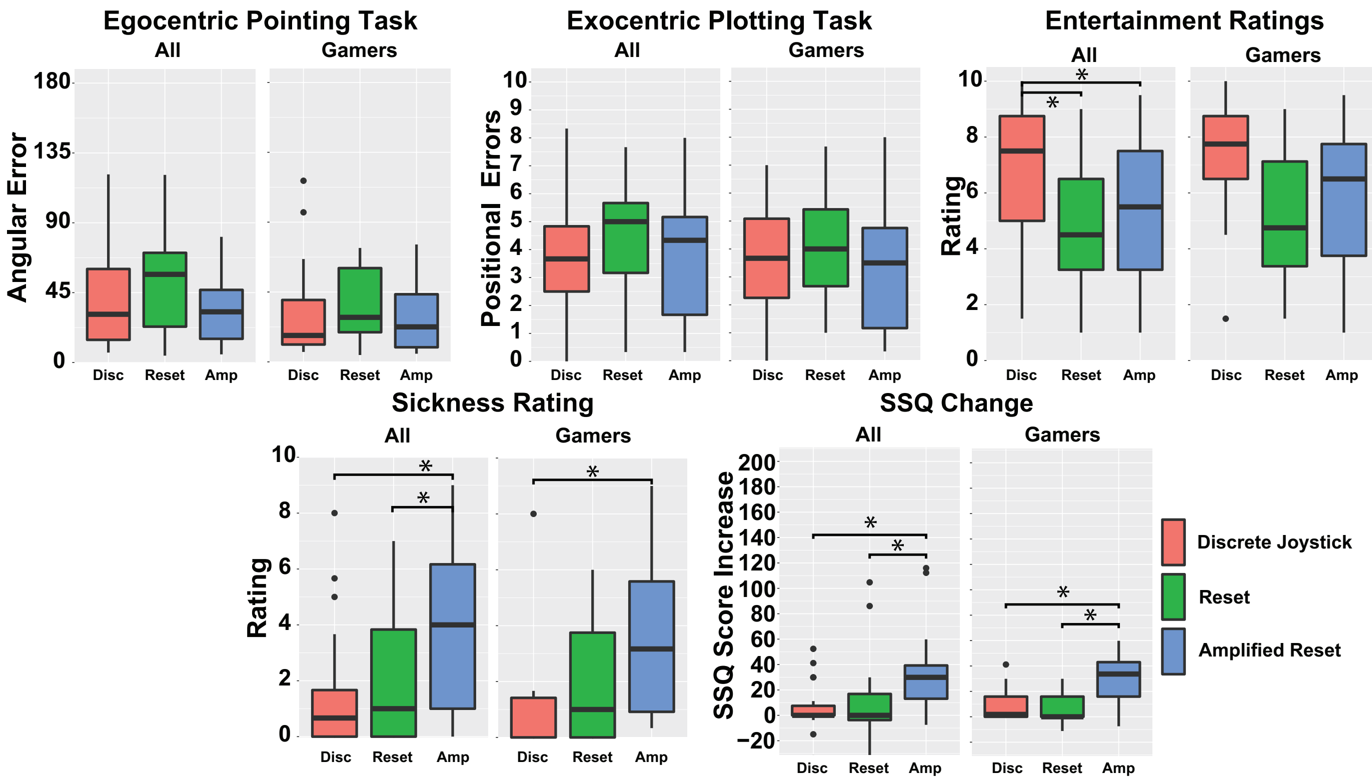

Fig. 4. Box plots displaying data from Experiment 1 showing medians, quartiles, and outliers
. Significant differences at $p < 0.05$ are marked with an asterisk.

TABLE 2
Results of Friedman and pairwise Nemenyi significance testing for each measure in Experiment 1 for each technique: discrete rotation (D), resetting (R), and amplified resetting (A). Only pairs with significant differences are reported. In pairwise differences, the first technique produced a higher value for the measure. We also present Kendall's W showing effect size which can be interpreted using Cohen's guidelines [55].

Measure	All			Gamers		
	χ^2 (2)	p	W	χ^2 (2)	p	W
Ego. Error	4.52	0.104	0.098	2.16	0.338	0.098
Exo. Error	3.58	0.166	0.077	0.91	0.633	0.077
Entertainment	11.74	**0.003**	0.255	4.63	0.098	0.255
Pairwise difs.		*D vs. R*, **0.004**				
		D vs. A, **0.048**				
Sickness	22.02	**0.00001**	10.33	0.478	**0.006**	0.478
Pairwise difs.		*A vs. D*, **0.00015**			*A vs. D*, **0.009**	
		A vs. R, **0.014**				
ΔSSQ Score	11.34	**0.003**	9.05	0.246	**0.011**	0.246
Pairwise difs.		*A vs. D*, **0.022**			*A vs. R*, **0.022**	
		A vs. R, **0.011**				

for either orientation task when considering the entire set of participants or gamers only.

Specific to the egocentric pointing task, errors larger than 90 degrees would be oriented *away* from the starting direction, and would show that users were very disoriented as a result of the techniques. However, for the egocentric pointing task, most errors were small (less than 90 degrees) which means users were largely able to point towards the general direction from which they came. This may be due to the grid layout used for our environment, where different strategies such as room counting may help with determining their starting location. As a result of these findings, we reject our hypothesis **H1**.

4.5.2 Sickness

Responses from the post-study questionnaire on questions about nausea, headache and dizziness were grouped together for a general, aggregate sickness rating (Figure 4). For this rating, a lower score is associated with *less* sickness experienced. Changes in SSQ scores between trials for each technique were also examined.

Data did not meet the assumption of normality to use a parametric ANOVA test, so Friedman's non-parametric ANOVA was used. These tests revealed a significant main effect of technique on sickness ratings for all participant groupings. Posthoc pairwise Nemenyi testing indicated that for both groups, amplified resetting resulted in significantly worse sickness ratings than discrete joystick rotations ($p < 0.05$). When all participants were considered, amplified resetting was also significantly worse than the traditional resetting technique ($p < 0.05$).

In regards to SSQ changes, significant effects were only identified for gamers or all participants as a whole. Nemenyi testing shows that for gamers and all participants, amplified resetting was significantly worse than the other two techniques ($p < 0.05$). These findings are consistent with prior work that has examined sickness with amplified rotation techniques [21], [24].

Because we observed mixed effects of sickness and only amplified resetting produced significantly higher sickness scores, we partially accept our hypothesis **H2**.

4.5.3 User Preference

Questions from the survey relating to how much fun the techniques were, how interested participants would be to use them for home entertainment, how comfortable they were, and how much frustration was involved were averaged to determine the preferences for home entertainment. Friedman testing showed significant differences in ratings for entertainment based on technique.

Nemenyi testing revealed that for all participants, the discrete joystick technique was significantly more preferred than either of the other techniques ($p < 0.05$). Examining only gamers, entertainment ratings did not vary significantly at all.

Overall, discrete joystick rotations were most preferred. Gamers did not have a significant preference for any technique, suggesting that those with more gaming experience may be open to alternative methods of rotating their view outside the commonly used joystick technique.

Because only significant effect observed was a higher entertainment rating for discrete rotations compared to the other two techniques for the general population, we partially accept our hypothesis **H3**.

4.6 Experiment 1 Discussion

In this experiment, discrete, joystick-based rotations were compared against two view-resetting techniques using both regular and amplified head rotations in the context of rotation restricted (seated) travel. All techniques instantaneously applied a view transformation, hence their classification as *discrete* for the purpose of this work.

We identified a significant effect of technique on sickness with amplified resetting yielding worse sickness ratings and higher SSQ scores. This agrees with prior work, and is a known issue with these types of techniques [21], [24]. Changes in SSQ scores did not significantly vary for non-gamer participants, suggesting that no technique induces more sickness than others. However, as they become more comfortable with virtual travel over time their experience may become more similar to those of gamers.

Discrete joystick-based rotation was the most preferred technique by participants compared to either resetting technique. This may be due to the technique's simplicity and lack of additional head movement to modify the user's view. It is possible that resetting, which requires users to pause and move their head back to a neutral position, interrupts a user's *flow* which makes their experience in the environment less enjoyable. Interestingly, entertainment ratings for gamers were not significantly different, which could indicate a willingness to use alternative techniques like resetting. Application context (e.g., a VR game geared towards gamers or a continued operational use in professional settings) may play an important role in what type of techniques users find more appropriate to use.

Finally, the results suggest spatial orientation was not significantly affected by technique based on the egocentric and exocentric orientation assessments. Judging from the length of the travel path and the range of observed errors, the results suggest the experimental task would likely be difficult enough to detect differences between techniques, if present. Though it is possible that orientation was aided by the frequency of reference points in the environment which provide ample context for the users location in the scene, which may have assisted users with their spatial updating. Conducting the study with a sparsely filled environment may provide additional information on how each technique disorients the user, though we note that scenes with many unique features are more representative of real applications.

For participants as a whole, discrete joystick-based head rotations were found to be superior no worse than both resetting techniques on all fronts. Ease of use may be a factor since discrete rotations can be achieved by just a single button press or flick of a trigger. Resetting techniques require additional time and effort by users to select a new forward direction and turn their head back to the front, in addition to their negative impacts on sickness when amplification is also applied. We recommend VR application designers consider this aspect of resetting techniques when other techniques can be used in their place.

5 Experiment 2: Continuous Rotational Updates

After examining differences between discrete joystick-based rotations and resetting techniques, we wanted to determine if differences existed between discrete joystick-based rotations and similar continuous joystick-based techniques. We narrow our breadth-based approach by only considering techniques that utilize a joystick.

5.1 Techniques

In this experiment, we compare discrete joystick rotation against two different continuous techniques:

- *Discrete joystick rotation*: A fixed rotation is applied when a user moves the joystick. This was the same technique described for Experiment 1 (see Section 4.1.1).
- *Continuous joystick rotation*: A continuous rotation is applied with a constant speed.
- *Continuous joystick rotation* with *reduced FOV*: A continuous rotation is applied with a constant speed while the user's field of view is also decreased.

For all three techniques, 6 degree-of-freedom head-tracked rendering was enabled. As in Experiment 1, in addition to using the joystick technique, participants could also physically turn their heads to view more of the virtual environment.

5.1.1 Continuous Rotation

Moving the joystick to the right or left rotates the camera heading relative to the vertical axis. The implementation for the study used a constant speed of 30 degrees/second in the direction the trigger was pressed.

TABLE 3
Results of Friedman and pairwise Nemenyi significance testing for each measure in Experiment 2 for each technique: discrete rotation (D), continuous rotation (C), and continuous rotation with view reduction (R). Only pairs with significant differences are reported. In pairwise differences, the first technique produced a higher value for the measure. We also present Kendall's W showing effect size which can be interpreted using Cohen's guidelines [55].

Measure	**All**			**Gamers**		
	χ^2 (2)	p	W	χ^2 (2)	p	W
Ego. Error	0.58	0.747	0.012	0.11	0.929	0.003
Exo. Error	0.02	0.989	0.0004	0.85	0.651	0.025
Entertainment	1.40	0.495	0.029	0.10	0.950	0.003
Sickness	0.94	0.622	0.019	1.89	0.387	0.055
ΔSSQ Score	11.69	**0.003**	0.243	4.57	0.101	0.134
Pairwise difs.		*C vs. D*, **0.002**				

5.1.2 Continuous Rotation with Reduced Field of View

The experiment also included an additional version of continuous joystick rotation that reduced the FOV during virtual rotation in an effort to reduce discomfort from visual motion that does not match physical head turning. This *reduced FOV* joystick technique used continuous rotation with the analog stick in the same way as in the *continuous rotation* implementation that leverages a reduced FOV to reduce sickness [10], [11], [44]. The difference is that the *reduced FOV* technique applied a visual mask on top of the virtual view that limited the user's FOV to only a small circular region that reduced the Rift's normal FOV of approximately 90x100 degrees. The FOV reduction used a radial fall-off effect to give the effect of blurred edges around the view (see Figure 1, right) for an FOV of approximately 55x55 degrees. This FOV mask was applied whenever the user used the joystick to rotate. The *reduced FOV* allows continuous viewing of the rotational movement to allow the user to view the entire turn.

However, the drawback is that the FOV mask hides a considerable amount of visual content and might be expected to reduce spatial awareness while turning. For the implementation in the study, the extent of FOV masking was dynamic based on a transition that reduced the FOV from the default view to the most limited view showing content directly in front of the user. The mask increased with continued rotation such that the full mask was present after five seconds of turning.

5.2 Hypotheses

Since the *continuous rotation* technique adjusts the view gradually without any break in presence, we hypothesized that it might suffer lower penalties to spatial orientation as compared to the other joystick techniques. Reducing the FOV has been found to negatively affect performance during spatial search tasks [44]. So we hypothesized that the *reduced FOV* condition will deteriorate user performance in the spatial orientation tasks. We also hypothesized that the discrete rotations would make it more difficult to maintain spatial orientation because of the more sudden changes to the view.

In terms of sickness, based on the results from pilot testing, we hypothesized that the continuous camera rotations would make most users nauseous. Since reducing FOV during translational movements has been found to cause less sickness effects [11], we hypothesized that the *reduced FOV* technique would have less sickness compared to the *continuous rotation* condition. Since the *discrete rotation* does not involve continuous camera turns, we hypothesized that this condition would cause the least sickness effects of the three.

Finally, regarding entertainment, we hypothesized that due to the simplicity of the discrete technique it would be seen as most suitable for regular use by participants. Continuous rotation with reduced FOV would follow, since it reduces sickness which would adversely impact the participant's experience. Continuous rotation would have the lowest entertainment scores due to the expected sickness it would induce.

These experimental hypotheses are summarized as:

- **H4 (Spatial Awareness):** Continuous Rotation > Continuous Rotation with Reduced FOV > Discrete
- **H5 (Sickness):** Continuous Rotation > Continuous Rotation with Reduced FOV > Discrete
- **H6 (Entertainment):** Discrete > Continuous Rotation with Reduced FOV > Continuous Rotation

5.3 Experimental Design

Experiment 2 compared three types of joystick rotation techniques: *continuous joystick rotation*, *discrete joystick rotation*, and *reduced FOV* joystick rotation. The study design and procedure was similar to Experiment 1. The experiment followed a within-subjects design with each participant testing all three techniques. Each participant completed the navigation task 12 times split into three blocks corresponded to the three techniques. That is, participants completed the task four times for each technique, where the first was considered a familiarity trial with the technique. Technique order was fully counter-balanced across the participants.

5.4 Participants

Experiment 2 was completed by 23 participants. We note that this is a separate set of participants from those in Experiment 1. Of the included participants (13 male, 10 female), ages ranged from 18 to 55 (Mdn = 22). Seventeen were classified as gamers due to playing at least one hour of video games a week, with reported hours ranging from 1-30 hours (Mdn = 3 hours).

5.5 Results

For Experiment 2, we examined the effects of each technique on user performance in the egocentric and exocentric orientation tasks, sickness while using the technique, and overall preference of technique. We analyze all participants and only those classified as gamers (more than one hour of weekly 3D video play) to see if experience with 3D environment influences our measures. Data did not meet the assumption of normality to use a parametric ANOVA test,

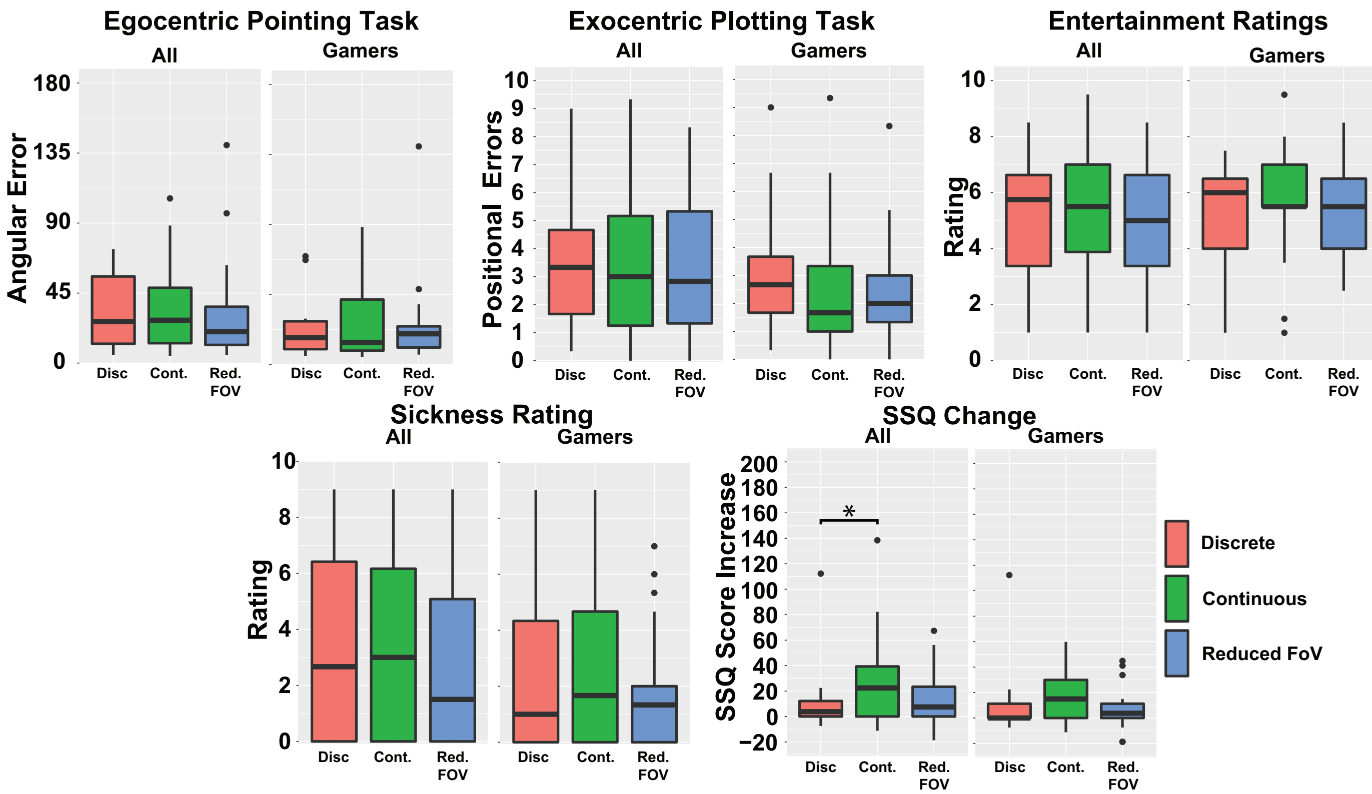

Fig. 5. Box plots displaying data from Experiment 2 showing medians, quartiles, and outliers. Significant differences at $p < 0.05$ are marked with an asterisk.

so Friedman's non-parametric ANOVA was used. Results from Friedman tests are shown in Table 3.

5.5.1 Spatial Orientation

Spatial orientation results are based on egocentric pointing error and errors from the 2D positional plotting measure (Figure 5). No significance of technique on error for the egocentric pointing task were identified based on results from Friedman's test.

While the discrete and continuous techniques maintained a full view of the scene while transformations were applied, the continuous technique with field of view reduction showed less of the environment. We could expect this to negatively impact orientation since user's would see fewer reference points while turning their head. However, we did not observe any difference any of the techniques. It is likely that participants were able to situate themselves in the environment sufficiently before applying rotations, which would account for a lack of observed differences.

Because we did not observe any significant effects on either spatial orientation outcomes, we reject our hypothesis **H4**.

5.5.2 Sickness

Responses from the post-study questionnaire on questions about nausea, headache and dizziness were grouped together for an aggregate rating of technique preference based on perceived sickness (Figure 5). For this rating, a higher score is associated with *less* sickness experienced. We also analyzed changes in SSQ scores.

A Friedman's test revealed no significant effects of technique on the sickness rating. However, the test did find a significant effect on SSQ score changes. When considering all participants, discrete rotation resulted in significantly lower ratings than continuous rotation ($p < 0.01$). While reducing the user's field of view during continuous rotation did lower the amount of change in SSQ scores, it was not to a significant level. Overall, these findings on sickness indicate that continuous rotation using a joystick may not be optimal, but when sickness reductions techniques (e.g., field of view reduction) are applied effects can be reduced to be similar to discrete rotations We observed few cases of significant impacts of technique selection on sickness, with only continuous rotation yielding higher SSQ scores than discrete. Because of this, we only partially accept our hypothesis **H5**.

5.5.3 User Preference

Questions from the survey relating to how much fun the techniques were, how interested participants would be to use them for home entertainment, how comfortable they were and how much frustration was involved were averaged to determine the preferences for home entertainment. No significant differences were detected between any techniques for both all participants and gamers only. It is possible that given the simplicity of each technique account for similar ratings: each technique used just an input from a joystick, which would not appear particularly novel or overly-cumbersome to most users.

Notably, we do see lower entertainment scores for the discrete technique compared to our findings in Experiment

1. This is likely due to participants rating all techniques at the end of the experiment and basing their responses based on comparisons to the other techniques. So, in Experiment 2, participants saw little difference in techniques and therefor rated them similarly. Entertainment ratings should only be interpreted as relative to other techniques in the experiment, and not as a baseline evaluation of the technique.

Because we did not observe any significant effects on our entertainment ratings, we reject our hypothesis **H6**.

5.6 Experiment 2 Discussion

This experiment compared discrete and continuous joystick-controlled rotations while head tracked viewing was also available. The study considered continuous joystick rotations with and without a reduced FOV during rotation.

For all measures but *change in SSQ* scores, no differences were found. Continuous rotation without a reduced FOV were significantly increased SSQ scores compared to discrete rotations when considering all participants, showing that reducing the FOV can reduce sickness. When considering only gamers, no effect of technique on SSQ ratings were found but overall SSQ scores were lower and less varied. This could be attributed to a comfort with VR or 3D environments due to prior exposure; adjustments to the HMD were easier to make than those with less experience.

A lack of differences in other measures may be attributed to similarities in input methods. All techniques directly map a joystick input to a view transformation, with the visual properties of the transformation varying. No additional head movement *during* a transformation is needed, as was for resetting techniques in Experiment 1. Direct control of the view may explain why the orientation and entertainment ratings are not largely different.

Reducing the FOV when using continuous rotation appears to be optimal due to the benefits of reducing sickness. However, because minimal differences were observed between techniques, it is not clear if sufficient trade-offs exist to recommend discrete rotations over continuous. The choice of technique may come down to individual user preference or application design. In applications where users are largely stationary, discrete may be well suited if areas of interested are located uniformly or reliably around the user. However, if users are more free to move around in a scene, continuous rotation affords more precise rotations which may be needed to navigate more accurately.

6 General Discussion

Our findings provide insight into the design of viewpoint rotation techniques during application use, specifically when users are unable to physically turn in 360 degrees. In these situations, physical turning is limited so alternative techniques are needed to facilitate interactions in a 360 degree environment. Our work examined both discrete and continuous techniques for updating a user's head rotation in VR, incorporating techniques such as resetting, amplified head reduction, and field-of-view reduction. Both experiments examined the effects of different techniques on user orientation, sickness, and entertainment.

In our first experiment, we identified a strong preference for directly controlled head rotation compared to resetting techniques. Later, we examined different methods of these direct, joystick-based techniques but did not much evidence that these variations were significantly worse or better than others. Joystick-based techniques are not only simple to understand, but provide convenience for users since they do not require extra time or movement to complete the rotation as is found in resetting techniques. Their simplicity is also advantageous for novice users who may not be familiar with alternative techniques. Pairing this with the fact that novices are particularly susceptible to sickness in VR [8], [56], direct manipulation techniques appear to be superior. This is exemplified by some comments from participants after the study:

- On resetting: "*Felt sluggish due to turning method. Was the least enjoyable of the three versions.*"
- On amplified resetting: "*With the quick turns it became slightly disorienting at first and was less enjoyable. Allowed for fast movement.*"
- On discrete rotations: "*Easy to move compared to the other two.*"

However, since we only examined user-initiated resetting it may be possible that the benefits of undetectable or system-initiated resetting would be preferable. One advantage of resetting techniques is their reduction of neck strain by frequently encouraging users to return to a comfortable forward direction. While not in the scope of this work, it is possible that joystick-based techniques may result in more neck strain as users can use the technique while their head is already turned. Future work that examines this kind of behavior may provide insight into cases where resetting may be advantageous.

Between joystick techniques, we did not identify any strong user preference of discrete or continuous rotation. However, we did confirm prior findings that FOV reductions can decrease sickness [10], [44]. Importantly, we demonstrate that despite the limited visual information present during reduced FOV rotation users were able to maintain similar spatial awareness.

The inclusion of amplified head movements only further sickened participants, as is expected [21], [24]. While amplification techniques can be useful in allowing more of a scene to be viewed with less movement, in some contexts of seated travel (e.g., on a plane or train) users may already be experiencing external movement which would only amplify these sensations compared to our controlled laboratory setting.

There are several limiting factors for this work. First, our grid-based environment limits the number of possible focal points to the four rooms adjacent to the participant's current room, and limits overall turning to increments of 90 degrees. Using more natural and detailed environments (e.g., that used in [33]) may reveal larger differences for spatial understanding that our experiments could not. Future work may also be able to consider rotation speed and accuracy trade-offs for each technique by utilizing a design with less exploration or travel (e.g., only having participants rotated in place and examining fixed angles).

Additionally, while we did provide some time between trials for participants to recover from cybersickness, the time allotted does not guarantee full recovery. However, we presented changes in SSQ scores to account for this. Future work may also consider sickness implications with longer periods of use.

7 Conclusion

We present the results of two experiments which compare discrete and continuous techniques for head rotations in virtual reality and their effects on sickness, entertainment, and orientation. We include an exploration into technique features such as resetting, amplified rotation, and field-of-view reduction in order to assess how each strategy affects user outcomes. This work was conducted in the context of seated VR use, where users physical turning is limited by their environment.

The results of our studies suggest an overall user preference for techniques with direct-control by users (i.e., discrete/continuous rotations from joystick input) rather than those that reset a user's head via controlled rotations. Direct-control techniques compared similarly to each other, with minimal differences in sickness and orientation. Because of this, we cannot recommend one over another. It may be beneficial to include an option for users to use any of the techniques in applications since preferences may vary between individuals.

These findings contribute to our collective understanding head rotation techniques and their effects on sickness, orientation, and preference by users.

References

[1] S. S. Chance, F. Gaunet, A. C. Beall, and J. M. Loomis, "Locomotion mode affects the updating of objects encountered during travel: The contribution of vestibular and proprioceptive inputs to path integration," *Presence: Teleoperators and Virtual Environments*, vol. 7, no. 2, pp. 168–178, 1998.

[2] R. A. Ruddle, S. J. Payne, and D. M. Jones, "Navigating large-scale virtual environments: what differences occur between helmet-mounted and desk-top displays?" *Presence: Teleoperators and Virtual Environments*, vol. 8, no. 2, pp. 157–168, 1999.

[3] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, and F. P. Brooks, "Walking > walking-in-place > flying, in virtual environments," in *Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques*, ser. SIGGRAPH '99. USA: ACM Press/Addison-Wesley Publishing Co., 1999, p. 359–364. [Online]. Available: https://doi.org/10.1145/311535.311589

[4] M. Slater, M. Usoh, and A. Steed, "Taking steps: the influence of a walking technique on presence in virtual reality," *ACM Transactions on Computer-Human Interaction (TOCHI)*, vol. 2, no. 3, pp. 201–219, 1995.

[5] E. D. Ragan, R. Kopper, P. Schuchardt, and D. A. Bowman, "Studying the effects of stereo, head tracking, and field of regard on a small-scale spatial judgment task," *IEEE transactions on visualization and computer graphics*, vol. 19, no. 5, pp. 886–896, 2013.

[6] F. Bacim, E. Ragan, S. Scerbo, N. F. Polys, M. Setareh, and B. D. Jones, "The effects of display fidelity, visual complexity, and task scope on spatial understanding of 3d graphs," in *Proceedings of Graphics Interface 2013*. Canadian Information Processing Society, 2013, pp. 25–32.

[7] A. Forsberg, M. Katzourin, K. Wharton, M. Slater *et al.*, "A comparative study of desktop, fishtank, and cave systems for the exploration of volume rendered confocal data sets," *IEEE Transactions on Visualization and Computer Graphics*, vol. 14, no. 3, pp. 551–563, 2008.

[8] E. D. Ragan, A. Wood, R. P. McMahan, and D. A. Bowman, "Trade-offs related to travel techniques and level of display fidelity in virtual data-analysis environments." in *ICAT/EGVE/EuroVR*, 2012, pp. 81–84.

[9] D. A. Bowman, D. Koller, and L. F. Hodges, "Travel in immersive virtual environments: An evaluation of viewpoint motion control techniques," in *Virtual Reality Annual International Symposium, 1997., IEEE 1997*. IEEE, 1997, pp. 45–52.

[10] J.-W. Lin, H. B.-L. Duh, D. E. Parker, H. Abi-Rached, and T. A. Furness, "Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment," in *Proceedings IEEE virtual reality 2002*. IEEE, 2002, pp. 164–171.

[11] A. S. Fernandes and S. K. Feiner, "Combating vr sickness through subtle dynamic field-of-view modification," in *3D User Interfaces (3DUI), 2016 IEEE Symposium on*. IEEE, 2016, pp. 201–210.

[12] N. Coomer, S. Bullard, W. Clinton, and B. Williams-Sanders, "Evaluating the effects of four vr locomotion methods: joystick, arm-cycling, point-tugging, and teleporting," in *Proceedings of the 15th ACM symposium on applied perception*, 2018, pp. 1–8.

[13] S. Razzaque, D. Swapp, M. Slater, M. C. Whitton, and A. Steed, "Redirected walking in place," in *EGVE*, vol. 2, 2002, pp. 123–130.

[14] B. E. Riecke and D. Feuereissen, "To move or not to move: can active control and user-driven motion cueing enhance self-motion perception (vection) in virtual reality?" in *Proceedings of the ACM Symposium on Applied Perception*. ACM, 2012, pp. 17–24.

[15] D. Zielasko, B. Weyers, M. Bellgardt, S. Pick, A. Meibner, T. Vierjahn, and T. W. Kuhlen, "Remain seated: towards fully-immersive desktop vr," in *Everyday Virtual Reality (WEVR), 2017 IEEE 3rd Workshop on*. IEEE, 2017, pp. 1–6.

[16] D. Zielasko, Y. C. Law, and B. Weyers, "Take a look around – the impact of decoupling gaze and travel-direction in seated and ground-based virtual reality utilizing torso-directed steering," in *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, March 2020, pp. 398–406.

[17] S. Razzaque, Z. Kohn, and M. C. Whitton, "Redirected walking," in *Proceedings of EUROGRAPHICS*, vol. 9. Citeseer, 2001, pp. 105–106.

[18] N. C. Nilsson, T. Peck, G. Bruder, E. Hodgson, S. Serafin, M. Whitton, F. Steinicke, and E. S. Rosenberg, "15 years of research on redirected walking in immersive virtual environments," *IEEE computer graphics and applications*, vol. 38, no. 2, pp. 44–56, 2018.

[19] I. Poupyrev, S. Weghorst, T. Otsuka, and T. Ichikawa, "Amplifying spatial rotations in 3d interfaces," in *CHI'99 Extended Abstracts on Human Factors in Computing Systems*. ACM, 1999, pp. 256–257.

[20] C. Jay and R. Hubbold, "Amplifying head movements with head-mounted displays," *Presence: Teleoperators and Virtual Environments*, vol. 12, no. 3, pp. 268–276, 2003.

[21] E. D. Ragan, S. Scerbo, F. Bacim, and D. A. Bowman, "Amplified head rotation in virtual reality and the effects on 3d search, training transfer, and spatial orientation," *IEEE transactions on visualization and computer graphics*, vol. 23, no. 8, pp. 1880–1895, 2016.

[22] L. L. Ngoc and R. S. Kalawsky, "Evaluating usability of amplified head rotations on base-to-final turn for flight simulation training devices," in *2013 IEEE Virtual Reality (VR)*. IEEE, 2013, pp. 51–54.

[23] L. Bölling, N. Stein, F. Steinicke, and M. Lappe, "Shrinking circles: Adaptation to increased curvature gain in redirected walking," *IEEE Transactions on Visualization and Computer Graphics*, vol. 25, no. 5, pp. 2032–2039, 2019.

[24] S. P. Sargunam, K. R. Moghadam, M. Suhail, and E. D. Ragan, "Guided head rotation and amplified head rotation: Evaluating semi-natural travel and viewing techniques in virtual reality," in *Virtual Reality (VR), 2017 IEEE*. IEEE, 2017, pp. 19–28.

[25] E. Langbehn, J. Wittig, N. Katzakis, and F. Steinicke, "Turn your head half round: Vr rotation techniques for situations with physically limited turning angle," in *Proceedings of Mensch Und Computer 2019*, ser. MuC'19. New York, NY, USA: Association for Computing Machinery, 2019, p. 235–243. [Online]. Available: https://doi.org/10.1145/3340764.3340778

[26] E. Langbehn, F. Steinicke, M. Lappe, G. F. Welch, and G. Bruder, "In the blink of an eye: leveraging blink-induced suppression for imperceptible position and orientation redirection in virtual reality," *ACM Transactions on Graphics (TOG)*, vol. 37, no. 4, pp. 1–11, 2018.

[27] T. Stebbins and E. D. Ragan, "Redirecting view rotation in immersive movies with washout filters," in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 2019, pp. 377–385.

[28] B. Williams, G. Narasimham, B. Rump, T. P. McNamara, T. H. Carr, J. Rieser, and B. Bodenheimer, "Exploring large virtual environments with an hmd when physical space is limited," in

Proceedings of the 4th symposium on Applied perception in graphics and visualization. ACM, 2007, pp. 41–48.
[29] T. C. Peck, H. Fuchs, and M. C. Whitton, “Evaluation of reorientation techniques and distractors for walking in large virtual environments,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 15, no. 3, pp. 383–394, 2009.
[30] C. Ware and S. Osborne, “Exploration and virtual camera control in virtual three dimensional environments,” in *ACM SIGGRAPH Computer Graphics*, vol. 24, no. 2. ACM, 1990, pp. 175–183.
[31] B. Bolte, F. Steinicke, and G. Bruder, “The jumper metaphor: an effective navigation technique for immersive display setups,” in *Proceedings of Virtual Reality International Conference*, 2011.
[32] E. Bozgeyikli, A. Raij, S. Katkoori, and R. Dubey, “Point & teleport locomotion technique for virtual reality,” in *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play*. ACM, 2016, pp. 205–216.
[33] T. Weißker, A. Kunert, B. Fröhlich, and A. Kulik, “Spatial updating and simulator sickness during steering and jumping in immersive virtual environments,” in *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 2018, pp. 97–104.
[34] A. Adhikari, D. Zielasko, A. Bretin, M. von der Heyde, E. Kruijff, and B. E. Riecke, “Integrating continuous and teleporting vr locomotion into a seamless” hyperjump” paradigm,” in *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE, 2021, pp. 370–372.
[35] K. R. Moghadam, C. Banigan, and E. D. Ragan, “Scene transitions and teleportation in virtual reality and the implications for spatial awareness and sickness,” *IEEE transactions on visualization and computer graphics*, 2018.
[36] K. Rahimi, C. Banigan, and E. D. Ragan, “Scene transitions and teleportation in virtual reality and the implications for spatial awareness and sickness,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 26, no. 6, pp. 2273–2287, 2020.
[37] F. Buttussi and L. Chittaro, “Locomotion in place in virtual reality: A comparative evaluation of joystick, teleport, and leaning,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 27, no. 1, pp. 125–136, 2021.
[38] E. Bozgeyikli, A. Raij, S. Katkoori, and R. Dubey, “Locomotion in virtual reality for room scale tracked areas,” *International Journal of Human-Computer Studies*, vol. 122, pp. 38–49, 2019.
[39] E. Langbehn, P. Lubos, and F. Steinicke, “Evaluation of locomotion techniques for room-scale vr: Joystick, teleportation, and redirected walking,” in *Proceedings of the Virtual Reality International Conference-Laval Virtual*, 2018, pp. 1–9.
[40] D. Zielasko, J. Heib, and B. Weyers, “Systematic design space exploration of discrete virtual rotations in vr,” in *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 2022, pp. 693–702.
[41] J. J. LaViola Jr, “A discussion of cybersickness in virtual environments,” *ACM SIGCHI Bulletin*, vol. 32, no. 1, pp. 47–56, 2000.
[42] S. Davis, K. Nesbitt, and E. Nalivaiko, “A systematic review of cybersickness,” in *Proceedings of the 2014 conference on interactive entertainment*, 2014, pp. 1–9.
[43] E. M. Kolasinski, *Simulator sickness in virtual environments*. US Army Research Institute for the Behavioral and Social Sciences, 1995, vol. 1027.
[44] M. J. Wells and M. Venturino, “Performance and head movements using a helmet-mounted display with different sized fields-of-view,” *Optical Engineering*, vol. 29, no. 8, pp. 870–878, 1990.
[45] D. Zielasko, A. Meißner, S. Freitag, B. Weyers, and T. W. Kuhlen, “Dynamic field of view reduction related to subjective sickness measures in an hmd-based data analysis task,” in *Proc. of IEEE VR Workshop on Everyday Virtual Reality*, 2018.
[46] J.-Y. Lee, P.-H. Han, L. Tsai, R.-D. Peng, Y.-S. Chen, K.-W. Chen, and Y.-P. Hung, “Estimating the simulator sickness in immersive virtual reality with optical flow analysis,” in *SIGGRAPH Asia 2017 Posters*, 2017, pp. 1–2.
[47] Y. Farmani and R. J. Teather, “Viewpoint snapping to reduce cybersickness in virtual reality,” in *Proceedings of Graphics Interface 2018*, ser. GI 2018. Canadian Human-Computer Communications Society / Société canadienne du dialogue humain-machine, 2018, pp. 168 – 175.
[48] Y. Farmani and R. Teather, “Evaluating discrete viewpoint control to reduce cybersickness in virtual reality,” *Virtual Reality*, vol. 24, no. 4, pp. 645–664, 2020.
[49] S. P. Sargunam and E. D. Ragan, “Evaluating joystick control for view rotation in virtual reality with continuous turning, discrete turning, and field-of-view reduction,” in *Proceedings of the 3rd International Workshop on Interactive and Spatial Computing*. ACM, 2018, pp. 74–79.
[50] A. N. Ryge, C. Vollmers, J. S. Hvass, L. K. Andersen, T. Berthelsen, J. R. Bruun-Pedersen, N. C. Nilsson, and R. Nordahl, “A preliminary investigation of the effects of discrete virtual rotation on cybersickness,” in *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 2018, pp. 675–676.
[51] F. Morganti and G. Riva, “Virtual reality as allocentric/egocentric technology for the assessment of cognitive decline in the elderly.” in *MMVR*, vol. 21, 2014, pp. 278–284.
[52] G. Weniger, M. Ruhleder, C. Lange, S. Wolf, and E. Irle, “Egocentric and allocentric memory as assessed by virtual reality in individuals with amnestic mild cognitive impairment,” *Neuropsychologia*, vol. 49, no. 3, pp. 518–527, 2011.
[53] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, “Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness,” *The international journal of aviation psychology*, vol. 3, no. 3, pp. 203–220, 1993.
[54] J. J. LaViola Jr, D. A. Feliz, D. F. Keefe, and R. C. Zeleznik, “Hands-free multi-scale navigation in virtual environments,” *Proceedings of Symposium on Interactive 3D graphics*, pp. 9–15, 2001.
[55] J. Cohen, P. Cohen, S. G. West, and L. S. Aiken, *Applied multiple regression/correlation analysis for the behavioral sciences*. Routledge, 2013.
[56] M. E. McCauley and T. J. Sharkey, “Cybersickness: Perception of self-motion in virtual environments,” *Presence: Teleoperators & Virtual Environments*, vol. 1, no. 3, pp. 311–318, 1992.

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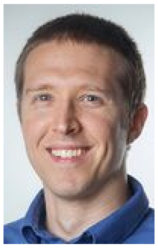

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