Guided Head Rotation and Amplified Head Rotation: Evaluating Semi-natural Travel and Viewing Techniques in Virtual Reality

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ABSTRACT

Traditionally in virtual reality systems, head tracking is used in head-mounted displays (HMDs) to allow users to control viewing using 360-degree head and body rotations. Our research explores interaction considerations that enable semi-natural methods of view control that will work for seated use of virtual reality with HMDs when physically turning all the way around is not ideal, such as when sitting on a couch or at a desk. We investigate the use of amplified head rotations so physically turning in a comfortable range can allow viewing of a 360-degree virtual range. Additionally, to avoid situations where the user's neck is turned in an uncomfortable position for an extended period, we also use redirection during virtual movement to gradually realign the user's head position back to the neutral, straight-ahead position. We ran a controlled experiment to evaluate *guided head rotation* and *amplified head rotation* without realignment during movement, and we compared both to traditional one-to-one head-tracked viewing as a baseline for reference. After a navigation task, overall errors on spatial orientation tasks were relatively low with all techniques, but orientation effects, sickness, and preferences varied depending on participants' 3D gaming habits. Using the *guided rotation* technique, participants who played 3D games performed better, reported higher preference scores, and demonstrated significantly lower sickness results compared to non-gamers.

Index Terms: H.5.1 [Information interfaces and presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities

1 INTRODUCTION

The ability to look around and navigate is a fundamental interaction for experiencing a 3D virtual environment. Many types of virtual reality (VR) allow the use of physical bodily movements to view and interact with 3D computer-generated environments. For example, consider VR systems using head-mounted displays (HMDs) or large surround-screen displays (e.g., CAVEs) that track the user's head to enable head-based rendering, thereby updating the position and orientation of the virtual viewpoint based on the user's physical head movements. Fidelity and naturalness are often seen as goals for VR [3], and many studies have found real walking and physical head control to be beneficial methods for experiencing and understanding virtual 3D environments (e.g., [6, 26, 33]).

However, realistic travel and viewing techniques are not always preferred for all situations. Realistic body movement requires a sufficiently large physical space and a suitable tracking system. Additionally, full body movements can be tiring, and users might opt for more convenient forms of interaction for relaxation or extended periods of use. With the recent availability of high-quality technology such as the Oculus Rift, Playstation VR, Samsung Gear VR, and the HTC Vive, many developers and consumers are considering VR for home entertainment, for which it could be desirable to experience VR from the comfort of the couch or at the convenience of an office chair.

To accommodate such use cases, our research considers semi-natural methods for travel and view control. Rather than focus on the highest level of interaction, we study viewing techniques designed to meet the constraints of seated VR. Our work builds off of prior research leveraging perceptual illusions and manipulating the mapping between physical movement and virtual view updates. For instance, as a means of allowing physical walking within a limited physical space, many researchers have studied *redirected walking* (e.g., [8, 24, 29]), which employs rotational adjustments during real walking to encourage (or trick) users to adjust their walking paths. As another example, amplified head rotation uses rotational gains to allow users to view a 360-degree virtual range via a much smaller range of physical head rotations [11, 18, 23].

Combining such prior techniques, we designed a *guided head rotation* technique for semi-natural travel and view control in seated VR. The technique uses amplified head rotations so that the required physical head turning is limited to a comfortable range. Additionally, to avoid situations where the user's neck is turned in an uncomfortable position for an extended period, we use rotational adjustments during virtual travel (via joystick) to gradually realign the user's head position back to the neutral, straight-ahead position. To support free choice of travel direction, the technique dynamically predicts the target destination for redirection.

In our work, we sought to better understand how semi-natural viewing techniques compare to other methods of physical view control for seated VR. Using standard one-to-one 360-degree head-tracked viewing as a baseline, we ran a controlled experiment to test *guided head rotation*, and we also compared to *amplified head rotation* without realignment during movement. In the study, participants virtually navigated through a series of interconnected rooms, and we assessed spatial orientation and user preferences for the different techniques. Our findings reveal important insights and limitations for semi-natural VR viewing techniques, and different effects were found for participants who play 3D video games as compared to those who do not.

2 RELATED WORK

Our research builds on prior research about navigation in VR.

2.1 Natural and Semi-Natural Navigation in VR

Many researchers have previously studied navigation techniques for VR and how different factors and methods influence spatial understanding. For example, studies suggest that natural head-tracked viewing supports faster and more accurate performance on tasks involving spatial inspection [2, 26, 22]. Chance et al. [6] compared the effects of different travel techniques on a spatial orientation task that involved remembering the directions of virtual objects for participants using an HMD. The authors found physical walking and

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turning provided benefits over virtual turning with a joystick. Also studying navigation, Ruddle et al. [26] tested participants' abilities to navigate a physical building after trying to learn to layout in different VR versions of the building. The results showed that practicing with a tracked HMD was superior over practicing with a desktop system using a keyboard and mouse.

In addition to spatial tasks, research has found that users experience a greater sense of *presence* (the feeling of "being there" in a virtual world) when using real walking [27, 33] as compared to alternative travel techniques with lower realism. In a study of semi-natural travel techniques for desktop environments, Terziman et al. [32] found evidence of improved presence when controlling travel by head movements rather than using keyboard and mouse.

Despite the benefits of realistic and natural interaction for travel and view control, many real-world constraints have led to the exploration of alternative and semi-natural travel methods. Bowman et al. [3] discussed potential advantages of "magic" techniques for interaction in VR that could even intentionally reduce fidelity. Additionally, many researchers have studied adjustments to standard viewing and walking techniques to overcome real-world limitations such as limited physical space (e.g., [11, 19, 24, 32]). However, it is important to consider the potential drawbacks of interaction techniques with reduced realism, as several studies have found evidence of less realistic travel techniques negatively affecting outcomes relating to spatial orientation [23, 26], cognitive resources (e.g., [4, 16, 37]), and sickness (e.g., [23]).

2.2 Rotation Amplification

Many VR systems track users' head orientations to enable one-to-one control of the virtual camera, but the rotations can be amplified to allow viewing a large virtual range with correspondingly smaller physical turns. Numerous previous researchers have considered the use of such *rotation amplification* (e.g., [15, 21]). The factor by which virtual rotation is increased or decreased from the physically-tracked rotation is referred to as the gain factor or amplification factor [18, 23, 29]

In some cases, amplification has been shown to affect tasks involving spatial search and viewing (e.g., [11, 18]). For example, Jay et al. [11] studied differences in performance on a visual search task with and without rotation amplification and concluded that amplification led to significant performance improvements. Ngoc et al. [18] studied amplified head rotation in a flight training simulator where a single display let a trainee have a panaromic view of the cockpit environment (whereas three displays would normally be used). The researchers found no evidence of additional task error, mental workload, or sickness effects due to amplified rotation.

Ragan et al. [23] studied rotation amplification with an experiment that compared different levels of amplification in HMD and CAVE systems. The study found that amplification had no effect on a spatial search task, but some types of amplification negatively affected training transfer when switching from amplified rotation to standard one-to-one viewing. The study also found evidence of sickness problems associated with high levels of amplification (up to four times the physical rotation) in HMDs. The results also showed evidence of worse spatial orientation with the HMD than in the large-screen scenario. One important difference between our work and this study was that it used virtual blinders in the HMD to simulate a partially-surrounding display system with a missing display area, and the authors concluded this may have had a significant impact on spatial orientation. To better understand the feasibility of amplification techniques in more natural usage scenarios, it is important to test the effect of rotation amplification on spatial orientation without such limitations.

Understanding human sensitivity to rotational adjustments is also important for using amplified rotation. Bruder et al. [5] conducted just-noticeable-difference testing for physical body turning, and they also tested detection of rotational adjustments with constant gain factors. Zhang et al. [38] also studied the effects of different types of rotation amplification during a 360-degree virtual rotation. They studied whether users could detect differences between dynamic amplifications that vary gradually and those with discrete jumps to different amplification factors. The study found no differences between the two methods. LaViola et al. [15] studied *auto-rotation*, a dynamic rotation amplification approach for three-sided CAVE setups, where the amplification level is based on the user's distance from the front wall of the CAVE setup and the orientation of the user's torso relative to the front wall of the CAVE setup. Our research also uses a dynamic approach to amplify head rotations gradually, but the amplification factor in our approach is based on the user's head orientation.

2.3 Redirection and Reorientation Techniques

Previous studies have considered techniques that physically rotate or reorient users for different purposes during travel in VR. For example, the *redirected walking* methods encourage users to rotate and walk along a curved physical path while they virtually move along a straight line. *Redirected walking* was introduced by Razzaque et al. [24], and its main objective is to maximize the use of a limited tracked space to simulate physical walking in larger virtual environments. The *redirected walking* methods exploit the user's inability to recognize minor (or sometimes major) adjustments to the view or the environment. The methods proposed by Razzaque et al. [24], Azmandian et al. [1], and Engel et al. [7] use rotational gains and rotational adjustments to redirect users along a curved physical path while users virtually move towards virtual targets.

Razzaque et al. [25] also investigated the use of a redirection approach for CAVE environments that do not completely surround the user, such as when the back screen is absent. The goal was to reduce occasions when users turn to face the missing wall of the CAVE, which would disrupt the experience. The authors presented *redirected walking in place* (RWIP) to gradually redirect the user's physical orientation towards the front screen. This was achieved by rotating the virtual world towards the direction of the front screen as the user virtually moved through the environment. The *guided rotation* technique functions similarly to RWIP but with modifications to be better suited for HMD use in seated positions in which physical rotation of the body is not desired.

Another example for physically rotating users in VR is via reorientation methods to divert users away from physical bounds. Williams et al. [35] studied variations of *resetting* techniques to reorient users away from the physical bounds of the tracking area during physical walking. Peck et al. [19] studied the use of virtual distractors to reorient users and thereby avoid real-world collisions when *redirected walking* is employed. These approaches reorient users as they physically turn in a single continuous rotation, whereas the *guided rotation* technique gradually realigns users' head orientation to a neutral forward direction.

Related to our interest in the effects of reorientation on spatial orientation, Hodgson et al. [9] studied whether redirection negatively affected the ability to remember spatial locations of virtual objects in VR. In their experiment, participants used redirected walking to physically walk while wearing an HMD. After traveling past a number of virtual landmarks, participants were asked to turn and face the direction of specified landmarks. The results suggested that redirection did not negatively influence performance on the orientation task. This finding is promising for the potential of redirection and semi-natural viewing, but additional studies are needed to understand the range of implications of view and travel adjustments. Another related study by Peck et al. [20] showed that users performed significantly better at navigating through virtual mazes using redirected walking with distractors than with walking-in-place or joystick-based travel. The techniques explored in our study incorporate adjustments similar to the redirection approach but for head realignment for scenarios where the user is constrained to a physical position such as when sitting in a stationary chair.

Also relevant to our work, Tanaka et al. [31] demonstrated the use of *guidance fields* to encourage travel towards predetermined target locations in a virtual environment. Our *guided head rotation* technique uses a different type of rotational guidance by applying minor rotational adjustments to realign users' real world head to a physical forward direction during seated VR experiences. The rotational adjustments are similar to those used in washout filters for motion simulation (e.g., [10, 34]). Motion platforms simulate motions to provide vestibular sensation during virtual acceleration, but the platforms are limited in their ability to simulate continuous motion in any given direction. Washout filters can be used to gradually return the orientation of the platform back to the neutral setting so the platform will be better situated to simulate the next motion.

3 Techniques

Our research studies two semi-natural techniques for seated viewing: *amplified head rotation* and *guided head rotation*.

3.1 Amplified Head Rotation

In this research, we consider *amplified head rotation* as a technique for semi-natural seated viewing because it allows 360-degree viewing of the virtual world using physical head rotations but without requiring full physical rotations. The differences in rotation angle of the tracked physical head is multiplied by an amplification factor to produce the rotation angle of the virtual viewpoint. Figure 1 shows the basic concept. As previously mentioned, this type of technique has been explored and studied by others using various different implementations, displays, and amplification factors (e.g., [15, 18, 21, 23, 38]).

Rather than use a constant amplification factor, our implementation used a dynamic amplification factor that scales based on physical head orientation. To do this, our implementation assumes a real-world scenario with a preferred forward direction, such as you might have while sitting on a couch or at a desk. The forward direction can be set when starting the application. Our technique dynamically calculates the amount of amplification based on the difference between the direction designated as forward and the orientation corresponding to the tracked head direction. Note that the current study only amplifies horizontal rotation (i.e., yaw or heading). Our implementation calculates the amplification factor using the formula, $a = 2 - cos(h)$, where a is the amplification factor and h is the heading difference between tracked HMD rotation and the neutral forward direction. Using a, the virtual camera's heading is computed using $\theta = h * a$, where θ is the angle of the virtual camera, and h and a are as described above.

With this formulation, the amplification factor is small (close to 1.0) when the user is facing a direction close to the forward direction. Amplification increases as the user turns farther away from the forward direction and reaches 2 when physically turned 90 degrees. The rationale for this design was to allow viewing to feel natural and normal when physically facing forward since this is likely the most comfortable range for physical viewing. By increasing the amplification for larger turns, it is possible for the user to virtually turn all the way around by only physically turning to the side. Figure 2 shows the real world HMD angles and the corresponding virtual camera angles calculated using the above formulas.

3.2 Guided Head Rotation

While *amplified head rotation* can allow 360-virtual viewing from a seated position, its use in scenarios that do not afford body rotation could lead to discomfort due to the neck being turned for long periods of time, and continued rotation in the same direction would be problematic. To address these limitations, we explored

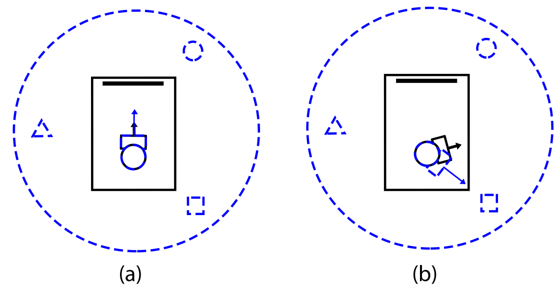

Figure 1: A top-down diagram demonstrating *amplified head rotation* shows the physical world and user's head in black. The virtual world and viewing direction are shown in blue. When the user physically rotates away from the real-world forward direction, the virtual view will have an amplified rotation based on the amplification factor.

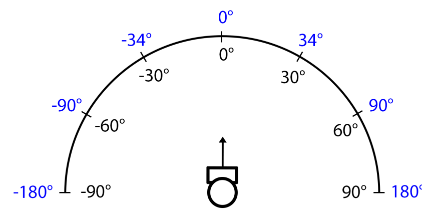

Figure 2: A top-down diagram demonstrating the real world and virtual yaw during *amplified head rotation*. The physical yaw angle is shown in black and the virtual angle is in blue. The black arrow represents the physical forward direction. Note that the amplification factor would continue to increase for physical rotation beyond 90 degrees, but this is not common in a stationary seated position.

another semi-natural technique for seated viewing and travel. We call this technique *guided rotation*. The technique uses the same implementation of *amplified head rotation* as described in the previous section, and it adds realignment during virtual travel. The technique employs an approach similar to that of washout filters (e.g., [10, 34]), redirected walking (e.g., [8, 24, 29]), and redirected walking-in-place implementations [25]. While traditional redirected walking techniques guide the direction of users' physical walking, our *guided head rotation* technique is responsible for realigning a users' head orientations as they virtually move (translate) through the VR environment. As with our *amplified head rotation* implementation, the realignment component of *guided rotation* also uses the given real-world forward direction. If the user's head is turned before virtually moving to a new location in VR, the technique gradually adjusts the view during travel to encourage the user to slowly physically rotate back towards the forward direction.

A straightforward approach to achieve this would be to apply a constant rotational adjustment as a user moves in the virtual world so that the user is always in the process of getting realigned towards the forward direction. However, users reported sickness problems with such constant adjustments during preliminary testing. The two main reasons for sickness reported by the users were: (1) the sudden change in the virtual camera's heading when they started moving virtually after being stationary, and (2) the proximity of the users to virtual objects and structures (e.g., walls, tables, doorways) when rotational adjustments were applied. Worse sickness was reported when users moved closer to a virtual object.

To reduce the sickness created by these two issues, we decided to interpolate the rotational adjustment value through an easing function. The easing function gradually increases the rotational adjustment value to a maximum as the user starts moving and gradually

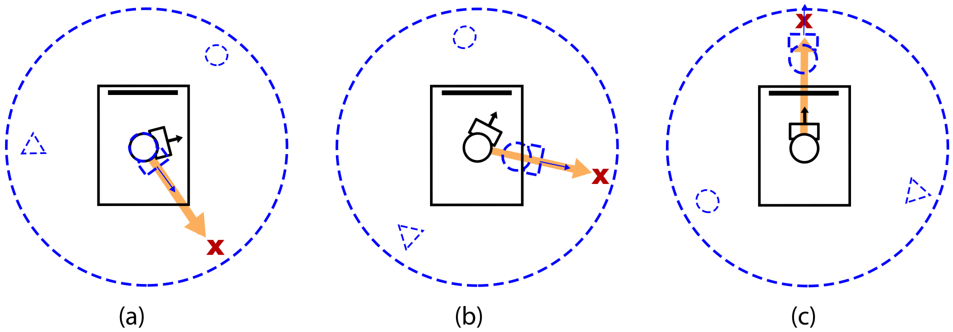

Figure 3: A top-down view demonstrating realignment during virtual travel. The black content represents the physical world and user, and the blue content represents the virtual world and user. The orange arrow shows the virtual path of travel. The images show three stages of travel progressing from left to right (in order: a, b, and c). By gradually rotating the virtual world as the user travels along the virtual path (orange arrow), the user is encouraged to rotate with the virtual rotation and ultimately faces the real-world forward direction (horizontal black line).

reduces it to zero as the user gets closer to virtual structures. To do this, the technique needs to be aware of the distance between the user and the nearest virtual structure along the user's direction of movement. This could be achieved by casting rays along the horizontal plane from the virtual camera to find the closest virtual structure and thereby its distance from the virtual camera. However, since we are studying this approach for the first time, we chose to test its general feasibility in more simplistic conditions with tighter control on the realignment. So, the implementation for our study maintains a set of known "areas of interest" (AOI) within the virtual environment that serve as potential destinations. As the user moves through the environment, the travel destination is dynamically selected based on the direction of virtual movement towards the closest AOI. The destination is selected by comparing the user's travel vector to the vectors from the user to nearby AOI. The AOI with the smallest angle between the travel vector and the AOI vector is selected. For example, Figure 3 shows the target highlighted in red is selected as the destination since it lies closer to the virtual gaze direction, and the direction of virtual movement indicated by the blue and orange arrows.

Once a destination is selected, the distance between the user's virtual position and the selected destination is input to the easing function to calculate rotational adjustment values. A Catmull-Rom spline [12] is used as the easing function in our implementation to calculate a smoothly interpolated value between 0 and 1 using:

$$i = 0.5 * (a + b * s + c * s^2 + d * s^3)$$

where s is the normalized proportion of distance covered by the user from the latest starting point towards the destination,

$$\begin{aligned} a &= 2 * p_1, \\ b &= p_2 - p_0, \\ c &= 2 * p_0 - 5 * p_1 + 4 * p_2 - p_3 \;\; and \\ d &= -p_0 + 3 * p_1 - 3 * p_2 + p_3, \end{aligned}$$

where p_0, p_1, p_2 and p_3 are the control points that form the spline. Our implementation used the values -1, 0, 1 and 0 for p_0, p_1, p_2 and p_3 respectively for the smooth interpolation. The input s varies from 0 to 1 based on the distance covered between the latest starting point and the midpoint between the starting point and the destination to get the i values that make the curve smoothly slope upwards (see Figure 4). Once the user crosses this mid-point, s varies from 1 to 0 based on the distance covered between the mid-point and the destination, making the curve smoothly slope downwards.

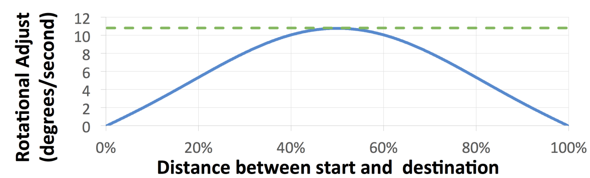

Figure 4: Guided rotation adds rotational adjustments following a spline based on the virtual distance between from the starting position (0%) to the target destination (100%). Our evaluation used a maximum adjustment of 10.8 degrees/second.

The interpolated values calculated using the above equations are still normalized and are multiplied by a maximum rotational adjustment value to get the rotational adjustment to be used for realignment. In the implementation for our study, this maximum value was 10.8 degrees per second. So, the magnitude of rotational adjustments starts at zero from the last stationary position, then gradually increases towards the maximum value at the midpoint between the previous starting point and the new destination, and then gradually reduces back to zero as the user approaches the predicted destination as shown in Figure 4. During the virtual travel, if the user changes the direction of movement and if the technique selects a new destination, the user's virtual position at the time of the destination change is treated as the new starting point for rotational adjustments to again start increasing from zero.

So, as the user travels virtually (e.g., by a technique such as joystick steering, walking in place, or leaning), redirection is achieved by gradually rotating the virtual world towards the physical forward direction so that the user slowly turns in the same direction to maintain focus towards the intended virtual direction. In doing so, their physical orientation is gradually eased towards the real-world forward direction. The rotational adjustments for redirection are calculated based on the direction of physical turning. For example, if the head is physically turned clockwise from the forward direction, the rotational adjustments would be applied to the virtual camera in the counter-clockwise direction. Figure 3 shows the relationship between real and virtual worlds using *guided head rotation*.

4 Evaluation

We conducted a controlled experiment with two high-level goals were: (1) to assess the general feasibility and usability of *amplified head rotation* and *guided rotation* for VR from a static seated position, and (2) to study whether the techniques affected spatial orientation as compared to a standard 360-degree baseline.

4.1 Hypotheses

Based on prior studies showing that low levels of rotational modification can go unnoticed (e.g., [5, 30]), we hypothesized that during seated VR experiences, amplified rotations or minor rotational adjustments might go unnoticed by some participants. To test overall feasibility and usability, we primarily sought subjective feedback related to perceived differences in the techniques for factors such as sickness, ease of use, and enjoyment. As the most natural and realistic technique, standard 360-degree rotation was expected to be preferred over the alternative techniques, and we expected *guided rotation* to be preferred over the *amplified head rotation* without head realignment during travel.

For our test of spatial orientation effects, we hypothesized that both *amplified head rotation* and *guided rotation* would negatively affect the ability to maintain spatial orientation when compared to standard 360-degree viewing with a rotating chair. Standard rotation was expected to be better, but was included for reference to study whether orientation errors would be higher with greater levels of rotational adjustment, which would mean *guided rotation* would have the worst orientation results.

4.2 Experimental Environment and Task

To address our research goals, we designed an experimental task that involved turning and moving to navigate through a grid of virtual rooms. The virtual environment was a 10x10 grid of large interconnected rooms with doorways to adjacent rooms. Figure 5 shows a screenshot of the environment from the application. All rooms were empty and identical, providing no additional landmarks or orientation cues. Rooms were square with lengths of approximately 33.2 meters. Participants started each trial from a room in the middle of the grid. Each trial had three components: initial path navigation, a pointing task, and return-to-start navigation.

First, for initial path navigation, participants had to travel through a sequence of rooms indicated by the appearance of blue guiding cubes that would appear in the centers of adjacent rooms. The guiding cubes would appear one at a time so that when the user reached a guiding cube, it would disappear and the next cube would appear in a neighboring room. Thus, upon reaching the location of a cube, participants first needed to turn around to find the next destination. The final room in the sequence was marked by a yellow disk in the center of the room instead of a cube.

Next, to assess spatial orientation after the initial navigation, participants were asked to perform an egocentric pointing task. For this task, participants were instructed to turn and face towards the room where they started the path navigation. Participants confirmed the direction by pushing a button on a hand-held game controller.

The last step was the return-to-start navigation task. Participants were asked to travel back to the first room where they started. No cubes or disks were visible during this task. While traveling back to the starting room, participants were not required to take the same route as original path. The experimenter explicitly explained that they could take any route back to the first room. When participants thought they were back at the starting room, they pushed a button to confirm completion.

For all trials, the navigation paths were taken from a predetermined set of 15 unique paths that were manually designed to require users to turn in different directions while traveling along the route. Path creation followed three simple constraints to ensure similar levels of path complexity and difficulty: (1) Each path is a sequence of seven rooms, which includes the starting and final rooms. (2) No three rooms in the path fall in a straight line, so the next room never appears directly in front of the user. This ensures that users always had to turn from the current travel direction to find the next destination. (3) Exactly one step of the path involves backtracking to the immediately prior room. In other words, at one stage of the path navigation task, users would have to rotate 180 degrees and return through the same doorway in which they entered the room. Each of the 15 trials used one of the 15 unique paths, but the order was chosen randomly for each participant.

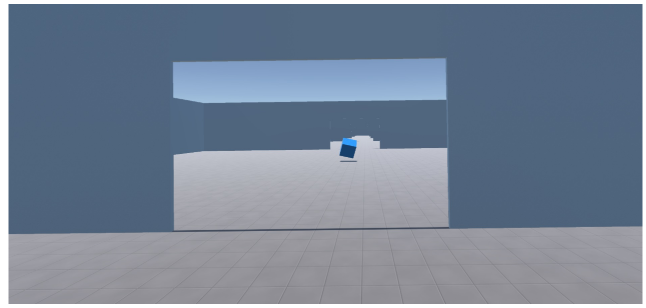

Figure 5: A screenshot from one of the virtual rooms of the experiment's application. The image shows a view while looking through a doorway into an adjacent room, where a blue guiding cube is visible.

4.3 Experimental Design

We conducted an experiment to evaluate the seated techniques for VR. We compared three techniques: *standard rotation*, *amplified head rotation*, and *guided rotation*.

The *standard rotation* technique was included as a baseline for reference, where traditional head-based rendering followed a one-to-one mapping between physical and real orientations. When using this technique, participants sat in a rotating chair with their feet on the floor, so they could freely spin to turn their bodies. This technique was chosen as a baseline condition allowing full physical rotation. This served as a reference for comparison with the other techniques designed to work without physical body rotation. The *amplified head rotation* and *guided rotation* techniques were implemented as previously described in section 3. We reiterate that the *guided rotation* technique also used the same type of amplified rotation as the *amplified head rotation* condition. In contrast to the *standard rotation* condition, participants used a non-rotating chair for the *amplified head rotation* and *guided rotation* conditions. This was done to limit body turning to approximate situations where 360-degree physical rotation is not preferred.

Positional head tracking was enabled for all three variations, but little positional head movement was required or observed during the study. An analog thumbstick on a game controller was used for virtual travel (translation only). The direction of virtual travel was mapped to the thumbstick direction, with the forward direction mapped to the direction of the user's gaze in the virtual world. The speed of virtual travel was mapped to the stick's analog input to a virtual rate of travel ranging from 0 meters per second to a maximum of 1.97 meters per second.

The experiment followed a within-subjects design. Each participant completed three sets of five trials—one set for each of the three viewing techniques—making a total of 15 task trials. The first trial in each set of five was considered a practice run to give participants the chance to adjust to the technique and the task. Technique order for the three sets was counterbalanced across participants with all combinations of orderings.

Participants were not explicitly informed about the different techniques, how they worked, or that trials were different. The experimenter required mandatory breaks (minimum of five minutes) after the sets of trials for the first two techniques. Participants were asked to stand up and walk around during breaks. The break requirement was enforced in an attempt to reduce the accumulation of any potential sickness effects and also so participants could have some time to reacclimate to normal real-world viewing before using the next technique.

Measures for the dependent variables included angular error from the pointing assessment (i.e., the difference in angle between the given direction and the actual vector towards the center of the starting room) and error from the return-to-start assessment (i.e., the number of rooms away from the starting room when the participant confirmed completion). We also collected subjective quantitative feedback about the techniques by asking participants to rate each technique in accordance to a number of metrics and prompts. Our priority for the subjective measures was to capture relative comparisons of techniques. For this reason, we opted for a post-study questionnaire after participants had completed all techniques rather than having participants answer questions after each trial block for each technique. The questionnaire included groups of questions related to: ease of travel and orientation, sickness, and entertainment. Each question asked participants to rate the three techniques with a whole-number 1–10 rating. We determined that a post-study questionnaire with an emphasis on relative comparisons was more appropriate for the within-subjects design than questions designed to elicit absolute ratings. This is also the rationale for why we opted against using standard questionnaires such as commonly-used presence questionnaires (e.g., [27, 36]) or sickness questionnaires (e.g., [13]).

4.4 Apparatus

The experiment was run in a lab using an Oculus Rift (consumer version 1) HMD. Six-degree-of-freedom head tracking was enabled using the Oculus Constellation tracking. The software was developed in Unity 5.3.6f1 and run on 64-bit Windows 7 Professional. The computer had a 3.6 Ghz Quad Core processor and a GeForce GTX 980 4GB graphics processing unit. The application ran with a frame rate ranging between 103 and 115 frames per second. Participants used a wireless Xbox One controller for additional input; an analog thumbstick was used for virtual travel, and buttons were used to confirm responses in the application.

4.5 Procedure

The study involved participants answering a background questionnaire, completing trials using the techniques, and finishing with an experience questionnaire. The research was approved by the organization's institutional review board (IRB).

At the beginning of the study, after providing consent, participants were asked to complete a background questionnaire with questions about information such as gender, age, education, occupation, average weekly gaming time, and prior experience with VR. Then, the experimenter explained the tasks with the aid of a paper printout showing a top-down view of a grid of rooms. It is important to note that the different techniques were not explained or discussed, and no preliminary familiarity session was provided to avoid additional time spent with any one technique.

Participants then completed the 15 trials in blocks of five for each technique. Each trial took approximately three minutes. Instructions for the stages of each trial (initial path navigation, pointing, and return-to-start navigation; see section 4.2) were conveyed verbally by the experimenter as well as through instructional text in the application. After the first and second trial blocks, participants were required to take the mandatory breaks.

After all trials, participants completed the post-study questionnaire and a brief interview. The entire procedure took approximately 60–75 minutes.

4.6 Participants

The experiment was completed by 24 participants (16 males and 8 females). All were university students with ages between 18 and 27. All participants had a good knowledge of computers and technology, and their self-reported average weekly computer usage was 45.5 hours. Aligning with our interest in studying techniques for home entertainment, we sought participants with a mix of gaming experiences. Many participants (13 of 24) reported regularly playing 3D video games for at least one hour a week, and median reported 3D gaming time was 10 hours a week. The participants reported mixed levels of experience with VR, and 13 (not the same exact 13 as in the gamer group) had previously experienced VR with HMD's before our study.

5 Results

Our evaluation uses standard 360 rotation as a reference condition to better understand how guided and amplified head rotation compare in situations that do not accommodate full physical turning (e.g., sitting on a couch). Quantitative results are shown graphically using standard box-and-whisker plots where the box represents the interquartile range (IQR) with a horizontal band for the median. Each whisker extends to the most extreme value falling within an additional half-IQR beyond the IQR (in both directions), and outlier dots show values outside this range. Note that the plots label the *guided rotation* condition as *guided+amplified* to again remind readers that the guided technique also included amplification.

We analyzed quantitative results from both the objective orientation tasks and the subjective responses. Despite the travel task requiring movement to six new rooms, participants performed surprisingly well on the orientation tasks. As a result, the metrics were not normal, so we used nonparametric Friedman tests for statistical analysis.

For the subjective ratings from the post-study questionnaire, we again opted for Friedman testing because of the ordinal natural of the rating data. Rather than testing every question individually, we conducted tests for groups of questions designed to capture metrics related to similar topics: ease of travel and orientation; sickness; and interest for home entertainment use. Since these groups were specifically chosen for targeted topics, we opted to treat the analysis of rating groups as planned analyses. Therefore, we present the results without multiple-comparison correction (e.g., Bonferroni adjustment). We also note that some individual questions asked about positive characteristics of the techniques (e.g., comfort, ease of use) while others asked about negative results (e.g., sickness, frustration). In grouping questions and analyzing results, we adjusted rating values so that a value of "1" always corresponds to negative ratings and a value of "10" always corresponds to positive values; in other words, higher ratings always mean "better" in the reported preference results.

5.1 Spatial Orientation Results

We analyzed the results of the pointing assessment and the return-to-start task as objective measures of spatial orientation from the experiment. The outcomes from trials for each technique block were averaged together (the first of the five trials was omitted, as this was considered as a familiarity trial for each technique). We tested for differences due to the three techniques with a Friedman test (a non-parametric repeated-measures test). The test found no significant effect for pointing error, though the effect was near significant with $\chi^2(2) = 4.75$ and $p = 0.09$.

For the results of the return-to-start task, errors were surprisingly low (see Figure 6), with the mean number of rooms away from the starting position ranging from 0.50 to 0.72 rooms for the techniques (standard deviations ranged from 0.71 to 1.00). A Friedman test found no evidence of technique differences, yielding $\chi^2(2) = 1.79$. The results for this orientation task generally indicate that participants could understand and remember their path of travel reasonably well for all techniques.

While the objective orientation tests for all participants did not generate conclusive evidence of detrimental effects of the *guided rotation* and *amplified head rotation* techniques, the subjective ratings are clear. Figure 7 shows the average ratings for the block

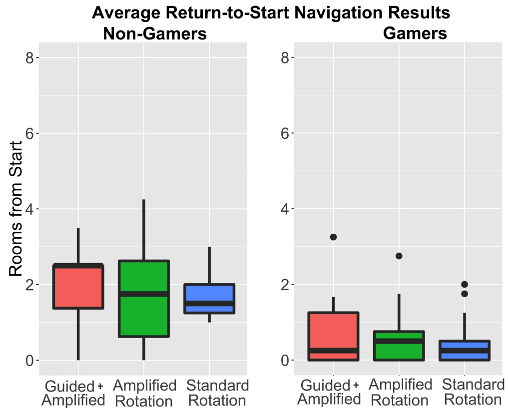

Figure 6: Average rooms away from the starting room after the return-to-start task. Higher values correspond to worse performance.

of questions relating to ease of travel and maintaining orientation. Participants felt the alternative techniques negatively affected their abilities to navigate and maintain orientation, with *guided rotation* received the worst ratings overall. A Friedman analysis found the effect to be significant with $\chi^2(2) = 10.53$ and $p = 0.005$. A posthoc Nemenyi test [17] detected a significant pairwise difference between *guided rotation* and *standard rotation* ($p = 0.007$).

Consideration for gaming experience provided additional insights. There was a clear correlation between reported weekly 3D gaming hours and results for the spatial orientation metrics. A Spearman correlation between gaming hours and pointing errors was significant with $\rho = 0.74$ and $p < 0.001$, as was the correlation for return-to-start errors, with $\rho = 0.76$ and $p < 0.001$.

Observing such strong correlations, we reanalyzed the effects of the techniques after separating the gamers (13 participants) and non-gamers (11 participants). The interaction with the techniques was clear for the pointing results. A Friedman test for the gamers detected a significant effect for pointing errors, with $\chi^2(2) = 6.00$ and $p = 0.046$, and a posthoc Nemenyi test found a significant pairwise effect between *guided rotation* and *standard rotation* ($p = 0.049$). Errors are notably worse with the *guided rotation* technique. The test for the non-gamers found no evidence of a difference, with $\chi^2(2) = 0.55$. Figure 8 shows the pointing results. The absence of effect for the non-gamers is likely explained by their higher overall error rates, which were much higher than the gamer group regardless of condition. Compared to the pointing error for the gamers ($M = 21.98$, $SD = 17.37$), the non-gamer group had more than twice as much error ($M = 46.52$, $SD = 18.07$). It should be noted, however, that even the average pointing error for the non-gamers was significantly better than what would be expected due to chance (90 degrees).

For the return-to-start results, no significant effects from technique were detected for either gamer or non-gamer groups.

5.2 Sickness Results

A set of questions about nausea, headache, and dizziness were grouped together as sickness ratings. The responses for sickness ratings from all participants are shown in Figure 9, which shows non gamers having more sickness problems with the techniques involving more view manipulations, with *guided rotation* having the most negative responses. No effect was found for gamers ($\chi^2(2) = 0.19$), but the Friedman test for the non-gamers showed a significant effect with $\chi^2(2) = 10.21$ and $p = 0.006$, with the posthoc Nemenyi showing *guided rotation* to be significantly worse than *standard rotation* ($p = 0.008$). This suggests that those with

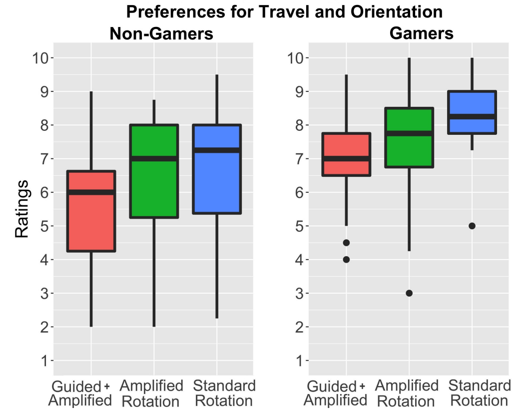

Figure 7: The ratings for the block of post-study questions relating to ease of travel and orientation.

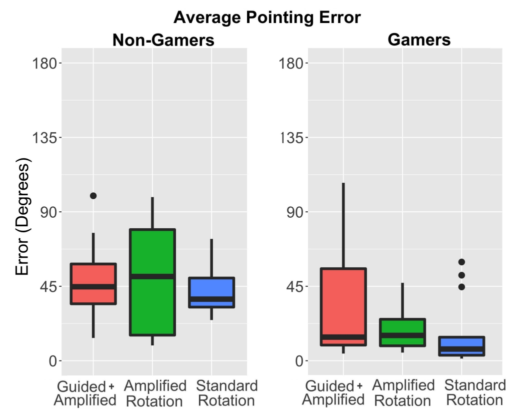

Figure 8: The absolute pointing errors for the techniques grouped by self-reported 3D gaming. Note the low median errors for the gamers.

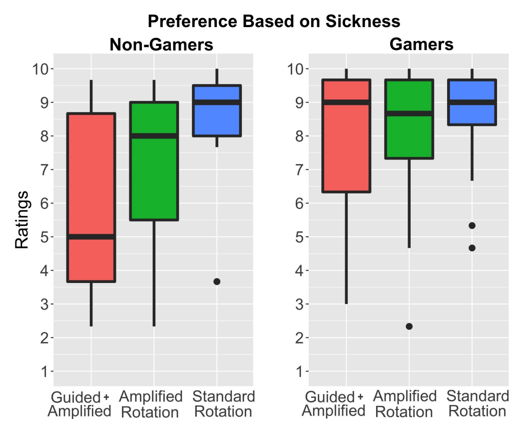

Figure 9: Technique ratings based on sickness. Higher values indicate lower perceived sickness.

more experience with 3D games may have higher tolerance for redirection and amplification techniques when it comes to sickness.

5.3 Preferences for Home Entertainment

A set of questions asked participants to rate the techniques based on how much fun they were, how much participants might be interested in using the techniques for home entertainment, how comfort-

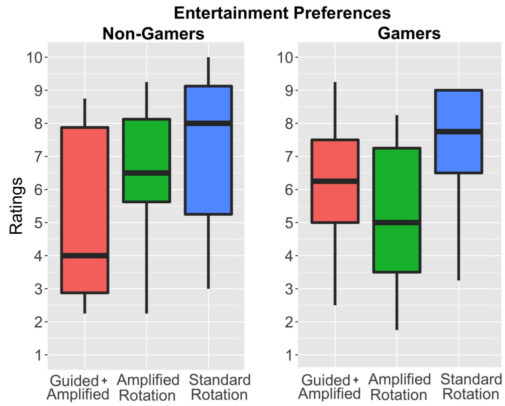

Figure 10: Ratings based on fun, comfort, and interest for home entertainment. Standard 360-degree rotation was preferred best.

able they were, and how much frustration was involved. The Friedman test found a significant effect with $\chi^2(2) = 8.27$ and $p = 0.016$. The posthoc Nemenyi showed *standard rotation* to be significantly preferred ($p = 0.025$) over guided rotation techniques—which is not surprising given the superior realism of the reference condition.

After separating gamers and non-gamers, the test with non-gamers yielded similar results with *standard rotation* as the most preferred technique. Figure 10 show the results separated by gamers and non-gamers. For non-gamers, *guided rotation* was rated last, though the main effect was not quite significant, with $\chi^2(2) = 5.71$ and $p = 0.058$. The effect was significant for gamers, with $\chi^2(2) = 6.00$ and $p = 0.049$, but with a different ordering of preferences. While *standard rotation* was still the most preferred technique for the gaming group, more gamers rated *guided rotation* over *amplified head rotation* (see Figure 10). The posthoc Nemenyi showed *amplified head rotation* was rated significantly worse than *standard rotation* ($p = 0.049$).

5.4 Qualitative Feedback

Participants provided comments as part of the post-study questionnaire and interview. The most common feedback was that the *standard rotation* version was the most natural and comfortable version. It was clear that this was the most preferred of the three versions tested. However, four out of the 24 participants reported feeling lost in the environment with *standard rotation*. They reported that compared to the other two versions, so much physical turning with *standard rotation* caused them to forget the room they just came out of. One participant reported having worse dizziness with *standard rotation*.

Regarding the *amplified head rotation* conditions, most participants reported feeling stress around the neck due to extreme turns and that it made them uncomfortable. Interestingly, three participants felt that the *amplified head rotation* version made it easier to remember paths, but it was not clear why. The following are a few representative quotes about the *amplified head rotation* technique:

> "I wouldn't play a game with this version. There was much strain in the neck. Felt disoriented."

> "It was slightly easier to keep track of your orientation, but it put too much strain on the neck."

> "Turning my head was annoying."

The *guided rotation* technique received the most complaints relating to sickness; 18 participants reported some level of nausea or dizziness with the technique. Only three participants did not recognize being redirected to their physical forward direction in the *guided rotation* trials (these three participants were non-gamers). Few participants felt that the redirection made them lose track of their path. A few representative quotes from participants about *guided rotation* include:

> "I like this since I don't have to turn too much, like with the spinning chair. The spinning chair also made it difficult to remember the path. The adjustment is slow enough to not make me dizzy."

> "It makes me dizzy since it rotates me against my will."

> "I have less control with this one. I didn't like it forcing me to rotate."

6 Discussion

Semi-natural seated viewing techniques retain some degree of interaction realism while sacrificing the overall fidelity for convenience. The results of the experiment reveal a great deal about the ability to maintain spatial orientation during virtual travel as well as about subjective responses and perception of the three seated techniques.

6.1 Naturalness and Navigation

On one hand, the results of the study did show that the *amplified head rotation* and *guided rotation* techniques can work for their intended purpose of seated travel. Despite the fact that no explicit instructions or explanations about the techniques were given, participants could successfully navigate the virtual environment while performing a task that involved a large amount of rotation and movement. For all techniques, the relatively low amounts of error for the return-to-start task and the pointing task suggest that participants were reasonably able to use the techniques to effectively navigate while maintaining a general sense of their movement through the virtual space. Our observations and the participants' feedback made it clear that all participants easily understood how to use the techniques, which serves as some degree of verification for the "naturalness" of the three techniques.

However, the rating results about relative preference and ease for travel and orientation clearly indicate that the techniques were not perceived as equally natural. As expected, *standard rotation*, the reference technique with 360-degree physical rotation, was the favorite for most participants, and the results allow us to better understand tradeoffs for alternatives that do not require full physical rotation. As hypothesized, noticeable drawbacks came along with the "convenience" of reduced movement required for the semi-natural techniques. The results of the pointing task did indicate penalties to spatial orientation for the 3D gamers. As seen in Figure 8, average errors on the pointing task were slightly worse with *amplified head rotation* as compared to the *standard rotation* baseline, but much more substantial errors were attributed to the *guided rotation* technique. Though these differences were only significant for the gamer participants, this was mostly likely because the non-gamers had so much more error across the board that the experiment lacked the sensitivity to assess the impact of the techniques for that group.

6.2 Implications for Home Entertainment

The difference in effects for the gamer and non-gamer groups is important when considering implications for use of semi-natural techniques for home entertainment. If most interested in understanding the effects of using VR at home, then the results from the 3D gamers would presumably be most relevant since the gamers would be more representative of the target population. On the other hand, an alternative perspective is that because gamers are more experienced with 3D navigation, they might be more sensitive to alterations to the interaction techniques. Active gamers might always greatly prefer the highest level of fidelity available, and any negative effects on navigation or spatial understanding would impact them more meaningfully. Although, with this in mind, it was somewhat surprising to see that some gamers expressed more interest in *guided rotation* than amplified rotation (see Figure 10). This result might be partly due to the redirection being viewed as more fun due to its novelty, but we cannot conclude for certain.

Considering the non-gamers, if they are less concerned with performance and precise control, then semi-natural techniques could be more appropriate for the less-frequent or casual users. This idea is partially supported by the lack of a significant effect on spatial orientation for the non-gamers, as well as by the few non-gamer participants who did not even notice a difference among the techniques. However, the preference ratings do not support the notion that semi-natural techniques would be wanted by most non-gamers (see Figure 10).

Regardless of gaming habits, sickness effects are a clear drawback to using view adjustments. Redirection and rotation amplification involve unnatural matching of visual, proprioceptive, and vestibular cues, and greater modification clearly caused greater discomfort. This would probably be the greatest deterrent against adopting semi-natural VR for home entertainment. If the primary goal is entertainment, enjoyment, or relaxation, users are unlikely to be willing to put up with unnecessary sickness side effects. However, because the rating method used in the study prioritize relative comparison rather than absolute measurement, the results are limited in their ability to describe the extent of the sickness effects. Judging by our observations and participant feedback, sickness symptoms were relatively mild (at least compared to our experiences running demos and studies with older systems), and no participants needed to end participation due to discomfort.

6.3 Limitations

This section discusses specific limitations of the presented work and open opportunities for future research.

6.3.1 Technique Limitations

The *amplified head rotation* and *guided rotation* techniques are not without their limitations. Perhaps the greatest limitation is that *amplified head rotation* in a static (non-spinning) chair does not allow continuous rotation in the same direction. While it is designed to make it easy for the user to turn around 180 degrees (matching 90 degrees physically), continuing to turn beyond that point would be uncomfortable with a non-rotating chair unless the amplification factor was greatly increased.

Concerning *guided rotation*, the requirement for predetermined AOIs in the environment is a major limitation. While it could be possible to predict arbitrary destinations for realignment based on travel direction and gaze, we did not implement or evaluate such methods in this work, and the technique would not be expected to work well in situations requiring fine maneuvering or frequent destination changes. The effectiveness and comfort of *guided rotation* will depend on the distance of the virtual user's location from the predicted target destination for redirection. As such, we note that the size of the rooms used in our experiment were very large—large enough to allow gradual redirection during travel. Naturally, realigning the view while traveling shorter distances would require faster and more harsh rotational adjustments. Similarly, the virtual travel speed was relatively slow for the size of the space, though the speed used in the study (7.1 km/hour) is somewhat fast when compared to the speed of casual real-world walking.

6.3.2 Evaluation Limitations

Using *standard rotation* as a baseline, our experiment provides a comparison of two semi-natural viewing techniques for travel and view control in constrained seated situations where full 360-degree physical rotation is not ideal. Though the amount of time spent performing the navigation task with each technique was sufficient for addressing our hypotheses, we note that because of the repeated measures design, participants experienced all three techniques within a single session. This meant that experience with any given technique was limited (approximately 15 minutes). It would be interesting to study extended use of different semi-natural techniques, as it could be that users become better acclimated and comfortable with semi-natural techniques after longer periods of use. Stanney and Kennedy [28], for instance, explained that sickness effects can diminish over time as users become more accustomed to VR. Alternatively, it could be the case that frustration or sickness would accumulate and worsen over time with the semi-natural techniques. We cannot know for sure without additional research, as there are many factors that can influence sickness in VR [14],

Our study also did not account for variations in the level of amplification factor for amplified rotation or the gain factor for redirection. While we chose parameters for our tested techniques based on the work of others and our own pilot studies, the results of the comparison could change with different implementations. For example, the common complaints about neck strain with the *amplified head rotation* technique suggest that the technique may have worked better with a larger amplification factor, though it is also possible that great amplification could have further influenced sickness or spatial orientation. Our experiment also did not test different configurations of the environment or multiple travel speeds. The specific navigation task is another possible limitation, as it may have been too easy for some participants—particularly the gamers (see Figure 8). Further work remains to better understand practical implications of semi-natural techniques in a broader variety of environmental and navigational contexts.

Another consideration is whether results would be different for the guided rotation and amplified rotation techniques if a static chair had not been used. Since the chair did not rotate, it is likely that the chair served as a reference that may have helped with orientation, which would have contributed to the relatively low orientation errors. Thus, the results of this study do not generalize to versions of the techniques where full physical rotation is allowed (though such techniques would not be needed in such cases).

Additionally, we again mention that because the post-study questionnaire asked participants to provide ratings for the three techniques together, the ratings are more appropriate as relative comparisons rather than absolute measurements. While this design was intentionally chosen and worked well for the purposes of the study presented in this paper, more absolute and objective measures may be preferred for some metrics. In particular, we are interested in better understanding the severity of perceived sickness.

7 Conclusions and Future Work

Our research explores semi-natural viewing techniques that work for seated use of VR with HMDs when physically turning all the way around is not ideal, such as when sitting on a couch or at a desk. *Amplified head rotation* makes it possible to physically turn within a limited range to view a 360-degree virtual range. Additionally, to avoid situations where the user's neck is turned in an uncomfortable position for an extended period, *guided head rotation* uses amplified rotation but also gradually realigns the user's head position back to the straight-ahead direction over time.

Our evaluation found that the techniques worked as intended for seated navigation. However, the results clearly demonstrate negative side effects of the semi-natural techniques for outcomes such as spatial orientation, sickness, and overall usability when compared to standard 360-rotation with one-to-one head tracking. The effects varied for 3D gamer and non-gamer participants.

Overall, the study provides insights about practical implications of using semi-natural travel techniques for basic navigation in VR. To better understand whether techniques such as *guided head rotation* and *amplified head rotation* would be appropriate and effective for home entertainment VR use, more work is needed to understand how the techniques affect a broader range of virtual tasks and scenarios. Future work should also compare a wider variety of techniques suitable for constrained seated VR. For example, it would be interesting to study preferences and tradeoffs for other techniques such as full joystick-controlled rotation, teleportation/transitions, leaning, and other variations that continuously realign the head direction regardless of virtual travel (similar to washout filters).

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