EVALUATING SEMI-NATURAL TRAVEL AND VIEWING TECHNIQUES IN VIRTUAL REALITY

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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May 2018

Major Subject: Visualization

ABSTRACT

With seated virtual reality (VR), the use cases based on seating conditions need to be considered while designing the travel and viewing techniques. The most natural method in seated VR, for viewing interactions is the standard 360-degree rotation, for which a swivel chair that spins around the vertical axis is commonly used. However, the VR users will not have the affordances of a swivel chair or the physical space to turn around, all the time. This limits their VR usage based on the availability of certain physical setups. Moreover, for prolonged usage, users might prefer to have convenient viewing interactions by sitting on a couch, not rotating physically all the way around. Our research addresses these scenarios by studying new and existing semi-natural travel and viewing techniques that can be used when full 360-degree rotation is not feasible or is not preferred. Two new techniques, *guided head rotation* and *user-controlled resetting* were developed and were compared with existing techniques in three controlled experiments. Standard 360-degree rotation and three joystick-control based viewing techniques (*discrete rotation*, *continuous rotation* and continuous rotation with *reduced fov*) were the existing techniques compared in our experiments. Since the new techniques and some of the existing techniques involve some rotation manipulations that are not natural, they could disorient the users during a virtual experience. So, two VR puzzle games were designed to study the effects of the techniques on spatial awareness of the users. Convenience, simulator sickness, comfort and preferences for home entertainment were the other factors investigated in the experiments. From the experiments, we found out that the results were based on 3D gaming experience of the participants. Participants who played 3D games one or more hours per week had higher tolerance towards the new techniques that had rotational manipulations compared to the participants who did not play any 3D game. Among the joystick rotation techniques, *discrete rotation* was rated the best by users in terms of simulator sickness. In addition to these experiments, we also present a case study that demonstrates the application of *guided head rotation* in an experiment that studied natural hand interaction with virtual objects under constrained physical conditions.

ACKNOWLEDGMENTS

I would like to sincerely thank my thesis committee chair Dr. Eric D. Ragan for the guidance, support and motivation. Thanks for all the timely feedback and follow-ups. They kept me on track throughout my graduate program. I would also like to thank my committee co-chair Dr. Ergun Akleman and committee member Dr. Eric Jing Du for the guidance and support.

Next, I would like to thank my family for the continuous support and letting me pursue my passion all these years. Thank you for believing in me and my decisions. I feel grateful for being able to follow my dreams.

Finally, I would like to thank my friends and faculty members in the Department of Visualization for providing me with vast knowledge in computer graphics and human computer interaction that helped me complete my thesis work.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supported by my thesis committee consisting of Dr. Eric D. Ragan and Dr. Ergun Akleman of the Department of Visualization and Dr. Eric Jing Du of the Department of Construction Science. All work conducted for the thesis was completed by the student independently.

Funding Sources

The research carried out as part of this thesis, was not funded by any external or internal funding sources.

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1. INTRODUCTION

Virtual reality (VR) can be considered as an attempt to digitally simulate real world environments and to enable realistic interactions with virtual environments (VE). The level of realism offered by a VR system in terms of interaction fidelity is determined by how natural the interactions with the VE are. Because of real world constraints and technical limitations, simulating fully natural interactions is not always possible. In such cases, semi-natural approaches are used to complete the same interactions with few compromises. Our work focuses on studying such semi-natural techniques for travel and viewing in VR that could be convenient to use, compared with the natural, straight forward approaches. Our research mainly consists of the design and evaluation of semi-natural travel and viewing techniques. Three controlled experiments and a case study were completed and their results are presented. The first experiment [1] compared *guided head rotation* and *head rotation amplification* with standard 360-degree rotation. In the second experiment [2], we investigated three existing techniques that work based on joystick control: *discrete rotation*, *continuous rotation* and continuous rotation with *reduced field of view(FOV)*. In the third experiment two new viewing techniques: *user-controlled resetting* and *user-controlled resetting with amplification* were compared with the best joystick rotation technique (*discrete rotation*) from second experiment. All these travel and viewing techniques involve virtual rotation manipulation of some kind which could disorient users during a VR experience. So, to better understand the techniques and their effects on users, we tested the spatial awareness of users over time when each of these techniques is employed in the three experiments. The case study [3, 4] focused on natural hand interactions with passive haptics at multiple virtual locations, supported by the travel techniques: *guided head rotation*, *head rotation amplification* and *resetting*.

1.1 Motivation

Because of the recent advancements in VR technology, the head mounted displays (HMDs) and tracking equipment are gradually becoming more accessible. Many interactive applications, games and 360-degree experiences that use VR are being developed for mediums such as smart phones, gaming consoles and personal computers. Other than entertainment, VR is also used in important disciplines like education, scientific visualization, military training, architectural walk-through, etc., impacting a wide range of people. Researchers around the world have been studying several interaction techniques that could work well for different interaction scenarios involving VR thereby adding useful statistical and qualitative evidence about usability, user-preference, efficiency and other factors related to these techniques. Such evidence can help the VR application designers choose the best of all the available approaches, suitable to the use cases. Our research idea focuses on such interaction techniques that could potentially improve travel related interaction situations in VR.

Users have reported highest subjective sense of presence with physical walking in VR [5], where users travel in a VE by walking in real world, being able to turn freely around the three different axes. However, to support physical walking, vast tracked space is required and there are other complications like handling or avoiding real world collisions, etc., In conditions where physical walking is not practical or where a relaxed VR experience is preferred, seated VR is used, with a swivel chair where users can turn around the three axes to view desired sections of the virtual world by spinning the chair. A game controller is used to control the virtual travel in such cases. However, there are situations where a swivel chair could not be used or might not be preferred. For example, a user might want to have a more relaxed VR experience by lying down on a couch. Or, a user might want to always face in the same direction towards certain physical objects such as a keyboard, a mouse, etc., in the real world to maintain the ease of interacting with them throughout an experience. Or, a user might want to experience VR in commute. For example, during a flight where swivel chairs are not available. In these cases, users could not conveniently turn beyond 90 degrees in the same direction around the vertical axis. Our work studies semi-natural techniques that enable 360-degree viewing and free travel in virtual world in the above mentioned scenarios.

1.2 Objective

Our objective is to develop new semi-natural travel and viewing techniques for seated VR users and study them in comparison with existing techniques to gather empirical data in terms of usability, user-preference, efficiency, etc. Our research aims to address the following research questions:

- How should we design new semi-natural travel and viewing techniques in VR for constrained seating conditions?
- How do users understand and perform with the new semi-natural approaches compared to regular, full physical 360-degree viewing or joystick controlled viewing techniques?
- How do the techniques affect the spatial awareness of the users?
- How do the techniques affect the simulator sickness experienced by the users?
- Comparatively, which technique is preferred by the users for home entertainment?

To answer these questions, we designed semi-natural techniques and tested our implementations with users through three controlled experiments and a case study. The conditions in the consecutive experiments are either newly designed or are modified versions of prior techniques based on the results from the previous experiments. In this thesis, we present the implementation details of the techniques, describe the conducted experiments, discuss the results and their implications for future work.

2. RELATED WORK

Our research builds on prior research about travel and navigation in VR.

2.1 Semi-Natural Travel in VR

Our research investigates the techniques for seated VR usage where the user's physical position is constrained by the location of the chair. Researchers have explored many alternative techniques for similar situations where physical walking is not practical or not preferred. Some examples include: *walking in place* (e.g., [5, 6]) or *leaning metaphor* (e.g., [7, 8]). However, the common approaches being used in applications for virtual travel in such scenarios are *steering* (or *flying*) (e.g., [9, 10]) or *teleportation* (e.g., [11, 12]) using a hand-held controller. *Teleportation* disorients the users while moving from one place to another and it doesn't let the users gather information from VE while traveling, since the positional changes are discrete and instantaneous [10]. Since we focus on studying spatial awareness of users in our research, we avoided *teleportation* and used ground constrained *steering* instead.

2.2 Amplified Head Rotation

In VR, a user's real world head rotation is usually tracked and applied to the virtual camera without any modification to support 360 degree viewing of the VE. However, in some cases, the tracked head rotations are modified before being applied to virtual camera to let the users view large segments of a VE with smaller turns in the real world. This technique, called head rotation amplification has been studied in the past for various purposes (e.g., [13–15]). For example, Ngoc et al. [15] studied the effects of head rotation amplification in a flight training simulator where a single display was used to support a wide view of the cockpit, replacing the conventional setup of three displays. In our research, head rotation amplification is used along with *guided rotation* and *user-controlled resetting* in the first and third experiment respectively, to maximize the virtual viewing range.

2.3 Redirection and Reorientation

Redirected walking is a travel method used in VR to maximize the use of a limited tracking space to explore larger virtual environments with physical walking. The main objective of *redirected walking* is to redirect users away from physical bounds as they walk in real world. It was introduced by Razzaque et al. in 2001 [16] and has since been studied by many researchers. The techniques proposed by these researchers make use of perceptual illusion to achieve redirection. They exploit users' inability to notice minor rotational changes applied to virtual camera thereby making users to walk along curved path when they actually think they are walking straight towards certain targets in the VE. Our technique, *guided head rotation*, applies minor rotational adjustments to the virtual camera to realign a seated VR user's head to a physical forward direction as they move through a virtual environment using a game controller.

A related concept is the use of washout filters used in motion simulators to move the simulation platform to simulate linear acceleration and angular banks [17]. The washout filters perform the required positional and rotational changes to the simulation platform while allowing the motion simulator to remain within its physical bounds [17–19]. Once there's been a change in virtual acceleration, the physical changes are applied to the platform to simulate the corresponding vestibular sense. But these changes are gradually nullified and the platform is brought back to neutral orientation or close to neutral orientation over time.

Our research also incorporates *resetting*—another common technique that has been traditionally used to enable real-world walking. Usually, the VR experiences that allow users to walk physically, require the users to reorient themselves in the real world at some point during the experience to avoid colliding with physical objects or leaving the bounds of the tracked space For example, Williams et al. [20] studied variations of *resetting* techniques with real-world walking using HMDs, but they did not study resetting for experiences involving only physical rotation, as in seated VR.

Though the main objective of *redirected walking* techniques [16, 21, 22] is to redirect users away from physical collisions, they are not successful all the time. There are cases where redirected techniques fail and users have to reorient themselves anyway with the help of reorientation techniques. Peck et al. [23] studied the use of visual distractors (e.g., a flying bird or floating object) to reorient users whenever physical bounds are reached. The researchers found that users preferred visual distractors over audio instructions for reorientation. Our research explores other methods for coordinating rotational adjustments, though we do provide explicit visual cues after resetting transitions in our study.

2.4 Joystick Control for View Rotation

Many other studies have included joystick rotation as part of their research. For example, Chance et al. [24] compared physical rotation with *visual turning* in which the virtual camera is rotated based on the joystick input. Riecke et al. [7] 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. The most common problem being simulator sickness. As one approach to address this, researchers have considered limiting the FOV to reduce simulator sickness (eg., [25,26]). For example, Fernandes et al. [27] studied subtle and dynamic FOV reduction for reducing sickness during virtual travel. Despite the prior research involving travel techniques and joystick control, research specifically focusing on comparisons of different joystick-based travel techniques is limited.

3. RESEARCH OVERVIEW

Our research aims to answer the questions mentioned in section 1.2 regarding the new and existing semi-natural travel and viewing techniques. As such, it mainly involved design and evaluation of these techniques. Since most of the techniques we studied in our research involve rotation manipulation, we were interested in studying the spatial awareness of the users when these techniques are employed. We were also interested in investigating the simulator sickness and comfort level associated with these techniques. To understand these aspects of the techniques, we ran two controlled experiments and a case study. The first experiment [1] compared *guided head rotation* and *dynamic head rotation amplification* with standard 360-degree rotation. The second experiment [2] compared existing joystick-control based viewing techniques: *continuous rotation*, *discrete rotation* and continuous rotation with *reduced FOV*. Whereas, the third experiment compared the resetting based techniques: *user-controlled resetting* and *user-controlled resetting with amplification* with the best joystick technique, *discrete rotation*. In the case study [3, 4], *guided head rotation* and a *resetting* technique were applied for travel and viewing purposes in an experiment that focused on natural hand interaction with multiple virtual objects, with haptics provided by a single physical prop.

3.1 Technique Design and Implementation

The research involved prototyping new and existing techniques for the experiments. *Guided head rotation* and *user-controlled resetting* were developed as alternatives to existing semi-natural travel and viewing techniques.

1. *Guided Head Rotation* is a composite technique which has an amplification component and a realignment component. The technique was mainly designed to enable 360-degree view of VE's with lesser physical turns. *Dynamic head rotation amplification* is used to maximize the virtual viewing range and smoothly interpolated rotational adjustments are applied to the virtual camera to gradually reorient a user when the physical head orientation is offset from

a neutral forward direction.

2. *User-Controlled Resetting* is a straight forward technique that can be used to reorient users physically during virtual travel or viewing. Upon user input, the virtual world is rotated instantaneously so that a desired section of the VE is along the neutral forward direction of the user, when seated. This technique was developed as an alternative to *guided head rotation*, avoiding gradual rotational adjustments.

The other existing techniques that were implemented in our research were the commonly used joystick-control based techniques: *continuous rotation*, *discrete rotation* and continuous rotation with *reduced FOV*.

3.2 Experiment 1

The first experiment focused on studying the new techniques *guided head rotation* and *dynamic head rotation amplification*. They were compared with standard 360-degree rotation which was the base-line condition. A VR puzzle game was developed to test the techniques. The task for the users in the VE involved (1) travel, (2) egocentric pointing and (3) return-to-start subtasks. Based on the experience, the users were asked to complete a post-study experience questionnaire which had questions about naturalness, simulator sickness experienced, comfort, home entertainment preference, etc.

3.3 Case Study

The main focus of the case study was on studying natural hand interaction with multiple virtual objects supported by a single physical prop that provides passive haptics. *Guided head rotation* and *resetting* were used in this study for travel and viewing. *Guided head rotation* was used in one of the three conditions tested, to support virtual travel without introducing any break in presence and to make a user always face towards the physical prop for future interactions. *Resetting* was tested as a separate condition to redirect users towards physical prop with instant transitions, thereby introducing momentary interruptions during a virtual experience.

3.4 Experiment 2

The second experiment investigated three existing joystick-control based rotation techniques. The VR puzzle game from the first experiment was modified and 3D landmarks were added to avoid dis-orientation caused by the interruptions experienced while using the techniques. The task for the users in the VE involved (1) travel, (2) egocentric pointing and (3) exocentric plotting. Similar to the first experiment, the users were asked to complete a post-study experience questionnaire which had questions about naturalness, sickness experienced, comfort, home entertainment preference, etc.

3.5 Experiment 3

The third experiment compared the new techniques *user-controlled resetting* and *user-controlled resetting with amplification* with the best joystick rotation technique from second experiment (*discrete rotation*). The same VR puzzle game from the second experiment was used to test the techniques but the path complexity was increased. The task for the users in the VE were same as the second experiment: (1) travel, (2) egocentric pointing and (3) exocentric plotting. Similar to the first two experiments, the users were asked to complete a post-study experience questionnaire which had questions about naturalness, sickness experienced, comfort, home entertainment preference, etc.

4. TECHNIQUES*†

4.1 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. As previously mentioned, this type of technique has been explored and studied by others using various different implementations, displays, and amplification factors (e.g., [13, 15, 28, 29]). We used two different amplification factors in our research. In the first experiment we used a dynamic amplification factor that scales based on physical head orientation. Whereas, we used a constant amplification factor in the third experiment with *user-controlled resetting*.

4.1.1 Dynamic Amplification

Figure 4.1 shows the basic concept of dynamic head rotation amplification. The amplification factor increases or decreases in value based on the physical head orientation. To do this, our implementation assumes a real-world scenario with a preferred forward direction, such as what one 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

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[*] Part of this chapter is reprinted with permission from "Guided head rotation and amplified head rotation: Evaluating semi-natural travel and viewing techniques in virtual reality" by Authors' Shyam Prathish Sargunam, Kasra Rahimi Moghadam, Mohamed Suhail, and Eric D. Ragan, 2017. Proceedings of the IEEE Virtual Reality Conference, pp. 19-28, Copyright [2017] by IEEE.

[†] Part of this chapter is reprinted with permission from "Evaluating joystick control for view rotation in virtual reality with continuous turning, discrete turning, and field-of-view reduction" by Authors' Shyam Prathish Sargunam, and Eric D. Ragan, 2018. Proceedings of the 3rd International Workshop on Interactive and Spatial Computing, pp. 74-79, Copyright [2018] by ACM.

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.

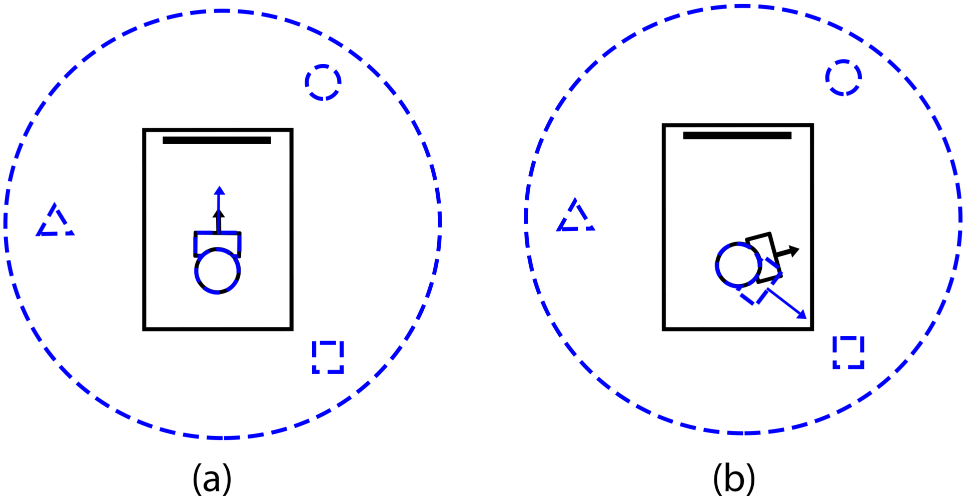

Figure 4.1: A top-down diagram demonstrating *amplified head rotation* [1]. The physical world and user's head are shown in black. The virtual world and viewing direction are shown in blue. When the user physically rotates away from the real-world forward direction, the virtual view will have an amplified rotation based on the amplification factor.

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 4.2 shows the real world HMD angles and the corresponding virtual camera angles calculated using the above formulas.

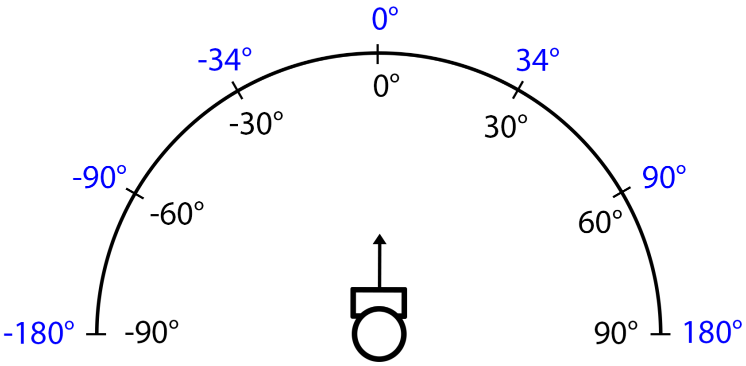

Figure 4.2: A top-down diagram demonstrating the real world and virtual yaw during *amplified head rotation* [1]. The physical yaw angle is shown in black and the virtual angle is in blue. The black arrow represents the physical forward direction. Note that the amplification factor would continue to increase for physical rotation beyond 90 degrees, but this is not common in a stationary seated position.

4.1.2 Constant Amplification

With the constant amplification used in our third experiment, the amplification factor was always a constant and was not affected by the physical head orientation. In our research, we used a constant amplification factor, a = 2. So, for example, a 90 degree turn in real world would result in a 180 degree turn in the virtual world and a 20 degree turn in real world would result in a 40 degree turn in the virtual world.

4.2 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 another semi-natural technique for seated viewing and travel. We call this technique *guided rotation*. The technique uses the same implementation of *dynamic head rotation amplification* 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., [18, 19]), redirected walking (e.g., [16,30]), and redirected walking-in-place implementations [6]. 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 *dynamic head rotation amplification* 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.

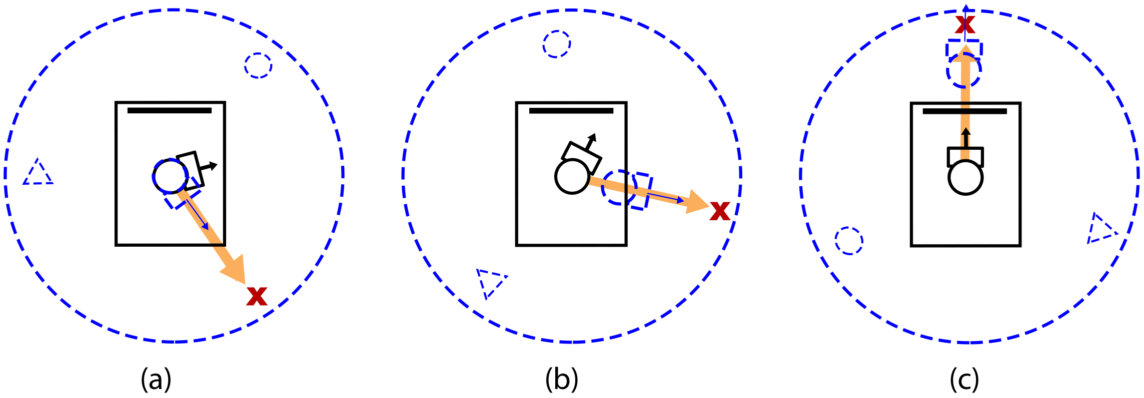

Figure 4.3: A top-down view demonstrating realignment during virtual travel [1]. The black content represents the physical world and user, and the blue content represents the virtual world and user. The orange arrow shows the virtual path of travel. The images show three stages of travel progressing 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).

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, so that the rotational adjustment value is gradually increased to a maximum as the user starts moving and gradually reduced 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 4.3 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 [31] 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,

$$a = 2 * p_1,$$

$$b = p_2 - p_0,$$

$$c = 2 * p_0 - 5 * p_1 + 4 * p_2 - p_3 \ \ and$$

$$d = -p_0 + 3 * p_1 - 3 * p_2 + p_3,$$

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 4.4). Once the user crosses mid-point, s varies from 1 to 0 based on the distance covered between the mid-point and the destination, making the curve slope downwards.

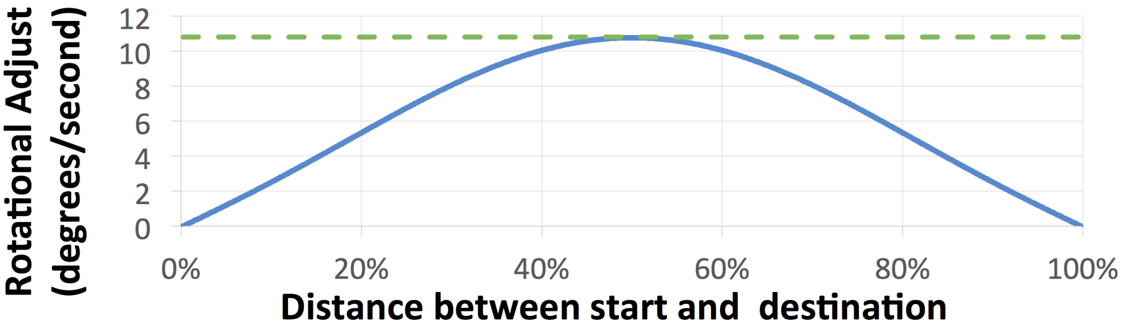

Figure 4.4: Diagram showing the spline followed by *guided rotation* to add rotational adjustments based on the virtual distance from the starting position (0%) to the target destination (100%). Our evaluation used a maximum adjustment of 10.8 degrees/second [1].

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 4.4. 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 4.3 shows the relationship between real and virtual worlds using *guided head rotation*.

4.3 Resetting techniques

Resetting is a straight forward method used to reorient users during a virtual experience. Whenever physical reorientation is required, discrete rotation is applied to the virtual camera through a fade-to-black transition effect. 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., [20, 23]).

With the *user-controlled resetting* technique studied in our research, *resetting* is used to add convenience to users during natural head-tracked viewing under physically constrained seating conditions. With this technique, users would be able to control which part of the VE has to be in their physical forward direction. Users can decide when they need resetting in real world, based on comfort or strain experienced in the neck when their head orientation is offset from the physical forward direction. Once a user decides to use this technique, an assistive cursor (a cross-hair in our implementation) can be launched through controller input, which moves along with the virtual camera if the controller input is held after being pressed. This cursor is used to determine the section of virtual environment that needs to be brought in line with physical forward direction after reorientation. Once the controller input is released, the user's virtual view is blocked completely with a mask and a 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 of VE still blocked by the mask, a green arrow is displayed to guide the user turn towards the physical forward direction to complete resetting. Figure 4.5 demonstrates this technique with screenshots and pictures from consecutive steps involved in *user-controlled resetting*.

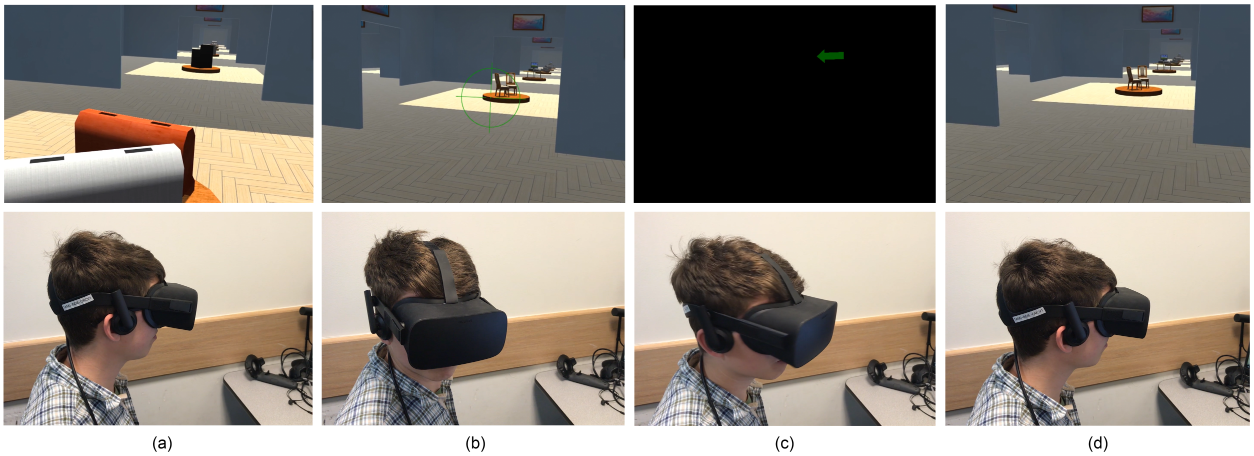

Figure 4.5: Screenshots and pictures demonstrating how *user-controlled resetting* works.[‡](a) user is facing along his physical forward direction, (b) user turns to look at a pair of chairs, launches the cursor (crosshair) through controller input, (c) user releases the controller input and turns along the direction of the green arrow, (d) once the user reorients physically with the forward direction, the mask is removed and the pair of chairs are in front of the user now, along the forward direction.

One of the three techniques studied in the third experiment uses *user-controlled resetting* with head rotation amplification. As mentioned in section 4.1, a constant amplification factor, a = 2 is

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[‡] The following free 3D models from Unity asset store were used as navigational landmarks in the virtual environment: Farm Machinery [32], Military Helicopter [33], Military Wheel [34], Traffic Barrier [35] and Toon Furniture [36]

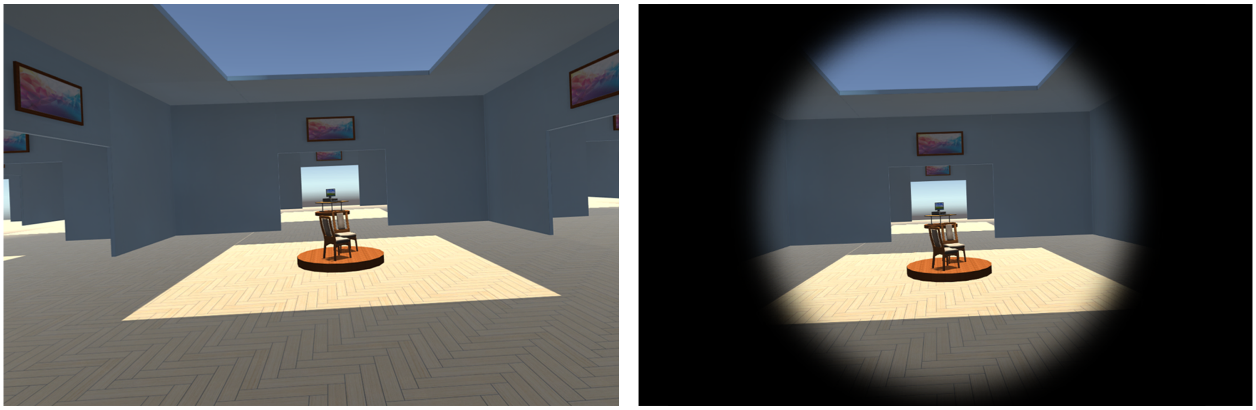

Figure 4.6: Screenshots showing perspective views of the virtual environment without FOV reduction on the left and with FOV reduction on the right [2].

used here. When this constant amplification is used with *user-controlled resetting*, users would be able to quickly view 360 degree range of a VE and can reorient themselves as per convenience.

4.4 Joystick Rotation Techniques

Our research also compared three types of joystick rotation techniques, which we will refer to as: *continuous rotation*, *discrete rotation*, and *reduced FOV*. The three techniques were designed to be controlled with an analog joystick on a common game controller used with many VR applications and 3D games.

The *continuous rotation* technique was included as the standard condition in one of the two comparisons and it is implemented how joystick rotation is usually used in virtual environments and games. Moving the joystick to the right or left rotates the camera heading relative to the vertical axis continuously. The implementation for the study used a constant speed of 30 degrees/second.

The *discrete rotation* joystick technique only allowed turning in discrete increments of 30 degrees. This technique still uses the analog joystick, but the magnitude of discrete rotation was constant (the user could not control or adjust the angular amount for each discrete rotation). This technique was chosen because it reduces visual updates and limits optical flow during turning. With this technique, the users can make a sequence of rotational jumps to have a new view orientation.

The *reduced FOV* joystick technique used continuous rotation with the analog stick in the same way as in the *continuous rotation* technique. The difference is that the *reduced FOV* technique applied a visual mask on top of the virtual view to limit the user's FOV to only a small circular region. The mask applied in our implementation reduced the Rift's normal FOV of approximately 200x135 degrees to approximately 95x95 degrees. The FOV reduction used a radial-falloff effect to give the effect of blurred edges around the view (see Figure 4.6). This FOV mask was applied whenever the user used the joystick to rotate. The FOV reduction was instant and not gradual. It was enabled in an all-or-nothing fashion. The *reduced FOV* allows continuous viewing of the rotational movement to allow the user to view the entire turn. However, the FOV mask hides considerable amount of visual content and is expected to reduce spatial awareness while turning.

Six degree-of-freedom head-tracked rendering was enabled with all the techniques in our research. So, with the joystick techniques, in addition to using the technique, participants could also physically turn their heads to view more of the virtual environment. Participants sat in a standard non-rotating chair that limited the range of comfortable physical turning. Virtual travel (translational movement) was controlled with a second analog joystick in the game controller.

5. EXPERIMENT 1*

5.1 Goals

The two high-level goals for our first experiment were: (1) to assess the general feasibility and usability of *dynamic 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 361-degree baseline.

5.2 Hypotheses

Based on prior studies showing that low levels of rotational modification can go unnoticed (e.g., [37, 38]), 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.

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5.3 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 5.1 shows a screenshot of the environment from the application. All the 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.

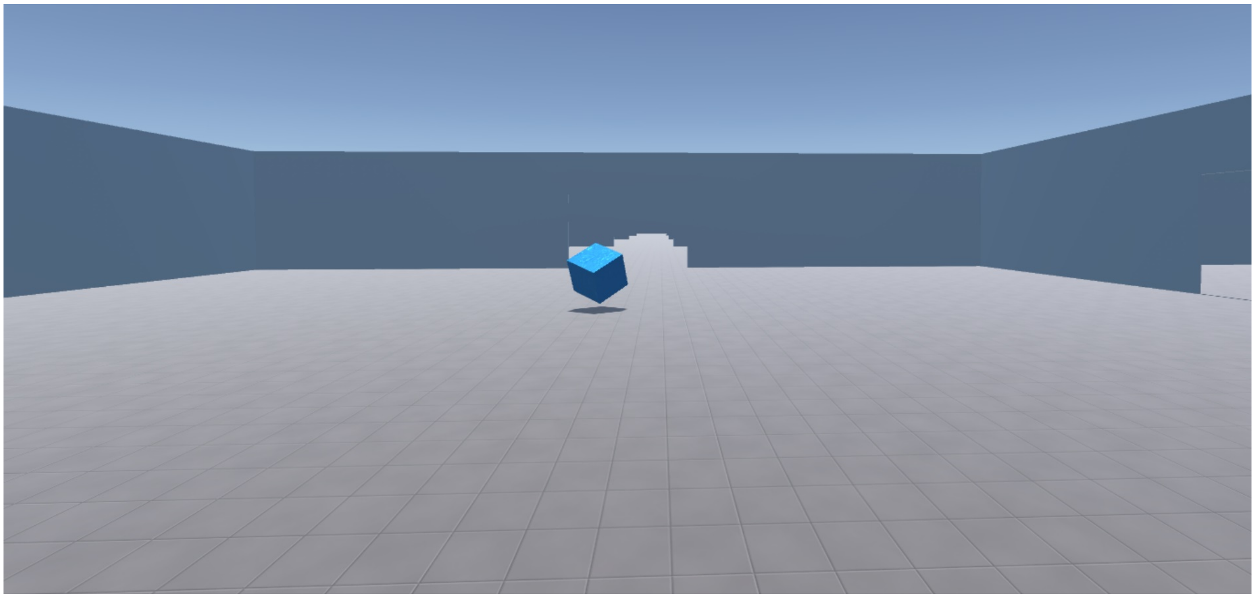

Figure 5.1: A screenshot from one of the virtual rooms in the environment used in first experiment [1]. The image shows a view while looking through a doorway into an adjacent room, where a blue guiding cube is visible.

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.

5.4 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*. As mentioned in section 4.1, the *amplified head rotation* used a dynamic amplification factor in this experiment.

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 chapter 4. 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., [39]) or sickness questionnaires (e.g., [40]).

5.5 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.

5.6 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 5.3) 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.

5.7 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.

5.8 Results and Discussion

Quantitative results are shown graphically using standard box-and-whisker plots. The plots label the *guided rotation* condition as *guided+amplified* since the guided rotation technique also included amplification.

Rather than testing every question from post study questionnaire 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. 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.

The gaming experience of the participants was considered during the analysis. The participants were grouped into gamers and non-gamers based on the reported 3D gaming experience. If they played 3D games weekly for one hour or more they were considered to be gamers whereas if they did not play any 3D game in a week they are considered non-gamers. After separation based on gaming experience we had 13 gamers and 11 non-gamers.

5.8.1 Spatial Orientation Results

There were no significant results from a Friedman test for the pointing task and return-to-start task indicating that participants could understand and remember their path of travel reasonably well for all the techniques.

But after the study, when the participants where asked subjective responses for questions related to ease of travel and maintaining orientation with each technique, the alternative techniques and especially *guided rotation* received the worst ratings. A Friedman analysis found the effect to be significant with $\chi^2(2) = 10.53$ and $p = 0.005$. A posthoc Nemenyi test [41] detected a significant pairwise difference between *guided rotation* and *standard rotation* ($p = 0.007$). Figure 5.2 shows the average ratings for these block of questions.

After taking the gaming experience of the participants into account, we found a clear correlation between reported weekly 3D gaming hours and results from the spatial orientation tasks. 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 $p < 0.001$. A Friedman test for the gamers detected a significant effect for pointing errors, with $\chi^2(2) = 6.00$ and

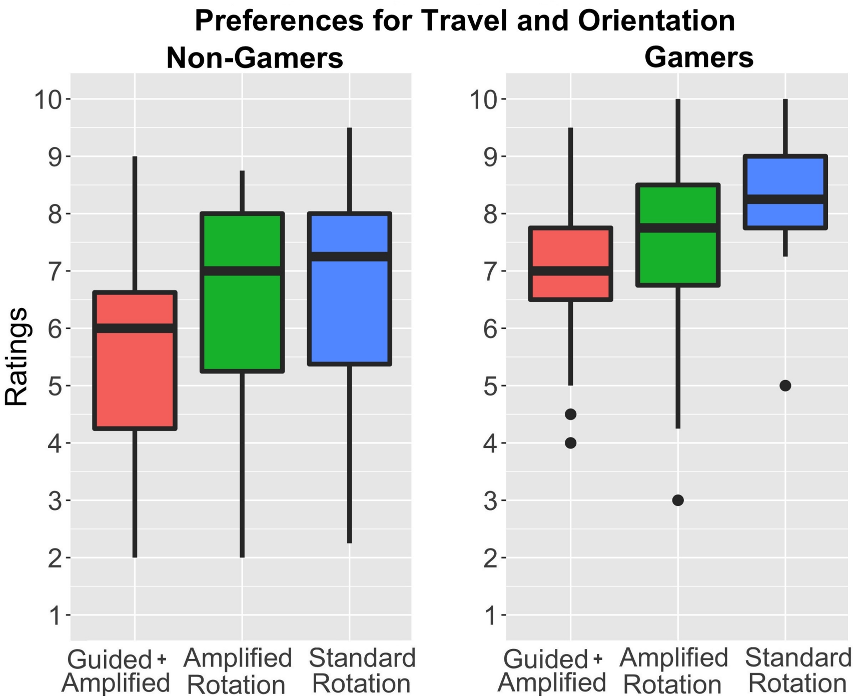

Figure 5.2: The ratings from experiment 1 for the block of post-study questions relating to ease of travel and orientation [1].

$p = 0.046$, 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 5.3 shows the pointing results.

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

5.8.2 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 5.4, 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

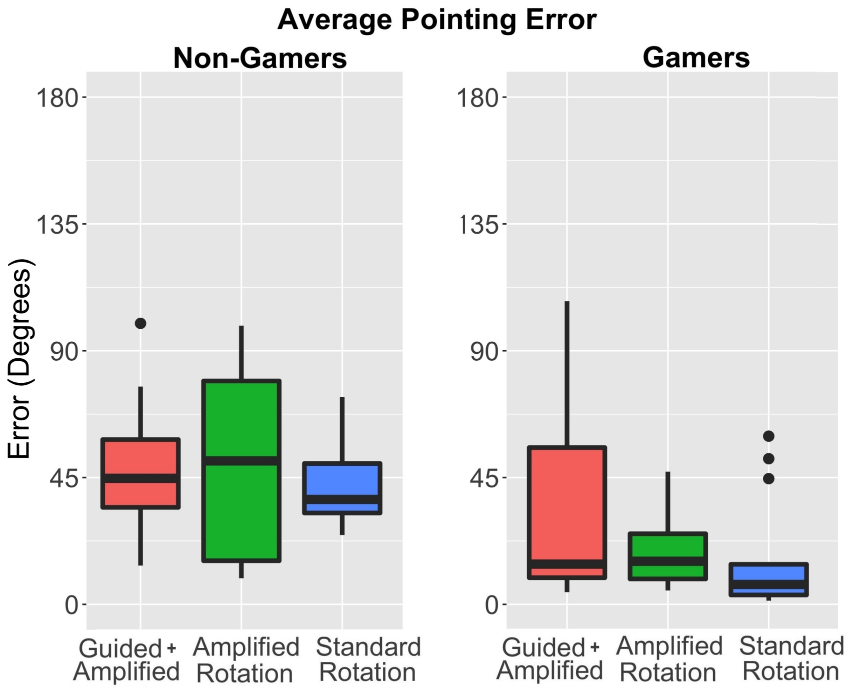

Figure 5.3: The absolute pointing errors for the techniques from experiment 1, grouped by self-reported 3D gaming [1]. Note the low median errors for the gamers.

$\chi^2(2) = 10.21$ 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 more experience with 3D games may have higher tolerance for redirection and amplification techniques when it comes to sickness.

5.8.3 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 comfortable 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 5.5 show the results separated by gamers

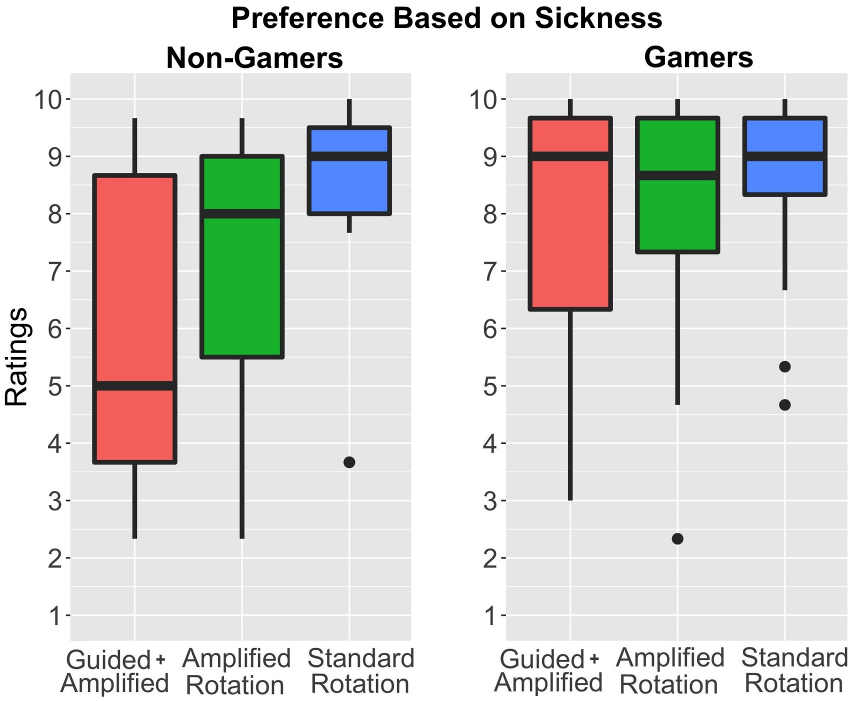

Figure 5.4: Technique ratings based on sickness from first experiment [1]. Higher values indicate lower perceived sickness.

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 5.5). The posthoc Nemenyi showed *amplified head rotation* was rated significantly worse than *standard rotation* ($p = 0.049$).

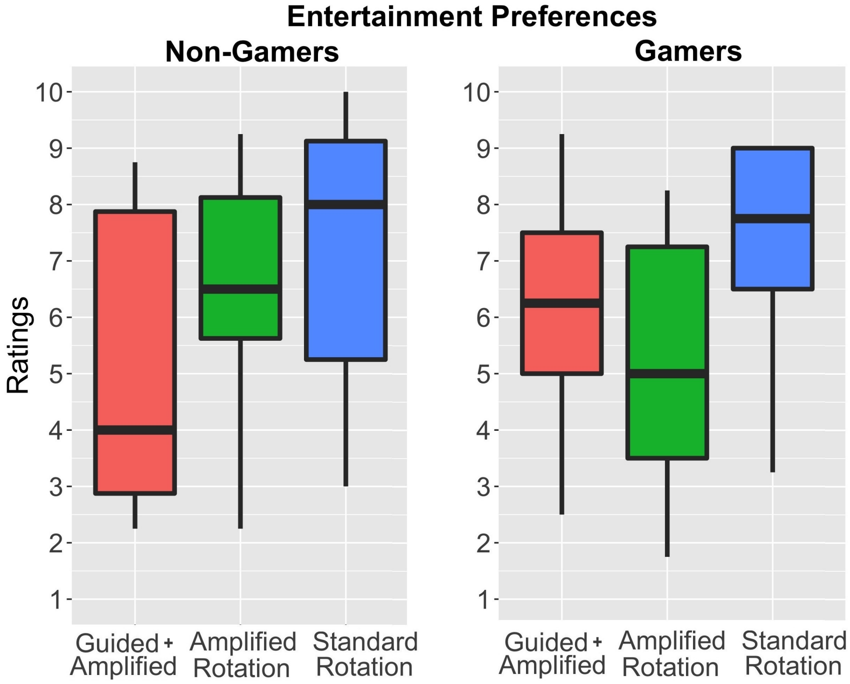

Figure 5.5: Ratings based on fun, comfort, and interest for home entertainment from first experiment [1]. Standard 360-degree rotation was preferred best.

6. CASE STUDY*

6.1 Goals

The main goal of this study was to evaluate natural hand interaction with virtual objects supported with haptics provided by a physical prop. However I was specifically interested in studying more about the *guided rotation* and *resetting* techniques that were used for travel and viewing in the experiment.

6.2 Experimental Environment and Task

We designed an immersive game environment (see Figure 6.1) that involved virtual travel and manipulation of virtual objects to solve a simple puzzle. The goal of the game is to collect five missing rocket pieces scattered across the environment. To collect the pieces, the player must complete a basic symbol-matching puzzle requiring traveling to different locations, moving objects to the correct target positions on an in-game tabletop map, and manipulating switches that toggle the availability of game objects. Once all five pieces are collected, a final switch is enabled that will complete the game once pulled.

The environment included multiple *interaction zones* at different locations that each included an interactive object. To test the feasibility of our techniques with different types of interactions, we implemented three different types of object interactions: (1) cylindrical puzzle pieces that could be moved, picked up, and set down, (2) large switches that slide back and forth along a fixed track, and (3) doors that swing open by moving the door handle (see Figure 6.2).

The game was designed to encourage exploration and free choice of what order to interact with different objects. Additionally, to test the flexibility of the interaction and travel methods, the environment was designed with different interaction points at different virtual orientations (see Figure 6.3). With this design, different interaction zones had different virtual orientations when

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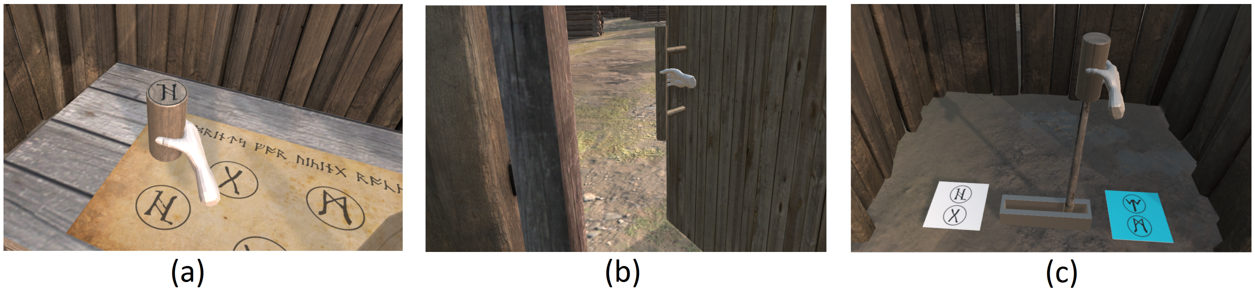
Figure 6.1: A screenshot from the game environment used in the case study [3]. An interaction zone is marked with a floating red marker.



(a) (b) (c)

Figure 6.2: Screenshots showing three different types of interactions in the game [3]. (a) Moving a puzzle piece during symbol matching, (b) opening a door, and (c) operating a switch.

compared with the physical world, so users had to physically rotate to orient themselves with the physical prop.

By default, the player did not have a visible virtual hand. Only when entering an interaction zone, the player's virtual hand appears to signify the ability to interact with the virtual object. To make the interaction zones easy to identify, they were labeled with a large rotating red symbol floating above them (see Figure 6.1).

6.3 Experimental Design

The following three conditions were compared:

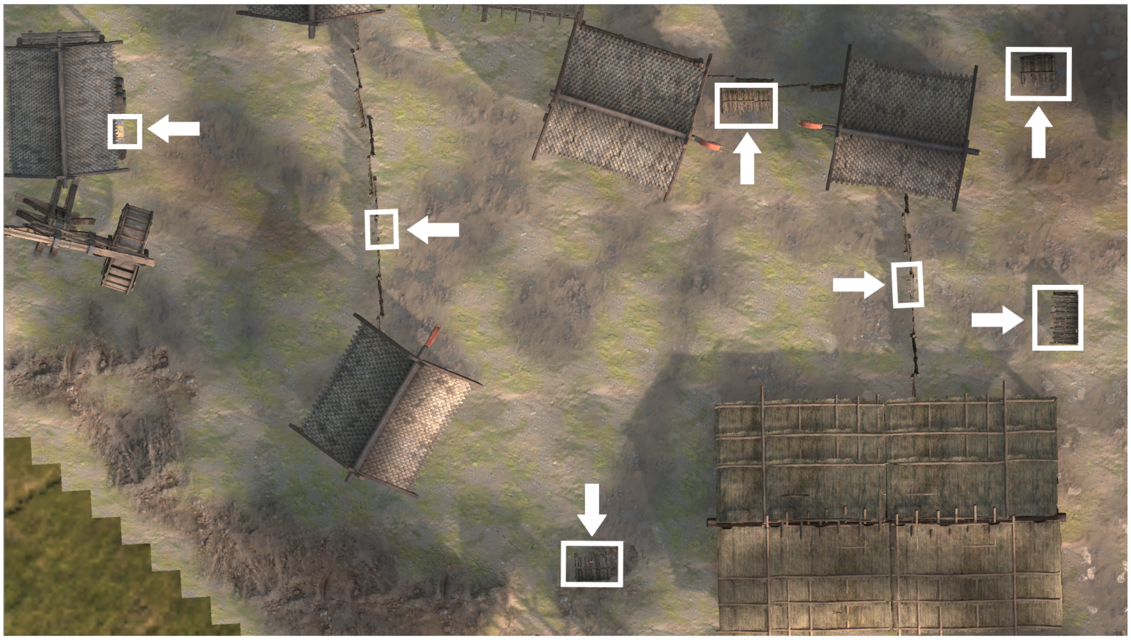


Figure 6.3: Top-down view of the game environment with interaction zones represented by white rectangles [3]. Arrows denote the expected direction of users approaching the interaction zones.

- **Resetting:** This condition used one-to-one head tracking and supported interaction with the passive haptic prop with the help of resetting transitions when users virtually entered the interaction zone. Redirected reach was applied to adjust the virtual hand.
- **Guided rotation:** This condition included interaction with the passive haptic prop. Rotational viewing was controlled via amplified head rotation with redirected rotational adjustment during virtual locomotion. Resetting transitions were also applied when entering interaction zones. Redirected reach was applied to adjust the virtual hand.
- **Air grasping:** This condition was included as a reference technique that did not support tactile interaction using the prop. Instead, participants used pinch gestures with a tracked hand to select and manipulate virtual objects. The condition used one-to-one head tracking, and one-to-one hand tracking was used to control the virtual hand. Redirected reach was not applied.

The experiment followed a repeated-measures design, so each participant completed three game trials—one for each of the three conditions. For ordering of conditions, we were concerned about sickness effects due to the rotational manipulations in the *redirection* condition, as we found from the first experiment [1], that some people get sick using these techniques. Consequently, to avoid confounding sickness effects, participants always tested the *redirection* condition as the last of the three. Ordering for the other two versions were balanced among participants for the first and second trials.

We were interested in understanding perceptions of the different techniques and evaluating preferences for different configurations when used in a fairly realistic gameplay scenario. As such, we were more interested in subjective and qualitative results than in assessing any particular task performance metrics (e.g., speed and accuracy). We collected measures about sickness effects using both the Simulator Sickness Questionnaire (SSQ) [40] and relative ratings of techniques on a 1–10 scale. We also collected relative Likert scale ratings for a variety of subjective measures such as disruption to the experience, fun, ease of use, fatigue, and comfort.

6.3.1 Apparatus

The game was implemented in the Unity game engine (5.4.1) using assets from the Viking Village 3D environment from the Unity Asset Store [42]. The application was run on a computer with 64-bit Windows 7 Professional, a 3.6 Ghz Quad Core processor, and a GeForce GTX 980 4GB graphics processing unit. The application ran at a frame rate of 98 frames per second.

The experiments were conducted in a lab using a Oculus Rift CV1 HMD. Head-tracked viewing (positional and rotational) was enabled using the Oculus Constellation tracker, though position head movements were limited because participants were seated. Participants sat in a rotating chair in front of a table holding the physical interaction prop—a plastic water bottle with some weights added inside for stability at the base.

To track the prop and the player's hand, the setup used an Optitrack capture system with eight Flex 13 cameras. Each of these cameras recorded tracking data at a frame rate of 120 fps operating with 8.33 ms latency (manufacturer-reported). The setup used rigid bodies for 6-DOF (degree of freedom) tracking. One of these rigid bodies was attached to the top of the prop (the bottle). The

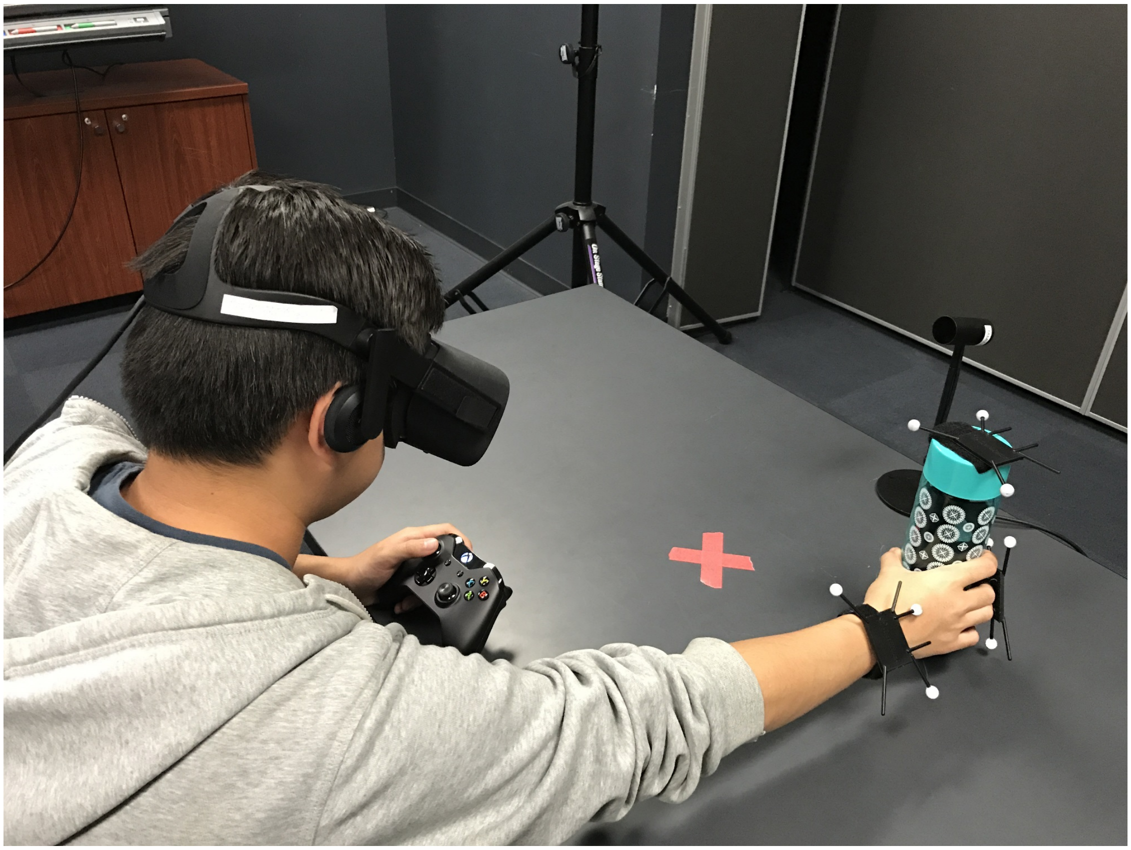


Figure 6.4: The physical setup used for the study [3]. Participants sat at a table and could reach and move a tracked prop (a plastic bottle). Tracking markers were placed on the wrist and fingers of the user's right hand, and the left hand was used to operate the analog stick of a game controller. Participants could rotate in a swivel chair.

other two rigid bodies were attached to the user's right hand using custom-made velcro strips—one on the outer wrist and the other on the middle and the ring fingers. Figure 6.4 shows the physical setup with the prop and tracking markers.

A wireless Xbox One game controller was used for additional input. The left analog stick of was used to control virtual movement (ground-constrained translation only), and the left bumper and directional pad were used to navigate and select game-menu options (i.e., showing and hiding instructions).

6.4 Procedure

The entire experiment lasted 45–60 minutes, and the study was approved by our organization's Institutional Review Board (IRB). On arrival, participants were seated at a table and were given an overview of the study. They were asked to sign an informed consent form in order to participate. Participants then filled out a brief background questionnaire about demographic information (age, gender, occupation) and their self-reported experience with 3D games and VR. Next, participants completed an initial simulation sickness questionnaire (SSQ; from Kennedy et al. [40]) as a baseline for the subsequent sickness questionnaires after using the techniques. The participants were explained about navigation and task-related controls before putting on the HMD.

Before starting each practice and trial session, participants were asked to face towards the forward direction to directly face the physical table, and the physical prop was always placed at the same starting location on the table before beginning. Before the main trials, participants were given a practice session to try both the air grasping and physical prop techniques. This practice session allowed them to read through the instructions of the game as well as perform virtual interactions in the environment to get an idea of what to expect in the main trials. After the practice session, participants were required to take a short break (5 minutes).

Next, the participants were asked to complete the entire game three times (one for each technique). Instructions and hints were given if the participant was having difficulty progressing in the game; since the purpose of the study was to assess experience with the techniques, we were not concerned with the gameplay efficiency. On average, each trial took approximately 5 minutes to complete. After each trial, participants were given another break and asked to complete two questionnaires: the SSQ [40] and a system usability scale questionnaire (SUS) [43]. The SSQ was used to evaluate any fatigue or sickness experienced after completion of each trial, and the SUS allowed the participant to give usability feedback on the game experience and the techniques.

For the third and final trial, participants were given an overview of the *guided rotation* technique specifically to explain that they would be experiencing amplified head rotations and realignment when traveling. Unlike the two previous versions of the game the participant had experienced, the guided rotation technique does not require users to use the complete 360 degree rotation within their chair, so participants were advised on how to use the technique properly and what to expect, to avoid any surprises with the changes in world rotations.

After all three trials, a final experience questionnaire was given to the participants to rate the three versions against each other in terms of fun, ease of use, preference, sickness, and overall experience. Finally, a semi-structured interview was conducted by the experimenter to collect additional feedback.

6.5 Participants

Sixteen participants (9 male, 7 female) took part in our study. Participants age was in between 21 and 28 with a median of 23 years. Participation was voluntary and no compensation was provided. All participants were university students in various programs, though most participants (12 of 16) were in computer science or computer engineering programs. Out of the 16 participants, 10 participants reported spending at least one hour every week playing 3D video games, and 11 reported some prior experience with VR before attending our study.

6.6 Results

The qualitative feedback and our observations make up perhaps the most important results for understanding the trade-offs among the techniques. The experimenter observed and took notes about participant behavior and comments during the study, and participants answered a semi-structured interview at the end of the study. Most of the questions were directed towards a set of themes that were intended to collect information on which type of interactions felt natural, whether the hand offset was noticeable or not, and whether the resetting and guided rotation were noticeable, distracting, or disorienting. From the comments received, we undertook a thematic coding method to examine and record common sentiments and emphasize information from user experiences.

6.6.1 Feedback about Resetting

The resetting technique was applied to orient the user towards the physical prop; this technique received mixed responses from our participants. Three participants indicated that they felt this technique was clean, intuitive, and did not interrupt their game experience, while four others said the resetting at the interaction zones was disorienting. Interestingly, five participants reported that they understood that resetting was necessary to be aligned to interact with physical prop. These responses show that many participants were aware of their physical surroundings when they were supposed to interact with objects in the real world. While not necessarily problematic, these results could suggest reduced sense of presence due to constant awareness of the real world. The following are representative comments from our study about the resetting technique:

> “I didn’t mind being rotated. I thought they are needed for the techniques and physical prop to work.”
>
> “I see the need for transitions to help in redirecting towards the prop.”

6.6.2 Feedback about Guided Rotation

The guided rotation technique combined amplified head rotations and realignment via rotational gains. In terms of user experience, participants commented on both these components. Four participants mentioned that the amplified head rotations were helpful in quickly exploring the game environment. These participants adjusted quickly to the technique and reported that they hardly noticed a difference in comparison to standard 360 degree rotation.

Recall that we explicitly explained the amplification and rotational adjustments to participants before they completed the guided rotation trial. Five participants preferred using guided rotation. These participants commented that they thought the rotational gains were slow enough to not cause disorientation. Regarding the overall experience, 10 participants commented that using guided rotation was difficult due to reduced control in exploring the virtual environment. Additionally, these participants reported symptoms of dizziness and disorientation after the trial. A few representative quotes on guided redirection include:

“I felt like redirection was forcing me to go a certain way, but I prefer having full control.”

“I prefer the quicker turns. And I didn’t get dizzy.”

“I didn’t feel much difference from other versions in term of experience except the learning curve involved.”

7. EXPERIMENT 2*

7.1 Goals

The goals for this experiment were: (1) to study how the three joystick-control based techniques (*continuous rotation*, *discrete rotation* and *reduced FOV*) affect the spatial understanding of the users and (2) to understand the effects of these techniques on simulator sickness, comfort, preferences for home-entertainment, etc.

7.2 Hypotheses

Since the *continuous rotation* technique adjusts the view gradually without any break in presence, we hypothesized that the users will perform better in the spatial tasks with this technique compared to the other joystick techniques. Reducing the FOV has been found to negatively affect performance during spatial search tasks [26]. 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 [27], we hypothesized that the *reduced FOV* technique would cause less sickness compared to the *continuous rotation*. Also, since *discrete rotation* does not involve continuous camera turns, we hypothesized that this condition would cause the least sickness effects of the three.

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7.3 Experimental Environment and Task

The environment and the task were similar to those from the first experiment except few changes. The virtual environment (VE) consists 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. 3D objects were placed at the center of every room to serve as navigational landmarks (see Figure 7.1). The landmarks were 3D models, with examples including a car, a desk, a couch, and a piano. Users could use the orientation of landmarks 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. Landmarks were chosen such that for any particular room with its four adjacent neighbors, their five landmarks were unique. But once the user steps out of these five rooms, one of the five landmarks from the previous set of rooms could be seen again.

Figure 7.1: Perspective view showing a 3D landmark in the environment with a blue marker above it to indicate the path [2].

In this environment, participants completed a VR navigation task that consisted of three subtasks: (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 landmarks 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 three simple rules: (1) each path will consist of seven of rooms including the starting and ending 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 and (3) 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, 15 unique paths were created, from which a single path was randomly picked for each trial tested by a participant.

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 participants were asked to push a button in the controller while facing towards the initial room in the path. A difference in the angle between the direction pointed by the user and the direction towards the actual starting room was recorded as the angular error. This error was one of the two metrics used to determine the spatial awareness of the users. Immediately following the pointing task, the users completed an exocentric plotting task using a 2D grid that represented a top-down view of the environment (see Figure 7.2). The 2D grid only displayed the landmarks 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 landmarks 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 controller inputs 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.

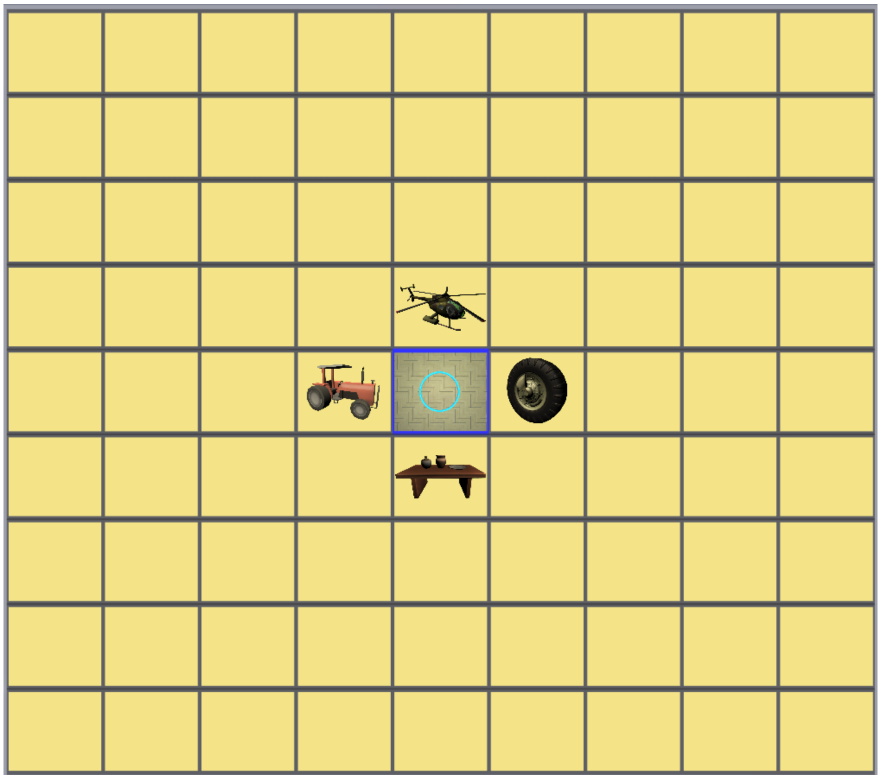

Figure 7.2: Screenshot of the 2D grid used in the exocentric plotting task [2]. It used a top-down view showing the neighbors of the end room with the cursor initially located at the ending room's position.

7.4 Experimental Design

Three joystick rotation techniques were compared: *discrete rotation*, *continuous rotation* and continuous rotation with *reduced FOV*. Eighteen participants (7 females and 11 males) tested the techniques under controlled experimental setup. 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 corresponding to the three techniques. Participants completed the task four times for each technique, where the first one was considered a familiarity trial with the technique. Technique order was counter-balanced across the participants. The dependent variables of this experiment were the errors from the egocentric pointing task, errors from the exocentric plotting task, subjective responses given in the post-experiment questionnaire, and responses on a simulator sickness questionnaire (SSQ) [40]. The post-experiment questionnaire consisted of nineteen questions based on ease of use, sickness, comfort, and preference for home entertainment. These questions were presented in the form of Likert scales with ratings ranging from 1 to 10.

7.5 Apparatus

The experiments were run in a lab environment and a non-rotating chair was used with all the techniques tested. 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. An Oculus CV1 headset was used with the default positional and orientation head tracking enabled. 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. An Xbox One controller was used for user inputs during the trials.

7.6 Procedure

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 a SSQ questionnaire 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 with four trials for each of the techniques compared in the study. In each technique block, the first trial was a practice trial for the participant to gain familiarity with the techniques, and three main trials followed whose data was considered for analysis.

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.

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 60 to 80 minutes for each participant.

7.7 Participants

Eighteen participants (eleven males and seven females) participated in the study. All the participants were university students aged between 20 and 24 years. All the participants reported having good knowledge on computers and technology. Twelve of the eighteen participants reported playing some 3D video game every week. And eight participants reported not having any prior experience with VR before taking part in the study.

7.8 Results and Discussion

We analyzed our results to compare the three joystick techniques in terms of spatial orientation, sickness, and preference.

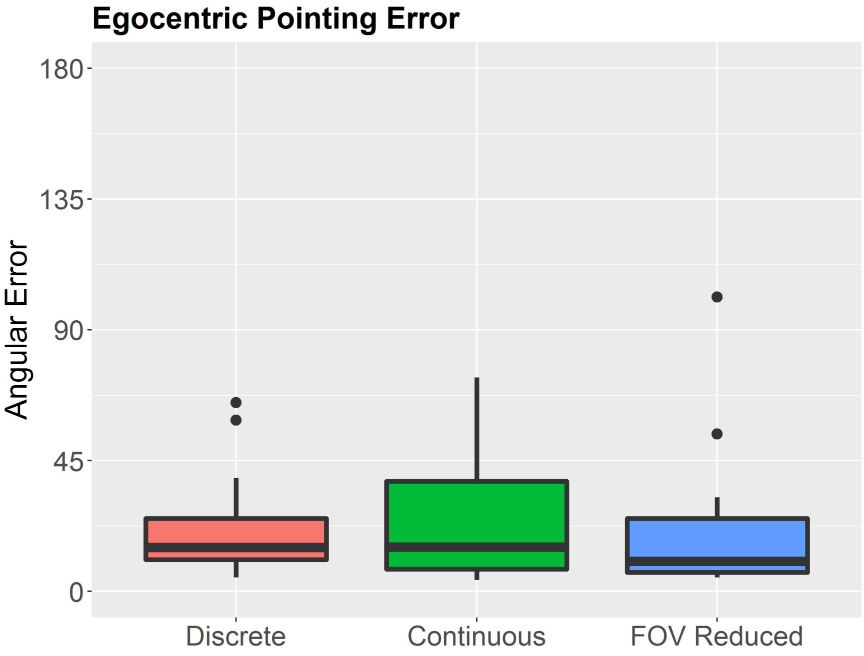

Figure 7.3: Error from the egocentric pointing task in second experiment [2]. Lower error is better.

7.8.1 Spatial Orientation Results

Despite the travel paths involving seven rooms with varied turning, the spatial orientation measures indicate that participants were able to maintain their sense of spatial awareness fairly well. The error results for the egocentric pointing task are shown in Figure 7.3. The pointing data were skewed right, so it was corrected with log transformation to meet the assumptions for parametric testing. A repeated measures ANOVA failed to detect any differences in pointing errors due to the techniques, with the test showing $F(2, 34) = 0.45$.

Similarly, no differences were detected for the exocentric plotting errors, with $F(2, 34) = 0.53$. Overall error was low. For many trials, participants were able to exactly select the position of the starting room from the top-down grid view in the exocentric plotting task.

With these results, we are unable to identify any differences in the extent to which the three techniques affect spatial orientation. However, the results also demonstrate that all variations can be used to travel while maintaining awareness of travel path. It may be that the presence of the landmarks made the task easy, but on the other hand, landmarks are common in many types of virtual experiences. Thus, these results demonstrate general usability and conclude that all three techniques can support spatial awareness during travel—at least in certain types of environments.

7.8.2 Sickness Results

Our assessment of sickness effects considered both relative ratings and SSQ results for the techniques. The relative sickness ratings are summarized in Figure 7.4. The Friedman test found a significant difference from the techniques with $\chi^2(2) = 9.93$ and $p < 0.01$. The post-hoc Nemenyi test found *discrete rotation* technique to be rated significantly better than *reduced FOV* with $p = 0.03$, and *discrete rotation* was nearly significantly rated over continuous rotation with $p = 0.06$.

Overall, the SSQ results had $M = 38.92$ and $SD = 33.36$. For the analysis of the SSQ results, we were interested in the resultant effects from each technique rather than in the overall cumulative sickness over the duration of the study. Since participants took an initial SSQ test before beginning

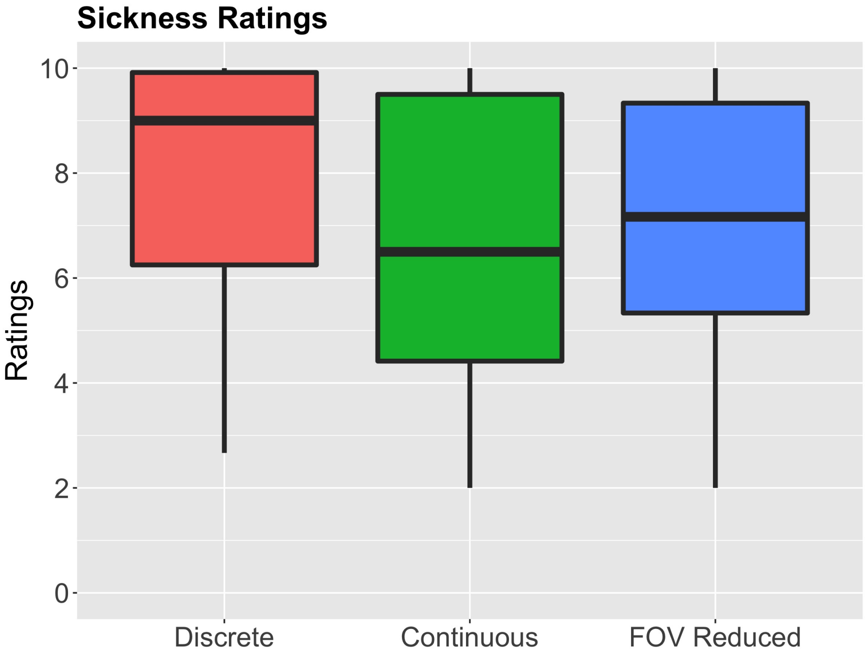

Figure 7.4: Comparative ratings based on sickness from the second experiment [2]. Higher ratings indicate higher preference and lower sickness.

and another SSQ test after trying each technique, we were able to calculate the difference in SSQ from the previous sickness state. We analyzed this SSQ change for each technique. We note that it was possible to achieve negative score changes, meaning a decrease in perceived sickness. SSQ changes were relatively low across conditions with moderate variance ($M = 9.97$, $SD = 19.15$). For statistical comparison of SSQ changes for the techniques, we conducted a non-parametric Friedman test because the data failed to meet the assumption of normality, and we were unable to correct with transformations. The test failed to find a significant effect with $\chi^2(2) = 3.97$.

Thus, the SSQ results found relatively low overall sickness scores, but the relative sickness ratings showed the *discrete rotation* technique to be significantly preferred. Due to the repeated measures design of the study and the compounding experiences in VR, we find the ratings to be a more meaningful metric for the study.

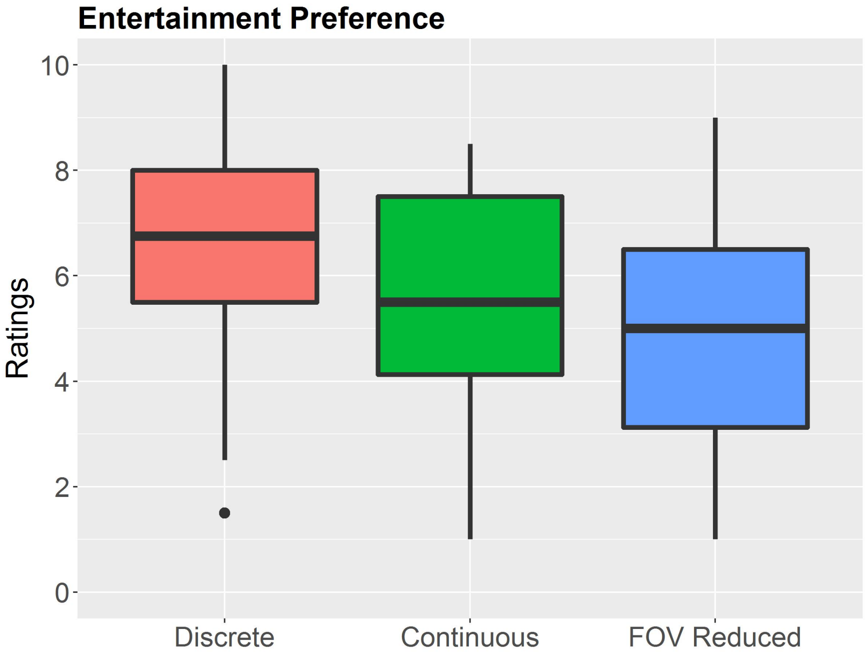

Figure 7.5: Comparative ratings based on preference for home entertainment from the second experiment [2]. Higher ratings are better.

7.8.3 Preferences for Home Entertainment

We tested for differences in preferences for home entertainment using a Friedman test. The test failed to detect a significant effect with $\chi^2(2) = 4.46$ and $p = 0.11$. Preferences varied greatly with no clear consensus on preferred technique (see Figure 7.5). In general, these results allow us to be confident that there was no clear "best" joystick technique from our group. Although the *discrete rotation* technique was the top preferred technique more than the others, individual differences and opinions make a strong impact in preference or interest using any given technique for real applications.

8. EXPERIMENT 3

8.1 Goals

The goals for this experiment were: (1) to study how the resetting based techniques affect the spatial understanding of the participants when compared with *discrete rotation* and (2) to understand the effects of these techniques on simulator sickness, preferences for home-entertainment and travel. The *discrete rotation* was chosen as the best joystick technique for comparison because it was found to be the most preferred technique for home entertainment from the first experiment and it caused the least sickness effects among the three joystick control based techniques.

8.2 Hypotheses

The *amplified head rotations* reduce the number of the resettings needed during a virtual experience since users can view a wide range of VE with smaller turns. Since frequent resetting could disorient users, we hypothesized that users will make more errors in the spatial tasks with *user-controlled resetting* than *user-controlled resetting with amplification*. Because of the frequent resetting needed with *user-controlled resetting* without amplification, we hypothesized that this condition would receive least ratings in terms of preference for home entertainment.

Since the *amplified head rotations* have been found to cause sickness problems [1], we hypothesized that *user-controlled resetting with amplification* will cause worse sickness effects among the two resetting based techniques being compared. Compared to these two techniques, since *discrete rotation* does not require users to rotate physically, we hypothesized that *discrete rotation* would cause the least sickness effects among the three techniques compared.

8.3 Experimental Environment and Task

The environment and the tasks in the third experiment were the same as the second experiment except the changes in the virtual paths. The number of rooms in each path was increased from seven to ten in the third experiment because we found from the second experiment that the spatial tasks were too easy for the participants with seven rooms (the errors from the pointing task and the plotting task were too low). To increase complexity, some of the paths also included straight travel where three subsequent rooms fell in a straight line. The rules followed to determine the paths are: (1) each path will consist of 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, 12 unique paths were created, from which a single path was randomly picked for each trial tested by a participant. Other than these changes, the environment and the tasks performed by the users were the same as the environment and tasks from the second experiment.

8.4 Experimental Design

User-controlled resetting and *user-controlled resetting with amplification* were compared with the best joystick rotation technique (*discrete rotation*). Eighteen participants (twelve males and six females) tested the techniques. The experiment followed a within-subjects design. 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 dependent variables for the experiment were the errors from the egocentric pointing task, errors from the exocentric plotting task, subjective responses given in the post-experiment questionnaire, and responses on the simulator sickness questionnaire (SSQ) [40]. 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 simulator sickness. The post-experiment questionnaire consisted of nineteen questions presented in the form of Likert scales (ratings ranging from 1 to 10), based on ease of use, sickness, comfort, and preference for home entertainment.

8.5 Apparatus and Procedure

The apparatus and procedure for the third experiment were the same as the second experiment.

8.6 Participants

Eighteen participants (twelve males and six females) participated in the study. All the participants were university students aged between 19 and 36 years. Seventeen participants reported having good knowledge on computers and technology. Eleven participants reported playing some 3D video game for one or more hours weekly.

8.7 Results and Discussion

Similar to the first experiment [1], we considered the gaming experience of the participants during our analysis. We segregated the data based on number of weekly 3D gaming hours of the participants. Those who had weekly 3D gaming experience of one hour or more were considered to be gamers whereas those who had zero hours of weekly 3D gaming experience were considered non-gamers. Based on this criterion, we had eleven gamers and seven non-gamers out of the eighteen participants.

Note that, in the plots shown in the figures, the *user-controlled resetting* condition is labeled as *resetting* and the *user-controlled resetting with amplification* is labeled as *resetting+amp*.

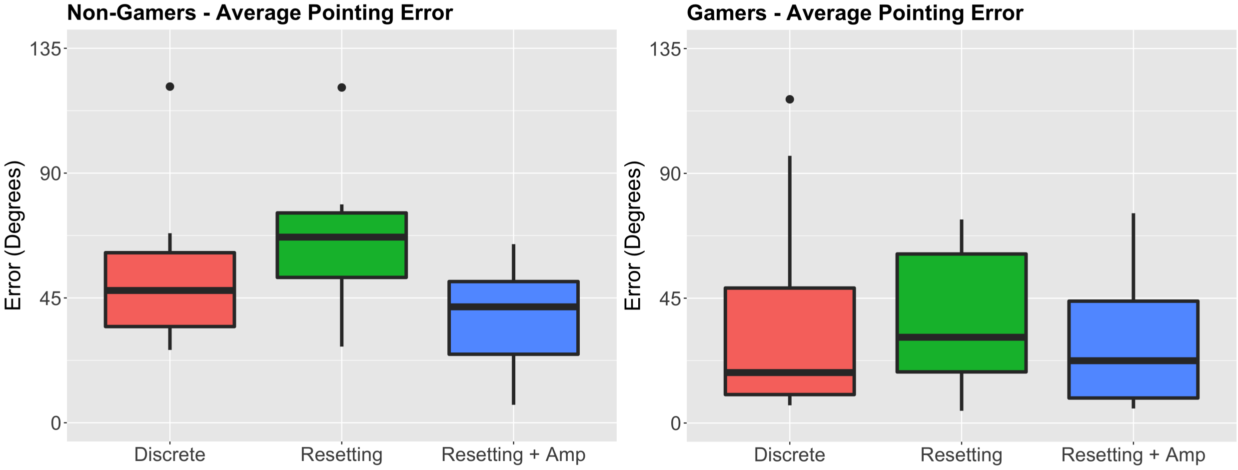

Figure 8.1: Error from the egocentric pointing task in third experiment. Lower error is better.

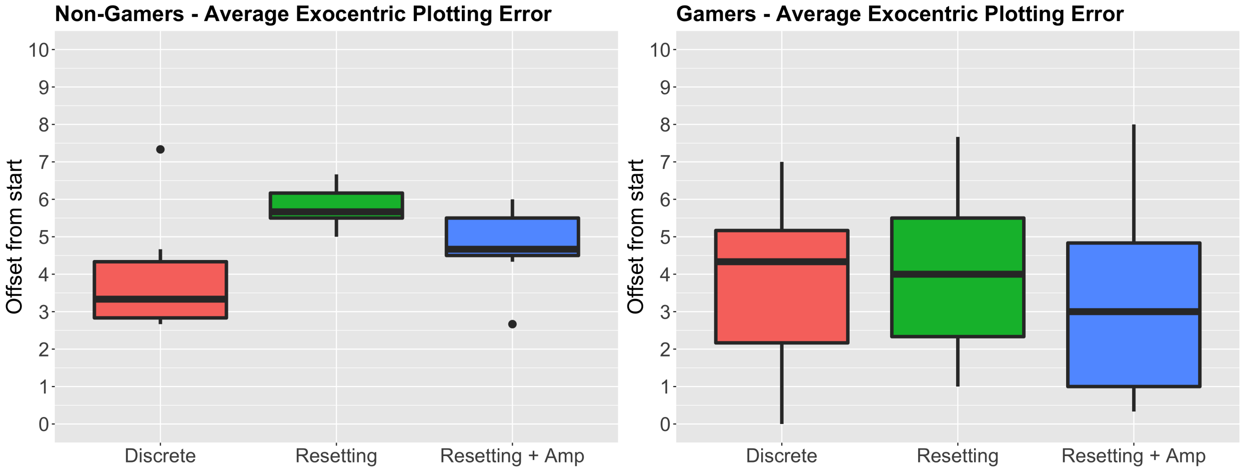

Figure 8.2: Error from the exocentric plotting task in the third experiment. Lower error is better.

8.7.1 Spatial Orientation Results

From Figure 8.1, we can observe that the gamers had lower overall pointing errors in the pointing task compared to the non-gamers. However, the Spearman's test and Pearson's test failed to find a significant correlation between the 3D gaming hours and the pointing error as well as between the 3D gaming hours and the exocentric plotting error. Overall, with both gamers and non-gamers combined, the Friedman non-parametric repeated measures test found significant effects of the techniques for the pointing error with $\chi^2(2) = 6.33$ and $p = 0.042$. The posthoc Nemenyi test found *user-controlled resetting with amplification* condition to be significantly better than *user-controlled resetting* with $p = 0.033$.

With the exocentric plotting task, the ANOVA and Friedman non-parametric repeated measures test did not find any significant effects of the techniques on the task. However, it can be seen from Figure 8.2, that for non-gamers, the errors were worse with the resetting based techniques compared to gamers.

8.7.2 Sickness Results

Responses from the post-study questionnaire on questions about nausea, headache and dizziness were grouped together for the sickness ratings. From Figure 8.3, we can see that the gamers

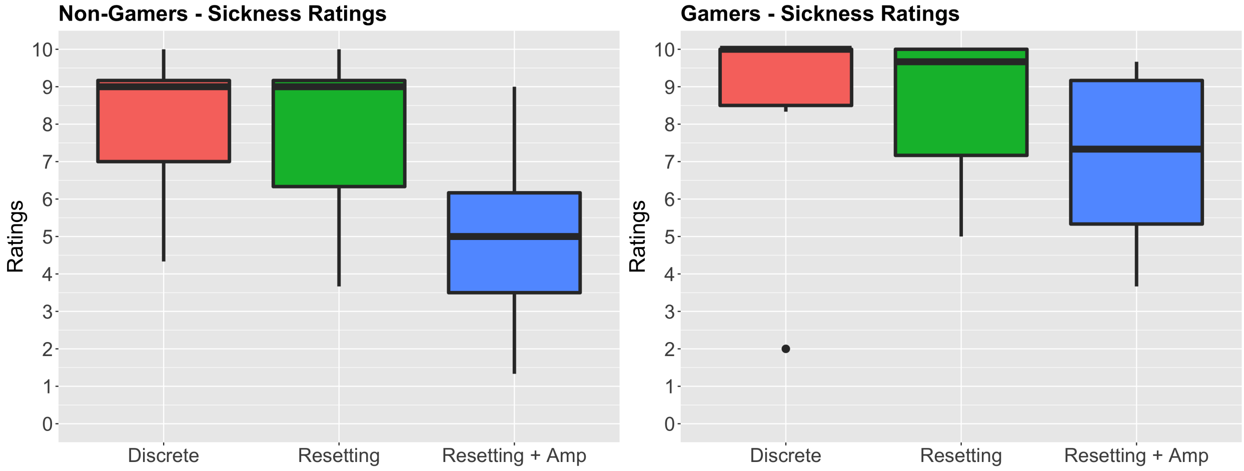

Figure 8.3: Comparative ratings based on sickness from the third experiment. Higher ratings indicate higher preference and lower sickness.

had higher tolerance towards all the techniques in terms of sickness. With both gamers and non-gamers combined, the Friedman non-parametric repeated measures test found a significant effect of the techniques on the sickness related ratings with $\chi^2(2) = 15.86$ and $p = 0.00036$. As expected, the condition with amplification was found to be significantly worse than the other two techniques. The posthoc Nemenyi test found *discrete rotation* to be significantly preferred over *user-controlled resetting with amplification* with $p = 0.0014$ and *user-controlled resetting* to be significantly preferred over *user-controlled resetting with amplification* with $p = 0.033$. Among the gamers, the Friedman non-parametric repeated measures test found a significant effect with $\chi^2(2) = 8.58$ and $p = 0.014$ and the posthoc Nemenyi test found that the gamers significantly preferred *discrete rotation* over *user-controlled resetting with amplification*, with $p = 0.021$.

8.7.3 Preferences for Travel and Orientation

The questions related to ease of travel and maintaining orientation were grouped together and the Friedman non-parametric repeated measures test found a significant effect of the techniques on both gamers and non-gamers combined, with $\chi^2(2) = 7.39$ and $p = 0.025$. The posthoc Nemenyi test, found *discrete rotation* to be significantly preferred over the *user-controlled resetting* (without amplification) technique ($p = 0.041$).

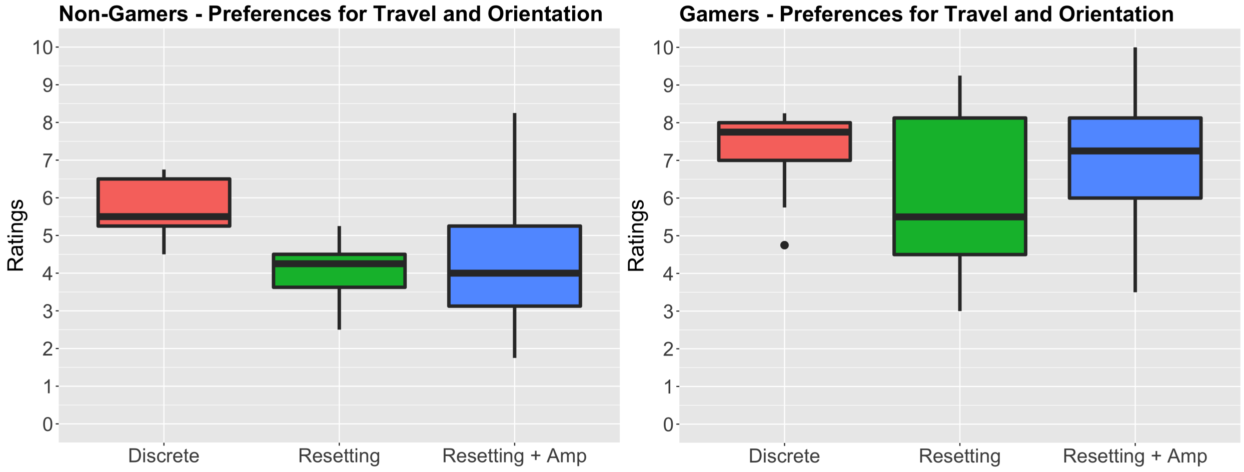

Figure 8.4: Comparative ratings on questions related to ease of travel and orientation from the third experiment. Higher ratings are better.

Figure 8.4 shows that gamers showed more overall interest in the techniques compared to non-gamers. And notably, from the figure, most of the gamers seems to have preferred the resetting technique with amplification over the technique without amplification whereas it is the opposite with the non-gamers.

8.7.4 Preferences for Home Entertainment

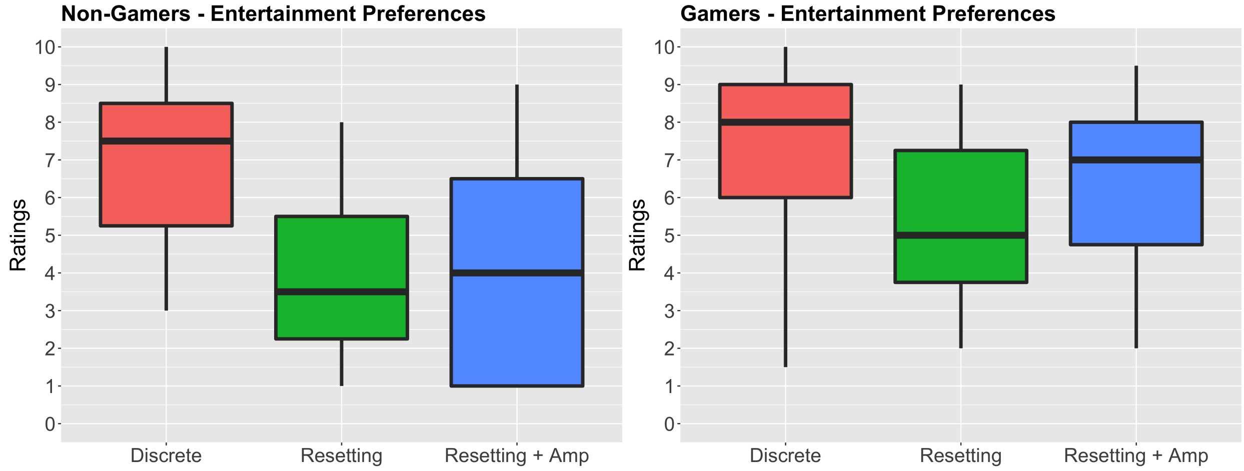

Figure 8.5: Comparative ratings based on preference for home entertainment from the third experiment. Higher ratings are better.

The questions based on how much fun the techiques were, how interested participants would be to use them for home entertainment, how comfortable they were and how much frustration was involved were grouped together to determine the preferences for home entertainment. The Friedman non-parametric repeated measures test found a significant effect of the techniques on both gamers and non-gamers combined, with $\chi^2(2) = 10.46$ and $p = 0.0053$. From the posthoc Nemenyi test, *discrete rotation* was found to be significantly preferred over the *user-controlled resetting* (without amplification) technique ($p = 0.0058$). From Figure 8.5, we can see that the gamers gave higher ratings to all the techniques compared with non-gamers. In particular, it can be seen that the gamers gave higher ratings to the condition with amplification than the non-gamers.

9. DISCUSSION & CONCLUSION

9.1 Summary

Our research work gave many useful insights about semi-natural travel in VR. The results contributed design guidelines for travel and viewing techniques in VR, especially for constrained seating conditions. New semi-natural techniques for travel and viewing were designed with considerations for comfort and simulator sickness. They were compared with existing techniques in controlled experiments to gather empirical data.

The first experiment showed general feasibility of the alternate techniques *guided rotation* and *dynamic amplification* and investigated their effects on spatial awareness of the users, sickness and comfort experienced by the users. One of the main implications from this experiment is that manipulations in rotations can cause sickness problems that affect a VR experience. It also showed that the 3D gaming experience of the users impacted the tolerance towards these new techniques and the preferences for home entertainment and ease of travel and orientation.

Even though the *guided rotation* was not preferred by most of the participants in the first experiment, few participants gave positive feedback about the technique in our case study. These participants were able to understand how the technique works and appreciate how it lets users have a quick 360 degree view and uninterrupted travel. The sickness associated with amplification and rotational adjustments is definitely a big concern. But further studies that extensively test the effects of *guided rotation* and *dynamic amplification* through multiple lab visits, checking if tolerance towards the rotational manipulations is gradually increased over time, will be beneficial to VR use cases that require continuous virtual travel under constrained seating conditions.

Though the joystick rotation techniques *discrete rotation*, *continuous rotation* and *reduced FOV* techniques are commonly used in many VR applications and experiences, there was no empirical evidence from studies that directly compared these three techniques. Our second experiment fills this gap by studying the joystick techniques and finding out that *discrete rotation* is significantly preferred over *reduced FOV* condition in terms of sickness.

A surprising result from the second experiment was the *reduced FOV* condition was rated worse than the *continuous rotation* in terms of preference for home entertainment and it did not considerably reduce sickness effects, compared to continuous rotation. The main reason for this could be the way *reduced FOV* condition was implemented. Unlike the dynamic FOV implemented in a prior research by Fernandes et al. [27], our research tested a single level of reduced FOV during continuous turning, with a mask that was enabled in an all-or-nothing fashion. This could have interrupted the experience of the users while turning and it is a limitation of our experiment.

The third experiment revealed important characteristics about the *resetting* technique when used for seated VR. Similar to the first experiment, the 3D gaming experience influenced the results. *Discrete rotation* was rated the best in terms of sickness, preferences for travel and orientation and preferences for home entertainment as expected. Even though the constant amplification employed in this experiment had sickness effects on the users, it was rated better than the *user-controlled resetting* without amplification and caused less issues in the spatial orientation tasks.

Despite the sickness effects and manipulations in rotations, users performed generally better with the amplification condition in the third experiment compared to the other two techniques in the spatial awareness tasks. This could be possibly because all the participants tested the *user-controlled resetting with amplification* as the last technique. Though this order was chosen to avoid sickness effects of amplification from being carried over to other trials, there could be learning effects because of this order. By the time, participants tested the third technique, they would have already completed the experimental task eight times corresponding to the first two techniques and this could have helped them develop a strategy to complete the tasks successfully while trying the third technique. However, despite the order in which it is tested, resetting with amplification might actually be better than the other two techniques compared because of some obvious benefits like faster rotations, lesser number of resettings and large range of continuous head turning. Further detailed studies that require multiple lab visits or a study following between-subjects design would give more evidences regarding the characteristics of this technique.

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