SOFTWARE TECHNIQUES FOR IMPROVING HEAD MOUNTED DISPLAYS TO CREATE COMFORTABLE USER EXPERIENCES IN VIRTUAL REALITY

BY

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THESIS

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ABSTRACT

Head Mounted Displays (HMDs) allow users to experience Virtual Reality (VR) with a great level of immersion. Advancements in hardware technologies have led to a reduction in cost of producing good quality VR HMDs bringing them out from research labs to consumer markets. However, the current generation of HMDs suffer from a few fundamental problems that can deter their widespread adoption. For this thesis, we explored two techniques to overcome some of the challenges of experiencing VR when using HMDs.

When experiencing VR with HMDs strapped to your head, even simple physical tasks like drinking a beverage can be difficult and awkward. We explored mixed reality renderings that selectively incorporate the physical world into the virtual world for interactions with physical objects. We conducted a user study comparing four rendering techniques that balance immersion in the virtual world with ease of interaction with the physical world.

Users of VR systems often experience vection, the perception of self-motion in the absence of any physical movement. While vection helps to improve presence in VR, it often leads to a form of motion sickness called cybersickness. Prior work has discovered that changing vection (changing the perceived speed or moving direction) causes more severe cybersickness than steady vection (walking at a constant speed or in a constant direction). Based on this idea, we tried to reduce cybersickness caused by character movements in a First Person Shooter (FPS) game in VR. We propose Rotation Blurring (RB), uniformly blurring the screen during rotational movements to reduce cybersickness. We performed a user study to evaluate the impact of RB in reducing cybersickness and found that RB led to an overall reduction in sickness levels of the participants and delayed its onset. Participants who experienced acute levels of cybersickness benefited significantly from this technique.

To my parents, for teaching me the values that have stood the test of time

ACKNOWLEDGMENTS

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To Tanmay, Jyoti, Gaurav and Aditi for their friendship, advice, encouragement, and for always willing to be the guinea pigs of all my experiments. This thesis would not be possible without their help.

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TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

Virtual Reality (VR) can be defined as generation of a simulated environment by a combination of software and hardware that can successfully manipulate human senses to feel present in the simulated environment. Ivan Sutherland is credited to have created the first VR Head Mounted Display in 1968 [1]. Although early VR systems existed around the mid-20th century, Jaron Lanier popularized the term in 1980s and later founded VPL Research, the first company to sell VR products. During early 90s, VR gathered public interest with the launch of VR headsets and arcades. Although these devices piqued consumer interest, lack of sufficient hardware, limited technology, poor ergonomics and high cost impeded their adoption by consumers. Past two decades have seen major developments in gaming and mobile industry to create powerful graphics hardware, high resolution screens, mobile graphics and mobile sensors. Availability of advanced hardware has enabled production of good quality, yet cheap VR devices leading to a wave of resurgence of VR.

While multiple devices have been used to display VR environments, Cave Automatic Virtual Environment (CAVE) and Head Mounted Displays (HMDs) are most popular. CAVE systems create VR environments by projecting on walls of a room-sized cube. CAVE systems successively project a pair of images (one for each eye) on each wall of the cube to create a virtual scene. Users can see 3D rendering of the virtual scene by seeing these projections through synchronized stereo shutter glasses. Motion capture systems are used in CAVEs to record real time position of users to enable perspective rendering. Although CAVEs are popular in research labs and training facilities for simulation and training applications, elaborate setup requirements and high cost make them prohibitive for general use.

HMDs are stereoscopic display devices worn on a user's head. Stereoscopic display, which when seen through a pair of lenses, creates 3D virtual environments with a large field of view. Along with the stereoscopic display, they also have Inertial Measurement Units (IMUs), magnetometer and gyroscope to accurately track user's head movements. Their ergonomic design and low cost of production make them ideal for consumer use. Next year is going to see public launch of HMDs like Oculus Rift, HTC Vive and PlayStation VR hopefully starting a new wave of popularity for VR.

While being highly immersive, HMDs occlude the real world, making physical and social interactions difficult and awkward. Currently, users have two choices: keep the HMD on and blindly interact with the world, or take the HMD off and break their immersion in the virtual world. Such context switching between worlds is expensive: it takes time to be immersed in a virtual environment [2], and frequent switching between worlds can be disorienting.

While exploring virtual environments using HMDs, users often experience a sensation called vection. Vection is the perception of self-motion elicited by a moving visual stimulus in the absence of any real motion. A common real life example of vection is the illusion of motion when sitting in a stationary train while watching an adjacent train move.

Users of VR devices commonly experience vection when they move in the virtual environment while remaining stationary in the real world. Although experiencing motion in a virtual environment adds to the sense of presence in the virtual environment [3], it often leads to a form of motion sickness called cybersickness.

Cybersickness is a form of motion sickness that often accompanies vection. Symptoms for cybersickness include dizziness, fatigue, cold sweat, oculomotor disturbances, disorientation, nausea and (rarely) vomiting. Although the symptoms closely match those of motion sickness, oculomotor disturbances and disorientation are more common with cybersickness than motion sickness [4]. Prior work indicates that long exposures to VR exacerbates cybersickness, while repeated exposures to VR reduces the severity and incidence of cybersickness [5].

CHAPTER 2

RELATED WORK

2.1 Mixed Reality

VR's long and rich history began with Ivan Sutherland's pioneering work on HMDs in the early 60s [1]. The recent commercial availability of low-cost HMDs have made VR experiences generally accessible to a wide audience. Since its inception, a large body of VR work has explored approaches for incorporating static and dynamic avatars into virtual environments, typically requiring users to wear motion capture markers or data input gloves (e.g., [6]).

There are many approaches that merge the physical and virtual worlds [7]. Augmented Reality (AR) superimposes virtual objects into the physical world, and has a rich history of use in mobile phones and HMDs (e.g., [8]). In contrast, Augmented Virtuality (AV) enhances virtual reality with parts of the physical world. Previous work in AV has focused on collaborative applications including displaying real world video on virtual office windows [9] or displaying group communication around a virtual table [10].

Researchers have traditionally used gloves [11], fiducial markers [12] or motion capture systems [13] to track and show a virtual rendering of users' hands in virtual reality. Some techniques ([14], [15]) have used computer vision algorithms on 2D RGB images to track users' bare hands and use them as an interface for interaction in mixed reality applications. More recent work (WeARHand [16] and I'm in VR! [17]) has used RGBD sensors to bring user's bare hands into the virtual world and use it as an interaction medium.

2.2 Cybersickness

A number of theories exist to explain the relationship between cybersickness and vection. One of the most prominent theories is based on the idea of sensory conflict during vection. According to this theory, a mismatch of information from the visual sensory system and the vestibular system (human sensory system sensitive to motion, equilibrium and spatial orientation) about motion during vection leads to cybersickness [18]. Another theory that explains cybersickness is based on the idea of postural stability. It posits that changes in stability of the human balance mechanism causes cybersickness [19]. Work by Hettinger et al. [20] is one of the early works to understand the relation between vection and SS. They exposed users to a fixed-based flight simulator and measured both vection and SS simultaneously. Later, work by Kennedy et al. introduced Simulator Sickness Questionnaire (a modification of Motion Sickness Questionnaire) to systematically measure the simulator sickness response of a virtual reality simulator [21]. Recent work by Keshavarz et al. [22] provides an in-depth review of the past work exploring this area.

Cybersickness is a major deterrent to large scale adoption of VR devices. Past research has explored several methods to reduce the cybersickness response in VR. Work by Dorado and Figueroa proposes that ramps induce less cybersickness when compared to stairs in VR [23]. Domeyer et al. studied the effects of giving breaks between consecutive driving simulator sessions on reducing SS for older drivers [24]. Jeng-Weei Lin et al. discovered that providing motion prediction cues in driving simulators help to reduce SS while not affecting presence [25]. Another work by the same group discovered that adding a virtual guiding avatar that provides motion cues helps to reduce SS in driving simulators [26]. They also found out that adding the virtual guiding avatar enhances a user's sense of presence in the virtual environment.

Research work in the past has explored using blurring to reduce cybersickness in VR. Carnegie et al. in their work [27] try to reduce visual discomfort by adding depth of field blur to the virtual scene. Work by Leroy et al. [28] proposes an algorithm for implementing a real-time adaptive blur to remove irritating high frequency content in high horizontal disparity zones of stereoscopic displays. The proposed algorithm helps to reduce eye strain caused by stereoscopic displays. Work by Jung et al. [29] proposes a selective depth of focus blur technique that is applied only to regions that induce high visual discomfort but are less important visually. Blum et al. investigated the effectiveness of adding artificial out of focus blur on visual discomfort to increase fusion limits of double vision occurring in stereoscopic displays [30].

CHAPTER 3

PERIPHERAL REAL WORLD INTERACTIONS WHEN USING HMDS

In this work, we explored a design space of renderings that enabled users wearing an HMD to interact with the physical environment. The goal was to make interactions with the physical world more seamless, while keeping the user immersed in the virtual world. Unlike previous work in augmented reality [31, 32] that explored using stereo cameras to show physical world in HMD, we overlayed the physical world on top of virtual environment (i.e. augmented virtuality [7]). Users can see their hands in the virtual environment, peripheral objects like a cup, or colocated players (see Figure 3.1).

We evaluated this design space of mixed reality renderings with a user study comparing different renderings of varying visual fidelity across different virtual experiences (a movie, a first person shooter, and a racing game). The results show that users prefer renderings which selectively blend virtual and physical, while maintaining a one-to-one scaling of the physical environment. The highest rated rendering allows users to see their hands, objects of interest and salient edges of the surrounding environment.

3.1 Design Space

When users are immersed in an HMD focusing on a virtual experience, including information from the physical environment can distract from the virtual experience. However, if too little information of the physical environment is included, then physical interactions are difficult. Therefore, we explore four rendering options (see Figure 3.3) using different amounts of information about the physical environment in the virtual experience. We envision these renderings could be activated by the user via a button on the game controller / keyboard, enabling the user to switch on the physical environment when needed.

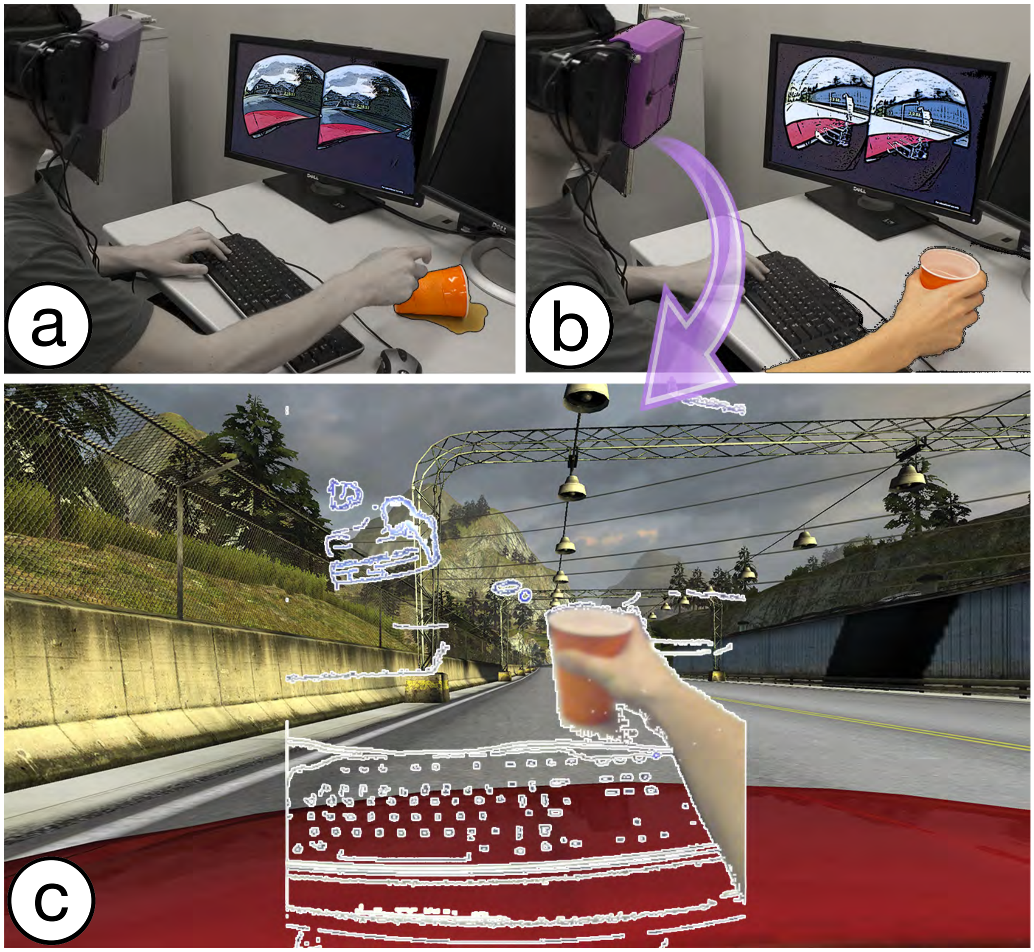

Figure 3.1: Performing real world, peripheral tasks while using VR HMDs can be frustrating and messy (a). Our system, comprised of 2 inexpensive webcams and novel augmented virtuality methods (b), allows users to achieve peripheral tasks, such as grabbing a drink, while still being immersed in the HMD experience (c) without knocking over your drink.

These renderings are enabled by a system combining an HMD with stereo cameras and simple vision processing. We use the Oculus Rift DK1, augmented with 2 Logitech C310 webcams to provide a stereoscopic view of the real world. The lenses of the cameras were replaced with 1.8mm lenses [1] to provide a wider FOV of approximately 120 degrees, and then mounted in a 3D printed mount [2] (see Figure 3.2). Users also wore headphones to create a fully immersive experience.

[1] http://www.thingiverse.com/thing:305355

[2] http://www.thingiverse.com/thing:323913

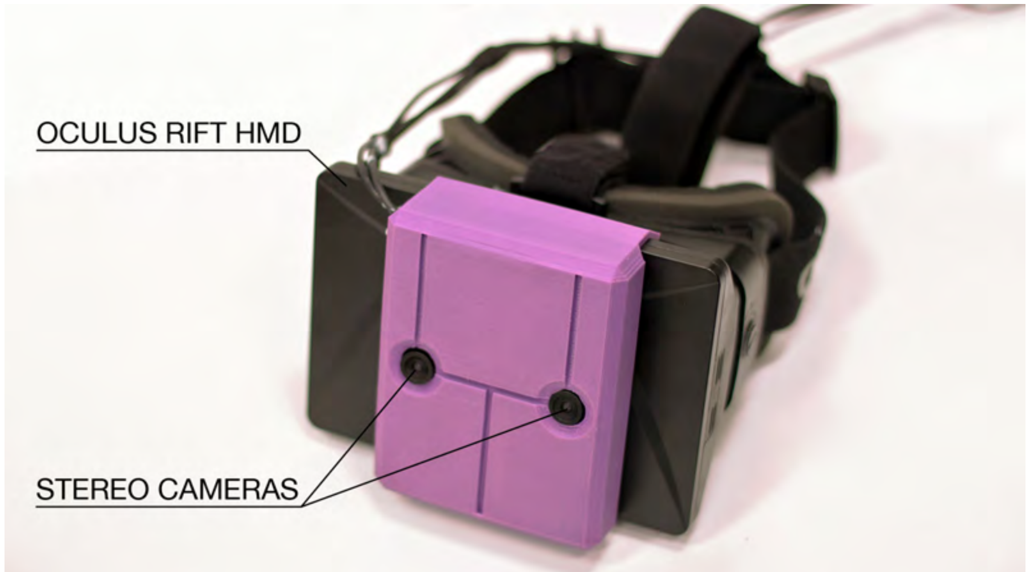

Figure 3.2: The HMD augmented with a stereo camera set.

Figure 3.3: All the different renderings. (a) Object and Hands, (b) Object, Hands and Context, (c) Real World Windowed, (d) Physical Picture In Picture

3.1.1 Renderings

In order to guide our selection of renderings, we performed a pilot study to understand the minimum amount of information needed to perform basic grasping interactions with the physical world. We discovered that users prefer to see, at the very least, their hands and the object of interest. Showing the object of interest allows users to spatially locate the object, and seeing their hands increases proprioception accuracy[33]. We experimented with showing only the object of interest, but it was universally disconcerting to users. With this information, we designed the following renderings:

Object & Hands (OH)

The first rendering shows the bare minimum information, only the object of interest and the user's hands. The supporting table and other physical objects were not shown in the virtual world. This rendering enables the user to focus on the virtual experience, at the expense of limited knowledge of the physical environment.

Object, Hands & Context (OHC)

The second rendering shows the object of interest, the user's hands and an abstract depiction of the surrounding physical objects, showing only the edges of surrounding objects. This rendering provides additional context at the expense of potential distraction from the virtual experience.

Real World Windowed (RWW)

The third rendering provides a windowed view of the physical world, with the virtual world still shown in the user's peripheral vision. The real world is rendered in a fully opaque window at the center of the user's visual field. This rendering allows the user to focus on their interactions in the physical world, while still maintaining peripheral cues about the virtual environment.

Physical Picture in Picture (PPIP)

The fourth rendering shows the physical world as a picture in picture rendering in the lower right hand corner of the screen. This mimics the behavior of picture-in-picture televisions. It is interesting to note that this method is the exact opposite of see-through wearable devices like Google Glass, which enable users to see a large version of the real world with the virtual world in a small picture in picture. This rendering allows users to interact with the physical world, without taking up as much screen real-estate as *RWW*.

In this paper, we focus on the user experience of each visualization, and less on the specific implementation of the rendering approach. We envision a future of natural user interaction systems which can easily track a user's hands [32], and detect and track physical objects (perhaps with the aide of embedded markers). For the user study, selective rendering was accomplished via color based segmentation in OpenCV [3], segmenting the users hands and a known object of interest (an orange cup). Future work can explore more complex object detection, recognition and tracking schemes to support these renderings.

3.2 User Study

The purpose of this study was to elicit qualitative feedback about the design space of renderings in the context of different genres of VR experiences. We specifically wanted to find if our renderings allow users to remain immersed in the virtual reality experience while seeing parts of their physical environment. We also wanted to evaluate how our renderings compare to the status quo (baseline) solution for interacting with the physical environment while wearing an HMD, namely to remove the HMD entirely. We hypothesize that (1) the preferred rendering will depend on the virtual content, changing with varying levels of user engagement, and (2) that users will prefer *OH* since it provides a balance between visual information of the physical world, without being overly distracting.

To select the VR experiences used in the study, we tested a variety of VR applications. We wanted to use rich visual experiences that are representative of real-world use cases in VR, and that require differing levels of user attention and user input.

3.2.1 Virtual Scenarios

To select the VR experiences used in the study, we tested a variety of VR applications. We wanted to use rich visual experiences that are representative of real-world use cases in VR, and that require differing levels of user attention and user input. We created the following experiences in Unity3D [4]: (1) watching a movie [5] in a movie theater, (2) a First Person Shooter (FPS) modified from Unity3D's 3rd person AngryBots sample, and (3) a racing

[3] http://opencv.org/
[4] http://unity3d.com
[5] http://sintel.org

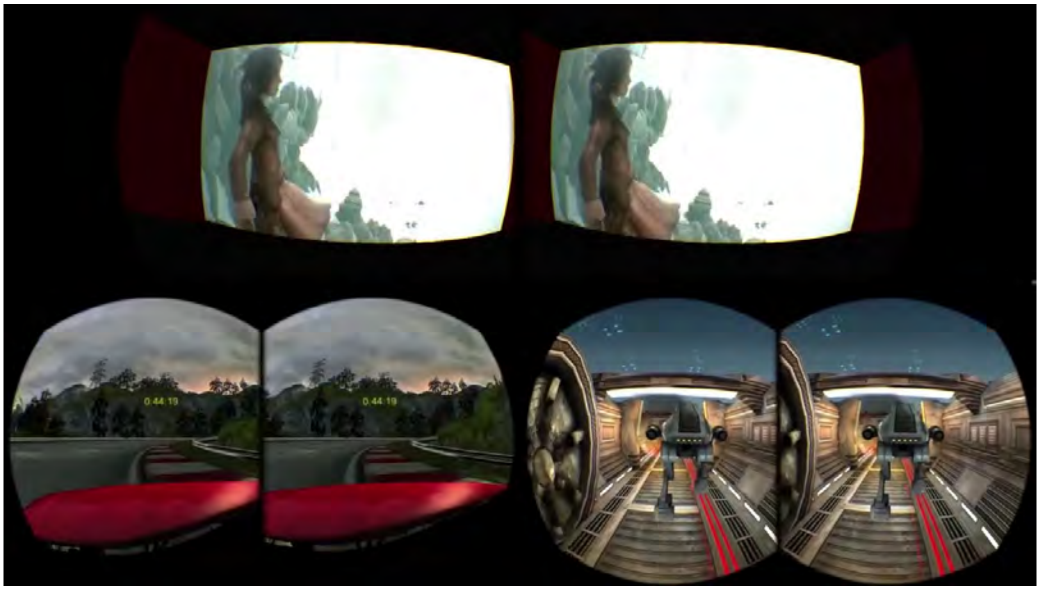

Figure 3.4: The three different VR scenarios that we used for the user study, Movie, FPS and Car.

game modified from Unity3D's Car Tutorial (Figure 3.4).

The movie is a passive experience with no user input that uses a limited field of view of the user and requires minimal head movement. The FPS is a fast paced experience that requires both mouse and keyboard input with lots of head motion, but still contains natural pauses in game play for the user to interact with the physical environment. The racing game is a continuous attention task, where the user must constantly steer their car or risk crashing, with only keyboard input needed leaving one hand free to interact with the physical environment.

3.2.2 Participants

We recruited 16 subjects (13 male), ages 18-24 years with some PC gaming experience and corrected to normal vision. Of our 16 participants, 6 were excluded from the study due to significant simulator sickness (even with brief pauses between conditions). Incidence rates of simulator sickness are very high with current HMDs [34]. As a result, 10 participants completed the study, producing a total of 300 grasping trials. We expect that improvements in display latency, resolution and refresh rate will decrease simulator sickness in the near future.

3.2.3 Tasks and Procedure

We conducted a within subjects user study, where subjects interacted with 3 VR experiences in a randomized ordering using a PC keyboard and mouse while seated at a table. While engaged in the virtual experience, subjects were externally prompted every 45-60 seconds to pick up a physical cup of water, drink the water, and place the cup back on the table. This physical task was repeated twice for each of the 4 rendering methods and the baseline method, in a randomized ordering with 5 minutes of rest between renderings. Subjects were instructed to focus on their performance in the VR experience and remain highly engaged in the game/movie. Physical distractor objects were included on the table as well (a mobile phone, speakers and pieces of paper). After each physical interaction with the cup, the experimenter moved the cup to simulate the user loosing track of the physical environment during more realistic long term play scenarios. In total there were 30 trials per subject, 3 VR experiences x 2 repetitions x (4 renderings + baseline).

Between each rendering, subjects completed a questionnaire inspired by the core modules of [35], where they rated their overall satisfaction, immersion, level of distraction, ease of play etc. (see Figure 3.5). At the end of the study, subjects ranked the rendering methods along various dimensions (see Figure 3.6), with visual mnemonics to remind the users of each condition. Finally, we conducted a semi-structured interview with think-aloud subject feedback. We also recorded video, which we analyzed for apparent ease of interaction with the physical world.

3.2.4 Results

The intra rendering results (see Figure 3.5) show an overwhelming support for OHC, which was rated as the most preferred method by participants across all VR scenarios (meanMovie = 3.7, meanFPS = 3.7, meanCar = 3.7). Using a Kruskal Wallis non-parametric test, we found significant differences between visual renderings. A post-hoc Bonferroni-corrected Wilcoxon test on the OHC performed significantly better than RWW and PPIP, both in Car ($Z = -2.713$, $p < 0.01$, $Z = -2.56$, $p < 0.01$) and FPS ($Z = -1.732$, $p < 0.01$, $Z = -1.99$, $p < 0.01$).

This result was further validated in the mean rankings analysis where par-

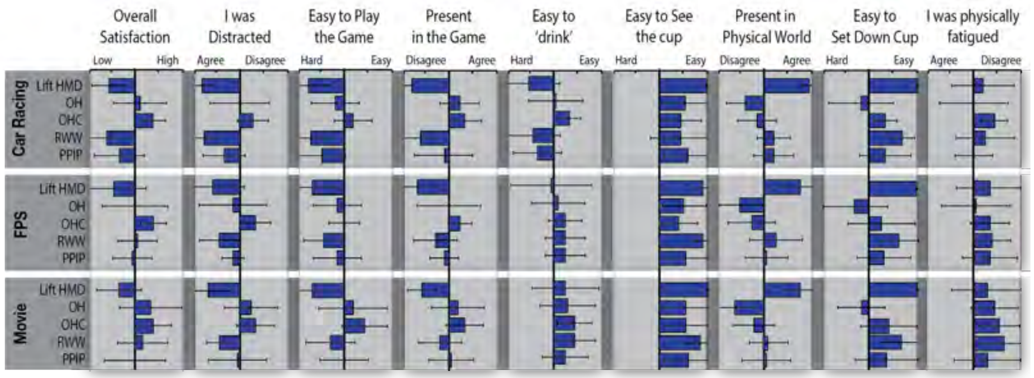

Figure 3.5: Mean ratings for each method evaluated in the user study. Participants rated 'overall satisfaction' and 8 other factors on a 5 point Likert scale. The errorbars represent standard deviations. OHC is highly rated for overall satisfaction in all 3 VR environments (meanMovie = 3.7, meanFPS = 3.7, meanCar = 3.7).

ticipants consistently ranked OHC highest in overall satisfaction across all VR scenarios and also for each individual VR scenario (Figure 3.6). In all cases, the baseline condition of removing the HMD was always the least preferred approach. However, Figure 3.5 illustrates a substantial pattern where Lift HMD, RWW and PPIP were more acceptable to participants in Movie, eventually becoming less tolerable in the higher engagement scenarios (FPS & Car). Contrary to our expectation of OH being ranked the best method, OH was consistently ranked second in overall satisfaction, immersion, presence and distraction with high variance across users (meanMovie = 1.174, meanFPS = 1.247, meanCar = 1.033).

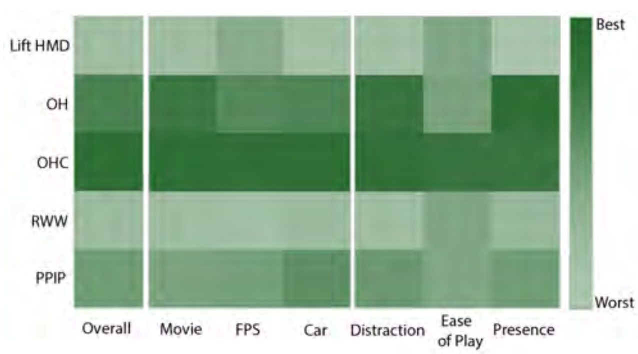

Figure 3.6: Post user study mean rankings. (left to right) Overall satisfaction across all VR experiences, overall satisfaction for each VR experience (Movie, FPS, Car), overall distraction, ease of play and presence across all VR experiences.

On the whole, participants' qualitative feedback reflected our empirical findings. With OHC, users described how the additional contextual information of their surroundings aided them in finding the cup. As one user described, *"The extra lines helped me find the cup and put it back, and it wasn't distracting, it didn't break my concentration on the game."* However, some participants liked the minimal nature of OH, with one user commenting *"even though I could not see the cup...I got used to the surroundings and the table and had a fair idea of where to look for the cup."* In contrast, one user who favored OHC noted for OH, *"I felt lost and had to feel the physical space around me to look for the cup."*

The Lift HMD approach was disliked across VR scenarios with one participant commenting, *"removing the goggles is immersion breaking, with [OH] and [OHC], I still felt pretty much in the game. [RWW] and [PPIP] are a little more immersion breaking."* With RWW, one user commented, *"you are kind of in limbo when you're doing [RWW], you might as well lift and do it quickly. I don't feel like I am part of the virtual world but I don't feel like I am in the real world."* When asked if participants would prefer any other location for rendering the preview window in PPIP, one user noted, *"it wouldn't make any significant difference since you still have to concentrate on a corner which takes away your focus from the game."*

3.3 Discussion & Future Work

The clear winner among our selection of visual renderings was to show users the object of interests and their hands while using edges to visualize the supporting surfaces. OHC allowed users to quickly re-acclimate themselves to the physical environment, particularly when significant head/body motions disconnected users from their physical surroundings. Some users suggested that pausing the game would be preferred, however this is only possible with non-multiplayer games. Future work could explore various methods for pausing the game experience via audio input, touch input on the HMD, controller input or even automatically detecting a user's reaching motion.

Designers looking to visualize aspects of the physical world should consider balancing the scale of the rendered objects with its placement in the virtual world. We found that users felt naturally comfortable seeing a version of the cup that was close in size to the actual physical cup and from their own ego-centric viewpoint. This was not the case with the PPIP technique which forced users to switch between seeing the game and the window while requiring additional time to acclimate to the small sized view of the physical world. Furthermore, visual rendering techniques could be designed in the future to take advantage of unused pixels in the virtual environment. For example, users frequently thought that the dashboard of the virtual car could be used to show parts of the physical world where it would otherwise provide little to no information in the virtual experience.

In the future, virtual reality experiences could be augmented to react to physical objects. For instance, new physical toys could be designed to act as controllers to the game (e.g., guns, wands, etc.). Designers could also leverage existing objects as weapons, or enable physical interactions with the environment to affect the game. For example, drinking a glass of water can be used to recharge a user's health in an FPS game.

CHAPTER 4

USE OF ARTIFICIAL BLURRING TO REDUCE CYBERSICKNESS IN VR FIRST PERSON SHOOTERS

For this project, the objective was to reduce cybersickness experienced in VR gaming to make gaming in VR a comfortable and enjoyable experience. Past research has shown that changing vection (changing the perceived speed or moving direction) induces more severe Simulator Sickness (SS) than steady vection (walking at a constant speed or in a constant direction) [36]. SS is another form of motion sickness experienced when using driving or flight simulators. Although minor differences exist between cybersickness and SS [37], they are closely related. Work by Trutoiu et al. [38] suggests that among all forms of movement, rotation causes the maximum amount of SS. Given these findings, we focused our attention towards reducing cybersickness during rotations. Work by Riecke et al. [39] indicates that photorealistic looking virtual environments enhance the amount of vection users experience when compared to the scrambled version of the same virtual environment.

We propose a novel navigation technique for VR games called Rotation Blurring (RB) which can help to reduce cybersickness. As the name suggests, the technique blurs the rotational movements triggered by an external controller in the virtual world. We hypothesize that blurring the rotations will make the parts that cause the most cybersickness look less photorealistic, thereby suppressing the overall level of cybersickness induced by those movements. We performed a user study to evaluate this hypothesis. For the user study, we chose to test our technique in a First Person Shooter (FPS) game. The high action gameplay of the FPS requiring continuous navigation makes it an ideal environment to test our technique.

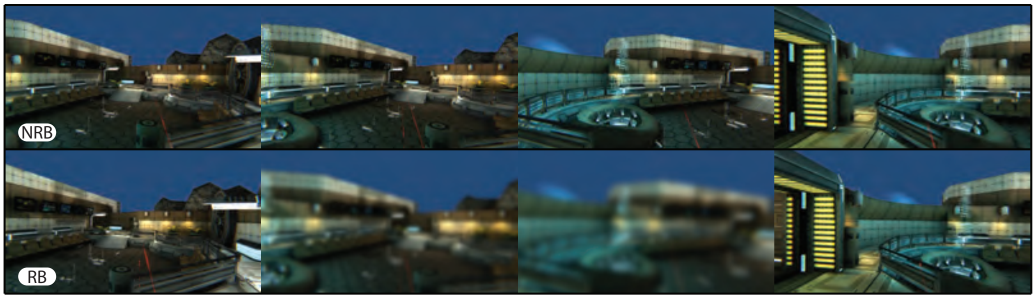

Figure 4.1: Screenshots of 2 versions of the game. One with Rotation Blurring disabled (NRB) and one with Rotation Blurring enabled (RB).

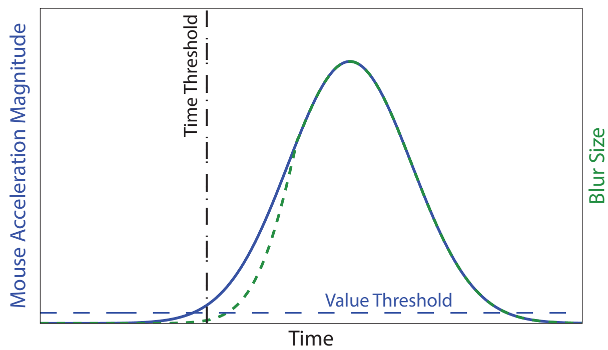

Figure 4.2: Blur size with respect to magnitude of acceleration of mouse. The blurring activates only when continuous rotation is detected and the mouse acceleration is greater than the value threshold

4.1 Blurring Technique Description

Rotation Blurring (RB) was implemented using shaders in Unity3D, a popular game engine that supports VR headsets. Typically for FPS games, character rotations are controlled by the mouse. Therefore, the movement of the mouse controller was the primary input signal to trigger and control RB. Whenever the mouse is used to rotate the game character by a user, a uniform Gaussian blur is applied to the screen. The amount of blur (standard deviation of the Gaussian function) was directly proportional to the magnitude of acceleration of the mouse movement. This proportionality ensured a smooth transition from a non-blurred to a blurred screen (and vice versa) as opposed to discrete jarring jumps between non-blurred and blurred screen. Figure 4.2 shows a comparison of the response curve of RB with respect to movement of the mouse controller.

For this research, we used an Oculus Rift DK2 HMD which tracks the orientation and position of the user's head. Any changes in the view point caused by user's real world head movements were not blurred.

RB was applied such that it only activates for rotations when navigating the game environment and not during other small movements like aiming the gun or dodging enemy fire. This was ensured by a combination of two rules (fig 4.2). First, the blurring would only activate when the magnitude of acceleration of the mouse is over a certain minimum threshold value. Second, the blurring would only activate if a continuous mouse motion is detected for a time threshold of 5 frames.

4.2 User Study

In order to understand the effects of RB on cybersickness, we conducted a within subjects user study where participants played a VR FPS game which was modified to enable RB. For comparison, participants also played another version of the game with RB disabled. We hypothesized that adding RB to the game will significantly reduce cybersickness experienced by the participants.

For this study, we used an Oculus Rift DK2 HMD connected to a Windows PC. To gauge the sickness levels of participants, we used the standard 16 question Simulator Sickness Questionnaire (SSQ) [21] where each question could be answered on a Likert scale of 0-3.

4.2.1 Virtual Scene Description

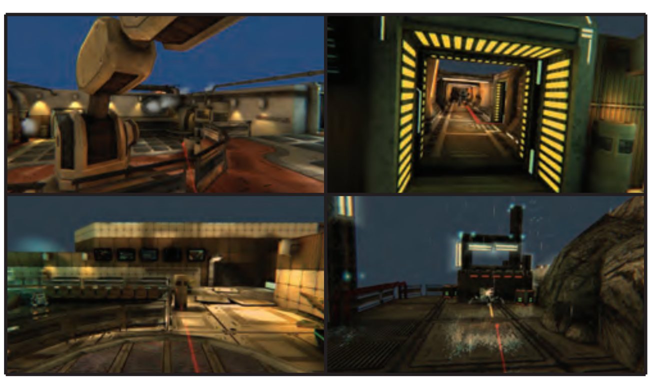

Figure 4.3: Screenshots of the Virtual Reality First Person Shooter game

We created the FPS shooter game using an open source Unity3D project called AngryBots. The game is set in an industrial setting and features many enemy bots spread across the arena (Figure 4.3). For the study, the objective was to explore the game arena and destroy as many enemy bots as possible in 10 minutes. Participants used keyboard and mouse to control the character (using standard FPS controller layout). We created two versions of the game - with and without RB. We refer to these as RB and NRB respectively (Figure 4.1).

In the game, the view vector of the character was coupled with the aim vector of the gun. Participants controlled the aim vector of the gun using the mouse. The coupling ensured that users did not have to move their head in conjunction with the mouse movement in order to see the gun's pointer. However, user's head movements could still independently control the viewing vector of the character. Doing this ensured that users did not have to move their head in the game all the time and suffer from the resulting neck sprain.

In order to reduce cybersickness from other types of movements except rotation, some modifications were made to the character controls. Rotational movements with the mouse were only restricted in the horizontal plane. This was done since past research claims that frequent rotations with two degrees of freedom cause significantly more SS than rotations with one degree of freedom [40]. The aim vector was fixed to be parallel to the ground and the game was modified to ensure all the enemy bots could be destroyed without any vertical rotations. Work by Trutoiu et al. [38] suggests that strafing (linear movement in left/right direction) is the most unconvincing form of movement in VR and also the second most SS causing form of movement after rotation. Hence, strafing movements in the game were disabled. In order to minimize cybersickness from linear walking, the character moved at a constant speed [36].

4.2.2 Procedure

The study was conducted over two sessions on consecutive days. During each session, participants were tasked to play either the RB version or the NRB version of the game. The ordering of the tasks was determined randomly. We avoided performing both tasks on the same day to avoid the

Figure 4.4: User study setup

cumulative nature of nausea from biasing the amount of cybersickness experienced by participants in the latter task. Before each task, participants were pre-screened for good health by measuring their Total Sickness (TS) score determined from a SSQ filled before each session. Any user with a TS score of over 7.48 was rejected for the study as recommended in [41]. This ensured that participants were in an equally healthy mental state before both sessions. All participants had normal or corrected to normal vision. Any participant who used glasses were given the option to use them inside the headset. Figure 4.4 shows the user study setup.

In each session, users played the game for 10 minutes with the objective of destroying most number of bots. Users were visually reminded of their score and the high score every two minutes in the game. The challenge of beating the high score kept users engaged with the game. During the game, after every 2 minutes, participants were shown a sickness scale from 0-6 and were asked to verbally report their level of motion sickness symptoms. We used the motion sickness rating scale used in [42] (which is a minor modification of the scale from [43]). We advise readers to refer to figure 4.7 for a detailed description of each rating level.

At the end of the task, users were asked to fill the SSQ to gauge their post-task sickness levels. This was followed by a post study questionnaire and an interview.

We received 18 responses from interested individuals for the study (14 males, 4 females) from an age group of 18 to 26 years. Users were required to have some past experience of playing FPS games. 1 user was rejected during pre-screening process as his/her pre-study TS score was higher than acceptable limit. 2 other users got very sick within first 2 minutes of the study and could not continue. In the end, we had 15 participants (12 males, 3 females) successfully complete the study.

4.2.3 Results

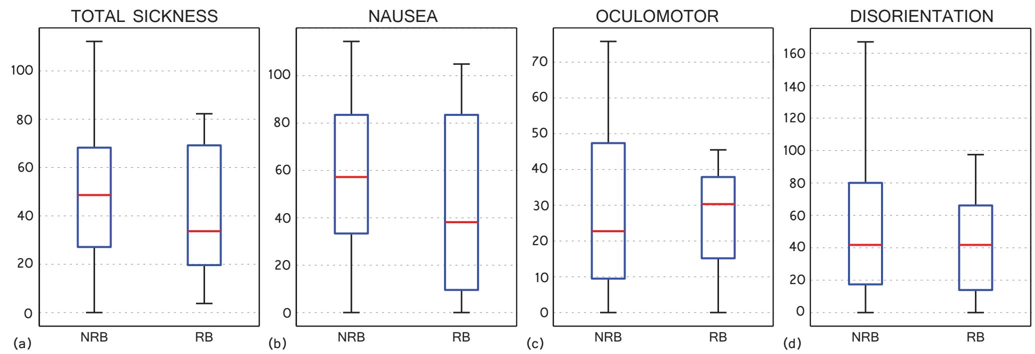

Figure 4.5: Boxplots of (a) Total Sickness (NRB - mean = 51.36 SD = 34.67 RB - mean = 42.14 SD = 27.61), (b) Nausea (NRB - mean = 57.24 SD = 35.51 RB - mean = 47.06 SD = 41.34), (c) Oculomotor (NRB - mean = 29.81 SD = 23.88 RB - mean = 25.77 SD = 15.11) and (d) Disorientation (NRB - mean = 52.90 SD = 47.70 RB - mean = 40.83 SD = 29.98), obtained from SSQ responses.

Participants were asked to fill a SSQ before and after each task. The pre-task SSQ response was used for pre-screening participants for good health before the start of a task. After each session, participants' post task questionnaire responses were used to derive their TS score for the task. Figure 4.5(a) shows the aggregated TS results for the NRB (mean = 51.36, SD = 34.67) and RB (mean = 42.14, SD = 27.61) conditions. The mean TS response went down from 51.36 to 42.14 when RB was enabled. We performed a Wilcoxon signed-rank test on TS results to establish whether this decrease was statistically significant. The tests indicate that results are not statistically significant ($p = 0.19$). Observing the TS levels of individual participants gives an insight to this. Figure 4.6 shows the TS results for each individual participant for both NRB and RB conditions. It can be observed that 2 participants (User 4 and 10) saw a significant increase in TS from RB. Some

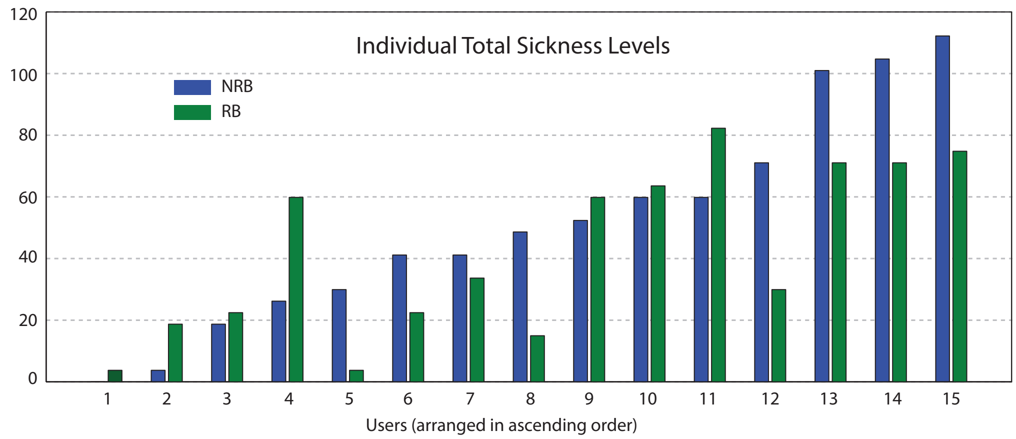

Figure 4.6: Individual TS scores of participants for NRB and RB versions

other participants experienced slight increase in TS on introducing blurring. All other participants (especially the ones who experienced acute levels of TS) reported a significant drop in SS with the blurring technique.

Figures 4.5 (b), (c) and (d) show box plots for the three discomfort symptoms: Nausea (N), Oculomotor (O) and Disorientation (D). These were calculated from the post task SSQ responses. We observed a decrease in the mean sickness measure for each of the three discomfort categories. Mean N decreased from 57.24 to 47.06, mean O decreased from 29.81 to 25.77 and mean D decreased from 52.90 to 40.83.

Participants were instructed to report their level of motion sickness symptoms on a scale of 0-6 after every 2 mins of gameplay. Figure 4.7 shows a plot of mean nausea levels at 2 minute intervals in both the NRB and RB versions of the game. Fig 4.7 indicates that blurring helped delay the onset of SS. At the end of the study, participants filled out a post study questionnaire to rate awareness of RB, distraction caused from RB and presence in VR, with and without RB, on a 5 point Likert scale. Figure 4.8 shows a summary of those responses. As the figure indicates, participants were highly aware of RB. They did not find RB very distracting. RB did not significantly decrease their level of presence in VR.

The subjective opinions of participants recorded during the interview about RB showed a lot of variation. Lot of participants found blurring to be helpful and it did not bother them. One participant said ”*I think blur helped. It was jarring at first but I got used to it. I do think it helped*”’ Another participant responded ”*Movement being blurred made it much easier. My eyes didn’t*

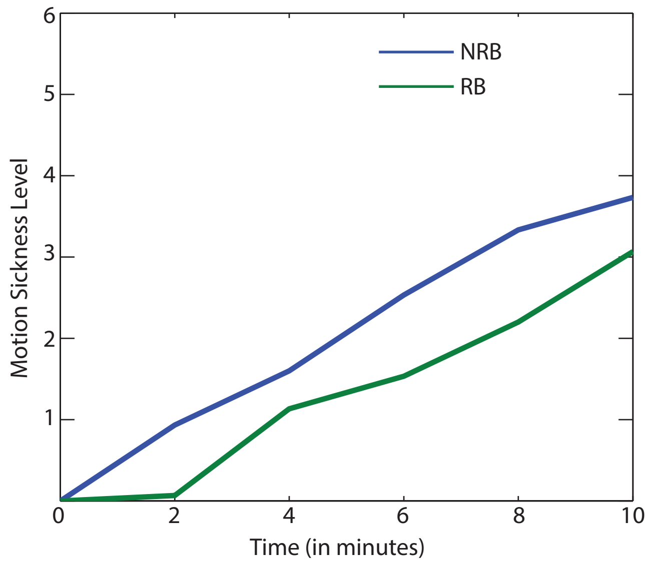

Figure 4.7: Plot of mean motion sickness levels vs time on a scale of 0-6. 0 - no symptoms, 1 - any unpleasant symptoms, 2 - mild unpleasant symptoms, 3 - mild nausea, 4 - mild to moderate nausea, 5 - moderate nausea but can continue and 6 - moderate nausea, want to stop

get dizzy this time. I was scared last time to make quick turns (NRB). I feel I could go on for 2 more hours!". Some users disliked blurring. One participant commented "*blurring distracted me from gameplay*". Another participant commenting about the amount of blur said "*lot of blur was not pleasant*".

4.3 Discussion and Future Work

The results from the user study show that RB helped in decreasing the overall cybersickness experienced by the participants. While it did not help some of the participants, it significantly helped those who experienced acute level of cybersickness. Post study interview comments about preference for RB also show this bipolar trend. While some participants felt that RB greatly benefited them in reducing nausea and would like it to be present in VR games, others felt that it distracted them from the game and made them more nauseous. The results also show the positive impact of RB on delaying the onset of nausea. All participants saw a gentler growth in nausea level over time when RB was enabled. The reduced nausea level, enabled by RB,

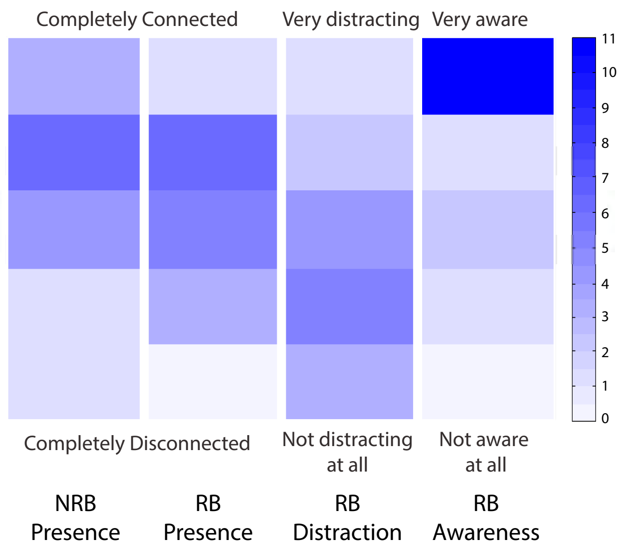

Figure 4.8: Post Study Questionnaire Responses

could help users play FPS VR games for longer periods of time.

Before the start of the study, we asked users to report their past experience of playing FPS games to ensure that they had some past FPS gaming experience. It was interesting to note that users who experienced low levels of cybersickness also reported lot of experience of playing traditional FPS games. The same set of participants also saw an increase in cybersickness when RB was enabled. We believe that a significant exposure to navigation in FPS games desensitizes them to experiencing vection and hence cybersickness. While this was an interesting observation, no conclusions can be drawn about it from the the current data. A thorough study in the future can help to validate or invalidate this theory.

The current results open up the opportunity to conduct further research in exploring other ways of applying blur to cybersickness inducing movements in VR. Since users are more perceptive to optical flow in the peripheral regions of the eye, future work can explore the effect of applying only peripheral blur during rotations to reduce cybersickness.

Since some participants found the blurring to be ineffective and disruptive, future Just-Noticeable Differences (JND) studies can find the optimal response curve of blurring relative to movement in the game and the optimal amount of blur to add to the game which minimizes cybersickness while avoiding discomfort.

Before the study we assumed that RB would cause a significant impact on presence in VR. Preliminary results indicate minimal impact on presence. Since the blur is present only for very short durations during rotational movements, its minimal impact on presence is understandable. While these results look promising, future work needs to explore this in an in-depth manner using the presence questionnaire to get a better understanding of the impact of RB on presence in VR.

CHAPTER 5

CONCLUSION

In this research, we explored different techniques that tackle two major problems of using HMDs, complete unawareness of the real world and cybersickness.

We explored a design space of bringing physical real world objects into a virtual reality experience. We selected four renderings from this design space and compared them through an empirical evaluation to understand which approach maximizes utility while reinforcing immersion. We also provide critical considerations necessary for the design of renderings of real world objects in virtual reality.

We tested a novel navigation technique for VR FPS games called Rotation Blurring which uniformly blurs the screen during rotational movements in the game. We evaluated its impact in reducing cybersickness and found that it helped majority of users who are sensitive to cybersickness in VR. We also found that while it benefited most users in reducing cybersickness, it had an adverse effect on some users. Given these bipolar results, we advice game developers to provide RB as an optional setting in their games. Users sensitive to cybersickness can significantly benefit from enabling Rotation Blurring.

It is worthwhile to note that all the techniques discussed in this thesis can be implemented at the SDK level by HMD developers. Supporting these techniques at the SDK level could allow VR games and applications to leverage the benefits of these techniques without making any changes in the source code.

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