DISTANCE PERCEPTION THROUGH HEAD-MOUNTED DISPLAYS

by

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ABSTRACT

It has been shown in numerous research studies that people tend to underestimate distances while wearing head-mounted displays (HMDs). We investigated various possible factors affecting the perception of distance is HMDs through multiple studies. Many contributing factors has been identified by researchers in the past decades, however, further investigation is required to provide a better understanding of this problem. In order to find a baseline for distance underestimation, we performed a study to compare the distance perception in real world versus a fake headset versus a see-through HMD. Users underestimated distances while wearing the fake headset or the see-through HMD. The fake headset and see-through HMD had similar result, while they had significant difference with the real-world results. Since the fake headset and the HMD had similar underestimation results, we decided to focus on the FOV of the headset which was a common factor between these two conditions. To understand the effects of FOV on the perception of distance in a virtual environment we performed a study through a blind-throwing task. FOVs at three different diagonal angles, 60°, 110° and 200° were compared with each other. The results showed people underestimate the distances more in restricted FOVs. As this study was performed using static 360° images of a single environment, we decided to see if the results can be extended to various 3D environments. A mixed-design study to compare the effect of horizontal FOV and vertical FOV on egocentric distance perception in four different realistic VEs was performed. The results indicated more accurate distance judgement with larger horizontal FOV with no significant effect of vertical FOV. More accurate distance judgement in indoor VEs compared to outdoor VEs was observed. Also, participants judged distances more accurately in cluttered environments versus uncluttered environments. These results highlights the importance of the environment in distance-critical VR applications and also shows that wider horizontal FOV should be considered for an improved distance judgment.

Dedicated to my wife and my parents

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

In recent years, Virtual Reality (VR) systems have been utilized in industry, education, entertainment, and as accessibility tools. This increasing prevalence of VR necessitates an accurate representation of the environment to users. Precise egocentric distance perception is one of the aspects of an accurate representation of Virtual Environments (VEs) that is important for intuitive interactions. The increasing number of VR games requiring fast movements, walking, and jumping around the room while interacting with objects highlights the importance of a precise and intuitive representation of a VE. However, previous research shows that people tend to underestimate distances in VEs [1, 2, 3]. Many factors have been identified to have a potential effect on distance perception in VEs, such as HMD attributes (weight, display resolution, and FOV), environmental attributes (indoor or outdoor, linear perspective, foreshortening, and texturing), and human attributes (height, age, and previous VR experience). However, most HMDs of the past such as the nVisor SX60[1] had restricted FOVs and lower display resolution; today, modern HMDs such as the Pimax[2] use a high-resolution display and an FOV which nearly matches that of human eyes' FOV thanks to technological advancements. This provides us with an opportunity to study much higher FOV HMDs than in past distance perception research, and also directly study the effect of FOV in an isolated manner by simulating FOVs of the older HMDs.

Contributions

Throughout our studies the results show that people generally tend to underestimate distances when using an HMD. We broke down the possible factors of distance underestimations in VEs and

[1] https://est-kl.com/manufacturer/nvis/nvisor-sx.html; retrieved 2021-12-31

[2] https://www.pimax.com/products/5k-xr-headset-only; retrieved 2021-12-31

focused on the effect of FOV and environments. Based on these studies we provide the following contributions in this document.

- A comparison of real world and HMD distance estimation
- A user study protocol that isolates FOV for direct investigation in VEs
- Evidence that reducing circular FOV results in greater distance underestimation VEs
- Evidence that horizontal FOV is a significant factor for distance underestimation, whereas vertical FOV is not
- Evidence that presence of items in a VE, and visual boundaries of a VE, provide significant visual anchor to reduce distance underestimation
- Design recommendations and roadmap for future study, identifying potential avenues to further reduce distance compression in VR

Organization

This dissertation is organized as follows. Chapter 2 discusses the preliminaries and presents the relevant background information upon which our research is based on and the existing work in the literature that are the most relevant to our research. Chapters 3 examines our study on distance perception with a video see-through head-mounted display. Chapter 4 describes our work on field of view effect in VEs using static 360° images on perception of distance. Chapter 5 focuses on our study on isolating the effects of horizontal and vertical FOVs in various environments on perception of distance. Chapter 6 describes our study on the effect of clutter and FOV in various environments on perception of distance. Chapter 7 summarizes our work and concludes this dissertation by providing guidance on future research directions.

CHAPTER 2: BACKGROUND AND RELATED WORK

The accuracy of distance judgment in virtual environments has been a long-studied topic. It has been shown by multiple studies that users tend to underestimate distances in VEs while performing the blind-walking task [4, 5, 6, 7]. Various possible causes of distance underestimation have been investigated by researchers in the past two decades which can be categorized into apparatus attributes, human attributes, and virtual environment attributes.

Distance Underestimation with Head-Mounted Displays

For over two decades, researchers have studied how users perceive distances in VR, and a common result is that users tend to significantly underestimate distances in VR compared to the real world [1]. There are a variety of factors that have been identified as contributors to a user's perception of their virtual environment. For instance, Mohler et al. investigated the inclusion of self-avatars (a virtual representation of the user), and found that these provided a significant frame of reference, resulting in more accurate distance judgements [8]. Likewise, Leyrer et al. show that camera height manipulations in a VE also affects a user's perception; for instance, by increasing the camera height in relation to the user's actual height, the authors found that users tend to underestimate distances [9]. Additionally, Kunz et al. show that the quality of computer graphics inside a VE affects judgements, such that lower-quality textures were more conducive to poorer distance estimations [10]. While these articles are pivotal to the VR distance underestimation literature, we note that these factors (presence of self-avatars, eye height, quality of graphics) are constants in the real world with VST displays. Therefore, these factors are not explored in our study. In our work, users can see their own body; the camera is mounted at their own natural eye height; and the graphics are live captures of the real world.

In the extant literature, researchers have utilized multiple procedures in order to measure distance estimations, including verbal judgments, blind walking, timed imagined walking, and blind throwing [1]. Verbal judgments have been used to draw out a user's estimation of depth with a simple procedure, but accuracy tends to decline as targets are located further away [1, 10, 11]. Perhaps the most popular method, blind walking consists of a participant viewing a target, becoming blindfolded, and then walking until they believe they reached the target. This procedure has been used in both real and virtual environments, and historically, participants viewing a VE have walked significantly shorter distances than those viewing the real world [4, 5, 6, 7]. One of the weaknesses of this technique, as reported by Jones et al., is that participants might be able to peek at the ground through the gap between the face and the HMD to use optical flow as feedback [12]. However, a more recent work by Jones et al. suggests that modern VR HMDs alleviate this problem, as wider FOVs fill the periphery of the viewer [13]. Similar to blind walking, timed imagined walking consists of a user viewing a target and becoming blindfolded, but instead of walking to the target, they imagine walking; then they tell the researcher when they believe they would have arrived, if they walked normally. Previous results have shown that this method elicits responses comparable to blind walking [14, 15]. Lastly, blind throwing measures a user's depth estimation while allowing them to remain stationary [16, 17]. Sahm et al. used blind throwing and found that responses were comparable to blind walking; they conclude that this procedure is a suitable measurement for when blind walking is not usable [16]. During a time when COVID-19 forces us to be diligent with safety precautions, we elect to use a blind throwing procedure for our study, in order to minimize the risk of spreading the virus; this allows us to remain socially distant from our participants, and eliminates the risk of participants tripping over HMD cables while their eyes are closed.

As noted in a recent literature survey by El Jamiy and Marsh, there is not as much work regarding AR distance estimation compared to that in VR [18], but there are some findings that have emerged in this area. Regarding device type, some researchers have studied the effects of wearing an OST

AR display. For instance, Grechkin et al. [14], Jones et al. [19, 12], and Livingston et al. [20] used the NVIS nVisor ST device, which could be used as a VR or AR display. As the participants could see the real world normally through the lenses, the authors were able to directly study if the limited FOV or additional weight of a device caused a difference in depth estimation. Grechkin et al. found no statistical difference between wearing the HMD and normal viewing [14]; however, Jones did find a significant difference in depth estimation, such that users wearing the HMD underestimated distances [19]. This same result was confirmed in another experiment by Jones et al.; the authors found similar findings when using a within-subjects and a between-subjects study design [12]. Livingston et al. compared OST AR distance estimation between indoor and outdoor environments, in the presence of AR cues, and found that participants underestimated distance in an indoor hallway environment, but overestimated distances in an outdoor parking lot environment [20]. Swan et al. used a different OST AR device - the Sony Glasstron - and found that users underestimated distance with this device as well [21]. Although there is conflicting evidence, it seems that FOV may be a significant factor that affects a user's ability to judge distances. The diagonal FOV of our device (the ZED Mini) is 100°.

Fewer researchers still have studied how VST displays affect distance judgments of a physical environment. Vaziri et al. used a custom VST device and implemented software techniques to transform the view into a live, non-photo-realistic representation of the environment [22]. Here, the authors were able to study the effects of varying graphical representations of the real world, and found that the non-photo-realistic conditions were conducive to significantly different responses compared to viewing the real world through a VST; however, they did not make a direct comparison to real-world viewing without wearing a device. In a separate study, Kyto et al. studied depth estimation while the user saw AR cues [23]. Instead of measuring how well a user perceived the physical environment through a VST HMD, they used an action-based measurement to understand perception of AR cue depth, with monoscopic and stereoscopic devices. Naturally, the authors found that stereoscopic rendering of AR cues was more conducive to understanding distance. In a recent study, Gagnon et al. used the HTC Vive with ZED Mini attachment in order to study user estimations of lengthier distances in a virtual environment [24]. Using a verbal reporting procedure, they found a trend where users moderately overestimated shorter distances (25m-200m), but then significantly underestimated larger distances (300m-500m). Although they used the same VST that we do, their setup involved the use of a green screen, to completely turn a physical environment into a virtual one. Our work differs in that the participants were able to view the real world instead of a virtual world, and we restricted our stimulus distances to 6m using a blind throwing task. While previous works utilize VST HMDs in various ways to measure distance estimation, to the best of our knowledge, ours is the first that directly compares perception of the real world when using and not using a VST HMD through a blind-throwing task.

Video See-Through Head-Mounted Displays

VST HMDs utilize forward-facing cameras affixed to the front of the device, allowing users to "see through" the hardware into the real world. Unlike OST AR displays that allow a user to see the real world normally, a VST HMD captures the real world and displays it on a screen that is typically used to show VEs. This subjects the user to some degree of latency, and it exposes the user to the HMD's screen resolution and FOV [25]. Although VSTs were conceptualized decades ago [26], we are seeing increased usage with modern technology. For instance, Kumaravel et al. utilized a suite of devices and visualization techniques to connect 2 remote users - one expert and one novice - and merge their environments [27]. Both users were able to see the first-person views of their own surroundings and that of their partner, by merging camera feeds. Similarly, Cao et al. used VST HMDs with AR to let a user see their surroundings while viewing an expert's movements, in a task akin to manufacturing / maintenance [28]. This allowed them to perform the task while simultaneously watching the expert's instructions. Walker et al. implemented a VST HMD to provide a remote collaborative AR experience to users [29]. Here, users saw the real world, with a graphical overlay of a virtual avatar that represented a live human partner. The authors studied the effects of using different sized avatars which were controlled by these remote users, and found that displaying to-scale avatars was more conducive towards an equitable interaction between both users.

Jones et al. discuss how to use computational approaches to simulate visual impairments [30]. They used a VR headset with eye tracking in order perform an appropriate transformation on the graphics, and then displayed the result in the HMD. By using a VST device, the users could see the real world with the distortion. Likewise, Masnadi et al. discuss a transformation that allows users with severe visual impairments, such as age-related macular degeneration, to see with better acuity [31]. It is implied that by using a VST HMD equipped with eye tracking, a visually impaired person could see the world normally during their daily lives. In a more general use case, Rabbi et al. deployed VST HMDs to users engaging in a weight training circuit [32]. Here, virtual feedback was shown to the users as they lifted the weights, to correct their form. Then, the "see-through" mode was engaged to allow them to navigate to the next station without removing the HMD. Although this example doesn't utilize the VST mode for intense usage, it still highlights the practicality of such a device in daily life, allowing the user to switch modalities without removing the HMD. We suspect that VST devices will see a surge of personal use, even if just for allowing users to see their physical space in-between VR sessions. As such, it is important to understand how people perceive their surroundings while using these devices.

Distance Underestimation Contributing Factors

Various possible causes of distance underestimation have been investigated by researchers. These factors can be categorized into apparatus attributes, human attributes, and virtual environment attributes.

Apparatus Attributes

The HMD and the computer supporting it have physical attributes that might affect the distance perception. The weight and inertia of the HMD have shown to contribute to the distance underestimation in VR [33, 30, 34]. Motion parallax is the displacement of image parts relative to each other when the observer moves or the objects move. Since in this study, the objects does not move and the user is stationary, the motion parallax is of small importance. If objects or the observer move at a constant speed, the objects closer to the observer will appear to move a greater distance comparing to the further objects [35]. In our study, the environment was static, but participants could make subtle movements before their tasks began. It has been shown in these conditions, the parallax effect does not affect the distance judgment blind-walking task [19]. Pfeil et al. showed that the underestimation of distances while using an HMD is still present when using a video see-through HMD and their result shows that it can be an effect of FOV and HMD's weight [36]. Vaziri et al. also observed the same underestimation of distances in a video see-through HMD [22, 37].

Despite the efforts on investigating how field of view changes a user's ability to determine distance, the findings are inconclusive. Studies conducted by Creem-Regehr et al. [38] and Loftus et al. [39] showed that using different FOVs did not show any impact on distance perception; however, Buck et al. [33], Jones et al. [40, 41], and Li et al. [42, 43, 44] found a significant effect of FOV on distance perception. More recent studies that used wider FOVs are inclined towards the significant effect of FOV [3, 1], but this effect was not isolated.

Wu et al. [45] found that in the real world, increasing FOV improves distance judgment, whereas Knapp and Loomis [46] found a non-significant effect. However, in these two studies, researchers utilized fake Head-Mounted Displays constructed out of lightweight materials to occlude vision and to circumvent the need for cables attached to the headset, and participants viewed the real world through these headsets.

One of the main differences in our work is that our selected HMD had a wide field of view, allowing us to precisely control the field of view along both the vertical and horizontal axis while participants were wearing the exact same HMD with constant physical attributes. Jones et al. found significant effect of VFOV on distance judgment, however in their study an extremely narrow FOV ($48^\circ \times 40^\circ$ and $48^\circ \times 56^\circ$) was used throughout the study [41]. To the best of our knowledge, our work is the first time that the effect of the vertical and horizontal field of view has been separately investigated in a wide FOV high resolution HMD.

Virtual Environment Attributes

In a VE, there are various factors that might affect the perception of distance. Mohler et al. examined the presence of self-avatars in VEs and found that it resulted in more accurate distance judgment by the users [8]. Leyrer et al. investigated the effect of camera height and found that placing the camera higher than the user's actual height leads to distance underestimation [9]. Additionally, Kunz et al. found that the quality of the VE's graphics affects users' ability to accurately judge distance [10]. Vaziri et al. showed that level of graphical detail provided in a VE is negligible for distance judgement [37]. Creem-Regehr et al. [2] revealed larger underestimations in outdoor VEs compared to indoor VEs. It is worthy to note that Andre and Rogers demonstrated with a blind walking study that in real-world scenarios, people tend to underestimate distances in outdoor environments comparing to outdoor environments [47].

Evaluation Techniques

To evaluate distance perception error, researchers employed different methods such as verbal estimation, blind-throwing, timed imagined walking, and blind-walking [1]. Here we will discuss each evaluation technique.

Blind Walking

Perhaps the most popular measurement, the blind walking method involves having the participant view a target, then become blindfolded or shown a black screen in VR, and finally asked to walk toward the target and stop when they think they have reached it. This procedure has been used in the real world and in virtual environments, and multiple results show that participants viewing a VE walked significantly shorter distances than those viewing the real world [4, 5, 6, 7].

Timed Imagined Walking

Similar to *blind walking*, timed imagined walking consists of a user viewing a target and becoming blindfolded or shown a black screen; however, instead of walking to the target, they imagine walking and let the researcher know when they think they would have arrived [14, 15].

Verbal Judgement

The simplest procedure is verbal judgement, in which the user is asked to simply tell the researcher their estimation of distance to a target. In literature, verbal judgements tend to have larger errors as distance increases [1, 10, 11].

Blind Throwing

In this technique, distance perception is estimated by showing the participant a target and asking them to throw an object towards it, while they are blindfolded or shown a black screen [16, 17]. This method allows physical interaction with the environment while allowing the users to remain stationary. Work by Sahm et al. shows that blind throwing responses were comparable to blind walking, and they suggest that when blind walking is not feasible, this procedure is a suitable measurement for distance judgement [16].

With modern cameras that now have increased resolution and frame rate, Video See-Through (VST) Head-Mounted Displays (HMD) can be used to provide an Augmented Reality (AR) experience. However, because users see their surroundings through video capture and HMD lenses, there is question surrounding how people perceive their environment with these devices. We conducted a user study with 26 participants to help understand if distance perception is altered when viewing surroundings with a VST HMD. Although previous work shows that distance estimation in VR with an HTC Vive is comparable to that in the real world, our results show that the inclusion of a ZED Mini pass-through camera causes a significant difference between normal, unrestricted viewing and that through a VST HMD.

In that corpus, authors typically compare how users perceive distances in real life to VR. In our study, our participants wear a VR head-mounted display (HMD) with a pass-through camera; they see the real world in stereo, but the quality of view - including FOV and resolution - is reduced due to the hardware. Therefore, in this section, we provide an overview of the relevant literature at the intersection of Distance Underestimation and VST HMDs.

In the past two decades, researchers have studied the perception of distance in VEs and the real world, and a common finding among this research is that distances in VEs are greatly underestimated by users [1]. Researchers have identified a variety of factors that affect the perception of distance such as FoV, weight of the HMD, presence of a self avatar, camera position, and display resolution.

Kunz et al. showed that lower-quality textures lead to poorer distance estimations [10].

The weight of the headset remains the same and the VE has the same resolution for all FoVs and meets the native resolution of the headset. We captured 360° images of our test environment at three different heights to compensate for different users' heights.

More recent studies on HMDs with wider FoV are inclined towards the significant effect of FoV [3]. For example, Wu et al. [45] showed that increasing FoV in real-world would improve distance judgement while Knapp and Loomis [46] saw no effect of FoV on distance judgments. However, these two studies were conducted using dummy/simulated headsets without any display or lens and the participants were viewing the real world. Buck et al. [33], Jones et al. [40, 41], and Li et al. [42, 43, 44] have found significant effects of FoV on distance judgement, while experiments by Creem-Regehr et al. [38] and Loftus et al. [39] using different FoVs did not show any impact on the distance judgement. Our study contributes to this body of literature by demonstrating how restricted FoVs - even in the same device - contribute to underestimation of egocentric distances.

In addition, because we elected to use the Pimax headset, throwing eliminates the risk of users tripping over VR headset cables, since they do not need to walk. In our study, users were not 'blind' in the sense that their eyes were blindfolded, but, since we used still images of our test environment, they were unable to receive visual feedback since the stimuli was static and unchanging.

Various possible causes of distance underestimation have been investigated by researchers in the past two decades which can be categorized into apparatus attributes, human attributes, and virtual environment attributes.

Pfeil et al. showed that the underestimation of distances while using an HMD is still present when using a video see-through HMD and their result shows that it can be an effect of FOV and HMD's weight [36]. Vaziri et al. also observed the same underestimation of distances in a video see-through HMD [22, 37].

timed imagined walking but with the participant physically walking towards the target until they believe they have reached the goal [4, 5, 6, 7]. We used the backpack computer to allow the participant to walk freely without any fear of cables pulling on their head or becoming a tripping hazard.

CHAPTER 3: DISTANCE PERCEPTION WITH A VIDEO SEE-THROUGH HEAD-MOUNTED DISPLAY[1]

In recent years, Video See-Through (VST) Augmented Reality (AR) devices have re-surged as a commonplace technology. To work, cameras are affixed to the front of a closed-view head-mounted display (HMD), and the live video feed is rendered in the display. This is unlike Optical See-Through (OST) displays, which allow the user to view the real world through a transparent panel (such as the Hololens[2]) [35, 26]. Common VST devices today include the Samsung Gear VR[3], which uses a smartphone's screen and embedded cameras to display the real world, and the ZED Mini[4], which is specifically designed to provide high-resolution, stereo views of the real world while a user wears an HMD. Although VST devices may be limited by the presence of a screen with lower resolution than that of natural human eyesight, and in some instances, the presence of depth quantization [48], Kruijff et al. note that VST devices do not suffer from the brightness and contrast hindrances that OSTs have, meaning that graphical overlays can be strongly seen in outdoor environments [49]. Other strengths of VST HMDs include ease of superimposing graphics into the view of the real world, a Field of View (FOV) based on the imaging device, and that these devices are capable of providing mixed reality experiences across the entire reality-virtuality continuum (see Milgram's definition [50]).

These HMDs naturally have the ability to render virtual environments (VEs). Using computer vision techniques, graphical overlays representing the real world can be added to the VE. Likewise,

[1]This chapter contains previously published material adapted from the following article: Pfeil, Kevin, Sina Masnadi, Jacob Belga, Jose-Valentin T. Sera-Josef, and Joseph LaViola. "Distance perception with a video see-through head-mounted display." In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems, pp. 1-9. 2021. https://doi.org/10.1145/3411764.3445223

[2]https://www.microsoft.com/en-us/hololens

[3]https://www.samsung.com/global/galaxy/gear-vr/

[4]https://www.stereolabs.com/zed-mini/

VST HMDs can naturally display the real world, and graphical overlays can be used to display AR cues [35]. Though originally conceived decades ago [26], we expect that these devices will increase in popularity, due to a variety of advantages. First, they provide users with the capability to switch between VEs and the real world without needing to take the headset off. Second, they can be used for both Virtual Reality (VR) and AR, instead of requiring a dedicated device for each modality. Third, they allow for unique AR experiences that OST displays can not provide. For instance, Jones et al. use VST HMDs to display the real world, but apply a graphics transformation to show users what it is like to have visual impairments [30]; and likewise, Masnadi et al. perform inverse transformations to *correct* eye-sight for visually impaired users [31]. In theory, these devices could be worn at all times, to correct more severe visual impairments during a user's daily life.

However, there is a large body of work that shows how users tend to perceive VEs differently from the real world. An HMD's screen resolution, FOV, and weight are all potential factors that degrade a user's perception of a VE [51, 4]. Although the displayed graphics are captures of the real world, and although modern technology is allowing human perception of VEs to become comparable to the real world [51], we question if users can properly perceive their surroundings while wearing a VST HMD. This would pose a problem for a variety of applications, including training, robotic simulations, spatial awareness acquisition, gaming, and accessibility [52, 53, 31]. Though there is a corpus of literature that discusses distance underestimation in VR, there is little work that focuses on distance estimation using VST HMDs. Therefore, based on previous work, we conduct a 3x4 within-subjects study in order to measure user perception of a static environment with multiple viewing conditions, asking the following question:

RQ1: How do users perceive distance in the real world when wearing a Video See-Through Head-Mounted Display?

The results of our study show that people tend to underestimate distances when using our selected device combination, the HTC Vive with ZED Mini attachment. Though recent work suggests that viewing a VE with the Vive is comparable to real world viewing [51], our results show that using it as a VST HMD significantly compresses a user's perception of distance. Our results suggest that this is in part due to the reduced FOV that is provided by the device. We hope the results of this study can be used to direct the work in the VR/AR area towards better imaging devices, and to help explain potential perceptual disparities in current applications using VST HMDs.

Methods

We conducted a user study to help understand distance perception in real world environments when wearing a VST HMD compared to normal viewing. The following sections describe our study details.

Study Design

We conducted a 3x4 within-subjects study with two independent variables - *Headgear* and *Distance*. The *Headgear* variable had three types - "Nothing", where the users did not wear any headgear; "VST", where the users wore a VST HMD; and "Shell", where the users wore just a plastic casing from a stripped-down HMD, effectively emulating the reduced field of view in the VST HMD condition. The *Distance* variable had four levels - 3m, 4m, 5m, and 6m. This resulted in 12 unique conditions, and the participants performed a blind throwing task 3 times each, for a total of 36 trials per participant; these trials were randomized for each individual. The task and Distance conditions were influenced by previous work by Sahm et al. [16]. While typical distance perception studies use blind-walking as the primary measure [1], we elect to use blind throwing, as it has been shown to elicit responses comparable to blind-walking [16], and it allows

(a) (b)

Figure 3.1: (a) Video See-Through HMD, the HTC Vive with ZED Mini attachment. (b) Shell of an HMD.

the researchers and participants to remain socially distant during times of COVID-19.

Subjects

We used the G*Power software package to perform a power analysis [54]. With a medium effect size and 12 conditions in a within-subjects study, our target N was 18 subjects. We recruited 28 participants from the University of Central Florida to participate in our study, but 2 were dismissed for not passing an eye test. Our final participant pool consisted of 26 individuals (24 male, 2 female). Their ages ranged from 18 to 29 (M = 19.46, SD = 2.45). We screened all participants for vision acuity using a Snellen eye chart, and all could see better than 20/32 in each eye. Participants were asked to read a printed chart 3 meters away while covering an eye at each time. If a participant wore corrective lenses, they were required to wear them for all conditions during the study. We asked participants to rate their experience with VR, on a scale of 1 to 5 where 1 means little and 5 means much. The mean response was 2.30 (SD = 1.03).

Apparatus

Our conditions called for participants to wear either no headgear, a VST HMD, or a plastic shell of a headset. For the VST conditions, participants wore an HTC Vive[5] that was equipped with a ZED Mini[6] pass-through camera mounted on the front. This pass-through camera operated at 60FPS, with a resolution of 2560x720, providing a stereo video feed which resulted in a 3D view. Although the HTC Vive display has an approximate field of view (FOV) of 110°, inclusion of the pass-through camera reduced the FOV to 90° vertically, and 60° horizontally. The rest of the display was filled with black pixels. The weight of the VST HMD was 550g. We used an out-of-the-box Unity3D program which was provided by the creators of ZED Mini – this program can be found on their website[7]. We only modified the scene such that pressing the space bar would turn the camera on or off; thus, we did not develop any additional software, and only used a commercial-off-the-shelf solution. For the Shell conditions, participants wore a stripped-down Oculus Rift DK2. Here, there was no display; all that remained were the plastic casing and the adjustable straps. Users could see the real world, though their FOV was limited by the plastic casing. We added black cardboard to the top and bottom of the plastic, to further restrict the FOV so that it more accurately matched that of the VST condition. See Figure 3.1 for illustration of the VST display and the shell device. The weight of the Shell device was 150g. For all trials, participants threw beanbags that weighed approximately 450g and were square, measuring 15cm on each side.

[5]https://www.vive.com

[6]https://www.stereolabs.com/zed-mini/

[7]https://www.stereolabs.com/docs/unity

The target that users were asked to throw the beanbag towards was a circle approximately 16cm in diameter.

The study was conducted in our closed laboratory. While typical distance estimation studies are conducted in an empty hallway, our lab was filled with desks, chairs, television monitors, and miscellany, resulting in a visually richer environment that is perhaps more representative of real use cases. Our space was large enough to accommodate the furthest distance of our study, 6m. There was approximately 1.8m of buffer from the 6m target to the closest non-study object, and there was at least 1.3m on either side of the targets. The ceiling was approximately 3m high. We did not move any of the objects in our lab until all participants completed data collection. Thus, any objects in the environment which could have been used as reference frames were constant across all participants. See Figure 3.2 for illustration of our environment.

Procedure

Upon arrival, recruited participants were asked to review an informed consent document, but we did not collect signatures. We introduced users to the different headset configurations and conditions that we would be testing throughout the session, and then had each participant perform an eye examination with a Snellen chart. We recorded their vision acuity. Next, we collected the remainder of user demographics. We then gave the participants an overview of our study. We explained that the objective was to toss beanbags at targets with varying distances, while wearing one (or none) of our headgear. Users were asked to first view the target, and then after a time that they were comfortable with, close their eyes and attempt to hit the target as close as they could with the beanbag. We noted to the participants that we would only count the initial contact with the ground, and not bounces or slides of the beanbag. Prior to starting the trials, we had the user practice throwing 4 bean bags at 4 different targets without closing their eyes (16 practice throws

Figure 3.2: Environment used for our study. The target distances were 3m, 4m, 5m, and 6m.

in total). These targets used the same distances as the actual trials, but were not the same as the ones used during data collection.

We then proceeded to collect data from our participants. During the trials, we instructed the user to which headgear (if any) they would need to put on. We encouraged participants to tell us if the VST conditions were too blurry, and showed them how to adjust the interpupillary distance when necessary. Before each toss, we instructed the user to close their eyes and to keep them closed after they tossed. The researcher ensured that the participants' eyes were closed during this time; for the VST conditions, we blacked out the screen, to verify that the user could not see. Then the user threw the beanbag, and a researcher used a tape measure to log the distance from the target to the beanbag. The traction between the beanbag and the carpet caused the beanbag to stay at its contact point. In the rare cases that beanbag slid, the researcher spotted where the beanbag first made contact with the ground and recorded that location. After each measurement, we removed the bean bag from the ground before telling the participant that they could open their eyes. This process repeated for a total of 36 times. After data collection was complete, participants were given 5USD in cash. The time to complete the study was approximately 30 minutes.

COVID-19 Considerations

Due to the ongoing COVID-19 pandemic, we wanted to ensure safety for the participants and researchers. Following our institutions guidelines, all individuals were required to wear face masks at all times. Between each participant, we sanitized all devices and surfaces that the participants and researchers would be in contact with, to ensure safety during the study. Furthermore, all users were required to wear a face mask in order to participate in the study, but we provided each individual face masks, hand sanitizer, cleaning wipes, latex gloves, and single-use VR Eye mask coverings, to reduce risk of contracting the disease. Though we cleaned all surfaces between participants, we allowed each individual to clean devices as desired.

Hypotheses

While findings have historically shown how people tend to significantly underestimate distances when wearing a VR HMD [1], recent work has shown that the gap of perception between the real world and virtual representations is shrinking [51]. However, when using a VST HMD to view the real world, there is an additional layer of graphics that might affect how users perceive distance. Moreover, the weight, limited FOV, and the mere fact of wearing a headset might affect the perception of distance. Therefore, we hypothesize the following for our study:

H1: Participants will under-throw the beanbag in the VST condition compared to the Nothing and Shell conditions.

H2: Participants will make comparable errors when throwing the beanbag in the Nothing and Shell conditions.

H3: Participants will make larger errors (magnitude) when throwing the beanbag to further distances.

Data Analysis Approach

The participants tossed the bean-bag 3 times for each headgear-distance pair, and the error of their toss in relation to the target (magnitude and direction) was recorded. If the bag was tossed to the side, we transposed the landing spot such that it aligned with the line from the participant to the target. Positive values indicate over-throwing the bag, and negative values indicate under-throwing. For each condition, we averaged the error of 3 tosses together to form one data point. Thus, though each participant threw the bag 36 times, each individual had 12 associated data points. We performed a Shapiro-Wilks test for normality on the data, and found that the responses were not normally distributed ($p < .01$). We therefore transformed our data using ARTool [55], so that we could run a repeated-measures ANOVA on our data. In the event of a significant omnibus test, we planned on conducting pair-wise t-tests on the main effects. Since we had multiple comparisons, we controlled for Type I errors using Holm's Sequential Bonferroni Adjustment [56].

Results

In this section, we report the findings of our statistical analyses. First we describe the descriptive statistics, followed by omnibus and post-hoc tests.

Table 3.1: Descriptive statistics of average user error, by Headgear and Target Distance

Headgear	**Target Distance**	**Error (centimeters)**
Nothing	3 meters	M = -5.24, SD = 27.3
	4 meters	M = -17.1, SD = 31.8
	5 meters	M = -23.0, SD = 29.9
	6 meters	M = -44.8, SD = 50.5
Shell	3 meters	M = -12.0, SD = 27.1
	4 meters	M = -25.5, SD = 34.2
	5 meters	M = -36.1, SD = 35.8
	6 meters	M = -58.5, SD = 43.0
VST	3 meters	M = -14.0, SD = 29.2
	4 meters	M = -19.4, SD = 43.4
	5 meters	M = -40.3, SD = 37.8
	6 meters	M = -66.7, SD = 53.3

Descriptive Statistics

Table 3.1 details the descriptive statistics for our data. Expectedly, our participants made greater errors with further targets; but, generally, participants threw the beanbags more accurately when not wearing any headgear.

Repeated Measures ANOVA Results

After transforming our data using the ARTool [55], we conducted a 3x4 repeated-measures ANOVA. We found a significant main effect of Headgear, and a significant main effect of Distance; but we did not find an interaction effect between these two variables. Table 3.2 depicts the results of our omnibus test. Having found statistical significance, we proceeded to conduct post-hoc tests.

Table 3.2: Repeated Measures ANOVA results

Effect on Error	**ANOVA Result**
Main Effects	
Headgear	$F(2,50) = 5.902, p < .01, \eta_p^2 = .191$
Distance	$F(3,75) = 25.62, p < .001, \eta_p^2 = .506$
Interaction Effect	
Headgear * Distance	$F(6,150) = 1.563, p = .162, \eta_p^2 = .059$

Table 3.3: Post-hoc t-tests results

Condition A	**M**	**SD**	**Condition B**	**M**	**SD**	**t-test Result**
Effect of Headgear						
Nothing	-8.86	14.78	VST	-13.65	18.13	$t(103) = 2.667, p < .01$*
Nothing	-8.86	14.78	Shell	-12.96	15.45	$t(103) = 2.626, p < .05$*
Shell	-12.96	15.45	VST	-13.65	18.13	$t(103) = 0.261, p = .80$
Effect of Distance						
3m	-4.27	10.26	4m	-7.88	14.42	$t(77) = 2.920, p < .01$*
3m	-4.27	10.26	5m	-12.82	13.81	$t(77) = 5.384, p < .001$*
3m	-4.27	10.26	6m	-22.35	19.46	$t(77) = 9.271, p < .001$*
4m	-7.88	14.42	5m	-12.82	13.81	$t(77) = 2.581, p < .05$*
4m	-7.88	14.42	6m	-22.35	19.46	$t(77) = 6.142, p < .001$*
5m	-12.82	13.81	6m	-22.35	19.46	$t(77) = 4.054, p < .001$*

Post-hoc Test Results

Using the transformed data, we conducted pair-wise t-tests on the Headgear conditions; see Table 3.3 for statistical test results, and Figure 3.3 for illustration. Testing for the effect of Headgear, we found significant differences when comparing Nothing with Shell, and Nothing with VST. However, we did not find a significant difference between the Shell and VST conditions. Generally,

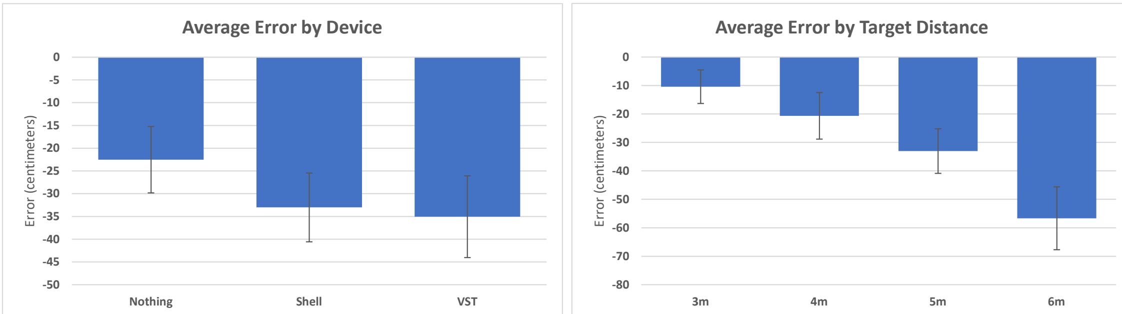


Figure 3.3: Left: Average error by device with 95% confidence. Right: Average error by Distance with 95% confidence. Generally, participants under-threw the beanbag to the targets, but were less accurate when wearing a device on their head; further, they were less accurate as the targets distance increased.

participants performed the task with less error when viewing the environment normally. Regardless of device, viewing the room with a reduced field of view induced more error. This can be also a result of the weight of the headgear.

We also performed pair-wise t-tests on the Distance conditions; see Table 3.3. We found statistical significance when comparing each of the target distances. Generally, as the targets increased in distance, the participants performed the task with greater error.

Discussion

The results of our study provide insight into distance perception when using a VST HMD. The following section details the implications of our findings.

Distances are Underestimated with VST Devices

The results of our study showed a significant difference in participants' ability to estimate distances when they used the VST device, compared to real-world viewing (H1). Though prior work has shown that viewing a VE with an HTC Vive is comparable to that of normal viewing of the real world [51], we found that the inclusion of the ZED Mini pass-through camera worsened distance estimation. There are a few factors which changed as a result of adding the ZED Mini. Device weight (and therefore weight distribution) immediately changed, as the ZED Mini is 63g, accounting for 11% of the total device weight which was attached to the frontmost part of the headset. Only when using the HMD as a VST device does the FOV reduce. The normal FOV of the Vive is approximately 110° (both horizontal and vertical), but the ZED Mini reduced this to 90° horizontally and 60° vertically. The ZED Mini's pass-through mode operates at a high resolution (2560x720), so we do not suspect resolution to be a significant factor for the present study.

Though previous works suggested that FOV is not by itself a main factor that affects distance estimation [1, 4], our work suggests that this very well may be the case (H2); however, our present study is unable to isolate the effects of weight on distance compression. Our participants exhibited statistically comparable responses between the Shell and VST conditions, although we note that the Shell elicited slightly more accurate responses. This slight error reduction might be attributed to the fact that the Shell weighed approximately 25% of the VST device's weight. Previously, Willemsen et al. concluded that reduced FOV *combined* with the weight of an HMD caused this difference; they used a Shell of the nVisor SX device which weighed approximately 1kg[8] [4], but our Shell only weighed a fraction of that (150g) and its mass is closer to the head, which produces near-negligible torque on the head. This reasonably suggests that FOV is a main factor that affects distance estimation, even with modern hardware. However, isolated investigation is required to

[8] https://est-kl.com/manufacturer/nvis/nvisor-sx.html

evaluate the effect of HMD weight, since 150g weight of the headset might produce enough torque to affect head movements and subsequently affect the distance judgement.

Implications for VST HMD Design

Although recent research has shown that distance perception between VR and the real world is comparable with modern VR HMDs such as the HTC Vive [51], our study demonstrates that when adding a VST device to the setup, the reduction of FOV, additional weight of the imaging camera, or a combination of both, significantly hinders user ability to perceive depth in an action-based context. Current VST devices have reduced imaging FOVs compared to their displays (common devices such as the HTC Vive and Oculus Rift boast approximately 110° for the display) - looking to VST exemplars, the ZED Mini has 90° by 60°; Varjo XR-1 has 87°; and the HTC Vive SRWorks has 96° by 80° (at a reduced resolution [57]). Therefore, our study implies that VST HMD designers should work towards improved imaging devices which will offer a FOV closer to 110°, and work towards miniaturizing the equipment such that weight can be reduced. Since FOV reductions cause users to rotate their heads more during visual acquisition, and since additional weight of an HMD can cause damage to the neck [58, 59], it is important to consider expanding FOVs.

However, we must be aware that an increased FOV might have a significant trade-off concerning simulator sickness. While our study did not assess this (e.g. through use of the Simulator Sickness Questionnaire [60]), previous research indicates that a reduced FOV helps to prevent users from experiencing discomfort when navigating an environment [61]. Since some envisioned use cases involve prolonged wearing of a VST HMD (e.g. for correcting visual impairments during everyday life [31], we ponder, then, if increasing the FOV would actually cause users to stop wearing the device. More work is necessary in order to isolate this problem.

Limitations and Future Work

We acknowledge the limitations of our study. Our work is grounded in the distance compression literature, in which the primary measurement is blind walking. Due to the COVID-19 pandemic, we chose to utilize the blind throwing method, to allow both participant and experimenter to remain socially distant from each other, and to eliminate risk of tripping over HMD cables. Here, although blind throwing has been shown to be comparable to blind walking [16], we are unable to make direct comparisons with previous literature. Although blind throwing has been shown to be an appropriate alternative [16], this technique is not well documented. Other, recent articles that employ throwing do so while the participants are not blindfolded, and do not compare against walking [62, 63]. When the threat of COVID-19 is reduced, we plan on conducting a similar experiment with the blind walking protocol; but in general, future work should consider investigations into alternatives to blind walking, as walking might not always be possible for participants. In addition, we also note that both blind throwing and blind walking procedures ultimately restrict the distances that we can use in a study, due to physiological limitations and safety concerns. As such, the findings of our present study cannot be generalized to great distances such as those used by Gagnon et al. [24], and verbal estimations could be employed in parallel to other data collection methods.

We also note that our sample is male dominated, and we were unable to test for gender differences; typically our lab recruits at a 2:1 M:F ratio, but we were unable to remotely approach that mark; we suspect that COVID-19 caused this disparity in recruitment. Thus, we cannot yet generalize our results for all genders. Further, though our results show that distance is compressed with VST devices, we acknowledge that we were unable to explore the effects of one of the limitations of VST HMDs - latency. Our participants were exposed to the latency of the camera, but ultimately, due to the blind nature of the experiment, we do not expect it to have affected our results. We do anticipate it to affect more action-based tasks that involve visual search and hand-eye coordination, such as catching a ball; we plan on conducting more in-situ experiments to understand how users perceive their surroundings when using VST HMDs during more intensive scenarios. Lastly, what is puzzling is that our device's FOV (90° x 60°) is wider than that of previous work (48° x 40°) [4, 14, 19], yet our Shell device elicited a significantly different response than unrestricted viewing. We are motivated to reproduce this study using an even wider FOV, generated by a device such as the Pimax HMD[9] and pass-through cameras that would fill up more of the screen.

Conclusion

In this chapter, we demonstrated with an action-based protocol that user perception of distances in a real-world environment is compressed with a reduced FOV and increased device weight. Modern VST HMDs currently exhibit reduced FOVs, and we thus question if these devices can be used continuously in daily life, in their current state. We anticipate future devices will provide wider FOVs, but we plan on pursuing a line of work that studies how people can safely use these devices until the next wave of VST HMDs are developed.

The findings of this study lead us to investigate the effect of FOV on distance perception. In the next chapter we will discuss our efforts on examining this issue in a virtual reality head mounted display.

[9] https://www.pimax.com

CHAPTER 4: FIELD OF VIEW EFFECT ON DISTANCE PERCEPTION IN VIRTUAL REALITY[1]

In this chapter we examine the effects of FOV on egocentric distance judgement while using the same HMD - the Pimax 5K Plus headset, which boasts a diagonal field of view of 200°. Using the Unity3D game engine, we programmatically simulated 110° and 60° FOVs in the headset, keeping the HMD weight and screen resolution constant. We chose these FOVs to match those of HTC Vive and NVIS nVisor ST60 which have been used in previous research [19, 51, 4]. Our results indicate that users significantly underestimate distances when a restricted FOV is used, contributing to the body of literature that suggests that FOV is indeed a significant factor by itself.

Methods

We conducted a user study to measure distance estimation when viewing a VE, with various FOVs. In this section we discuss the procedures used to conduct the study.

Study Design

To evaluate distance perception, we utilized a blind throwing task in which users were asked to toss a bean-bag towards a specified target. We conducted a 3x4 within-subjects user study; the independent variables were FOV and distance. The FOV levels were 200°, 110°, and 60°, each representing the FOV of a real VR HMD (Pimax, HTC Vive, and nVisor ST60, respectively). We

[1]This chapter contains previously published material adapted from the following article: Masnadi, Sina, Kevin P. Pfeil, Jose-Valentin T. Sera-Josef, and Joseph J. LaViola. "Field of view effect on distance perception in virtual reality." In 2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), pp. 542-543. IEEE, 2021. https://doi.org/10.1109/VRW52623.2021.00153

programmatically simulated 110° and 60° FOVs in the headset using the Unity3D game engine. The distance levels were 3m, 4m, 5m, and 6m; these distances were influenced by prior work [16]. This resulted in 12 different conditions in which we measured user responses. Each user performed a bean-bag toss 3 times for each condition, and the mean error (distance from the target) was recorded. This resulted in 36 trials which were randomized for each participant.

Subjects

We recruited a total of 18 participants, but 4 participants were excluded as they were unable to pass an eye exam (the eye exam will be described in Procedure). The final participant pool consisted of 14 users (3 female, 11 male) with ages ranging from 18 to 39 (M=22.21, SD=3.19) and heights between 154cm and 188cm (M=175.23, SD=10.91).

Apparatus

We used a Pimax 5k Plus VR headset with a field of view of 200° (diagonal). This headset has a resolution of 2560×1440 per eye with a refresh rate of 120hz, and it weighs 470g. The headset was connected to a PC equipped with an Intel 10700k CPU, an Nvidia 2080Ti GPU, and 32GB of memory. The bean-bags used for the study weighed approximately 465g and had approximate dimensions of 15cm$\times$15cm$\times$4cm.

Since most 360° cameras have a resolution lower than that of the Pimax, and since video see-through cameras (such as ZED Mini) could not cover the FOV of the Pimax, we decided to capture multiple images using a DSLR camera and stitch them into an equirectangular 360° image with a resolution of 30000×15000. We captured the 360° images of the environment using a Canon 7D paired with a 10mm-18mm lens – 10mm was used. The images were stitched together using the

Hugin photo stitcher program. We captured 3 images at 3 different heights (151cm, 163cm, and 175cm) and used the appropriate image per participant, based on the their height. The 360° image was displayed to the user using Unity3D, which also handled limiting the FOV to different values.

We designated an empty area in our closed laboratory to perform this study. The four targets were marked with letters *A*, *B*, *C*, and *D* – *A* being the closest. The furthest target was 6 meters away from the user and there was 1.8m distance between this target and the closest non-study object. There was at least 1.3m empty space on each side of the targets and the ceiling was approximately 3m high. Figure5.3 is a picture of the environment.

Procedure

The participants were asked to review a consent form before the study began and we verbally asked for their consent. Prior to the experiment we measured and recorded users' vision acuity using a Snellen Chart to ensure they had adequate eyesight to complete the study. The user's demographics (age, gender, and VR experience) were also collected. We described the task and objective of throwing the beanbags to the user and showed them the headset's adjustments.

Before using the headset and performing the tasks, users were asked to practice by throwing 5 beanbags at 4 different targets (20 throws in total) without wearing the headset. These targets were placed at the same distance of the actual target, but were not in the same location. We also described to the participants that we only count the initial contact point of the beanbag with the ground and if it bounces or slides only the first contact point would be measured. Since the user's body is not visible in the VRE, we created a cloth collar to prevent users from seeing their body, and the users were asked to wear it during the practice throws.

Then, we asked the participant to wear the headset and we proceeded to collect data. Before each toss, the FOV of the headset was changed by a researcher based on the pre-processed sequence of trials, and the target name was announced to the user. Then the user threw the beanbag at the announced target and the researcher used a tape measure to obtain the distance between the impact point and the target. Since users were unable to receive feedback (as the image they saw was static), they were not required to close their eyes during the toss. If the beanbag landed behind the target, the distance was recorded as a negative value; if it has been overthrown, the distance was recorded as a positive value. If the bag was tossed to the side, the landing spot was transposed to align it with the line from the participant to the target. The beanbag was collected by a researcher after the measurement. After the study was completed, the participants received 5USD in cash.

Hypotheses

Naturally, we would expect greater distances to draw out greater error from our participants in a throwing task; and, in accordance with previous work, we would expect reduced FOVs to result in compressed estimation of distance. Therefore, we hypothesized the following:

- H1: Participants will underthrow the target when viewing the environment with the narrow FOV, and be more accurate with the wide FOV.
- H2: Participants will make greater errors when throwing the beanbag at further targets.

Data Analysis Approach

Since our study design was within-subjects, we first performed a Shapiro-Wilks test and found that the data was not normally distributed ($p < .001$). Thus, we elected to use Friedman tests as our omnibus - one for FOV, and one for Distance. In presence of statistical significance, we planned

Table 4.1: Descriptive statistics of average user error, by FOV and Target Distance

FOV	Target Distance	Error (centimeters)
200°	3 meters	M = 13.9, SD = 47.5
	4 meters	M = 7.70, SD = 67.0
	5 meters	M = -9.00, SD = 74.0
	6 meters	M = -14.9, SD = 61.4
110°	3 meters	M = 11.7, SD = 66.2
	4 meters	M = -3.60, SD = 65.9
	5 meters	M = -3.50, SD = 79.3
	6 meters	M = -37.9, SD = 80.2
60°	3 meters	M = -10.4, SD = 47.2
	4 meters	M = -22.1, SD = 81.4
	5 meters	M = -19.1, SD = 78.6
	6 meters	M = -40.6, SD = 89.9

on using Wilcoxon Signed Rank tests to compare the conditions. We used Holm's Sequential Bonferroni Adjustment to control for Type I errors [56]. We did not hypothesize an interaction effect and therefore we did not test for one.

Results

In this section we discuss the results of our study. First, we present the descriptive statistics, and next we present the results of Friedman tests and post-hoc Wilcoxon signed-rank tests.

Descriptive Statistics

Table 5.1 shows the descriptive statistics of average user error. Figure 4.2 shows the plot of average error by FOV, and Figure 4.3 shows the plot of average error by target distance. As the data

Table 4.2: Post-hoc Wilcoxon Signed-Rank Tests Results

Condition 1	**Mean**	**SD**	**Condition 2**	**Mean**	**SD**	**t-test Result**
Effect of Field of View						
200°	-0.56	74.29	60°	-23.04	81.11	$Z = -4.071, p < .001$
200°	-0.56	74.29	110°	-8.32	84.24	$Z = -1.089, p = .276$
110°	-8.32	84.24	60°	-23.04	81.11	$Z = -2.994, p < .01$
Effect of Distance						
3m	5.08	61.63	4m	-5.97	88.80	$Z = -3.571, p < .001$
3m	5.08	61.63	5m	-10.54	85.61	$Z = -3.126, p < .01$
3m	5.08	61.63	6m	-31.13	88.80	$Z = -5.168, p < .001$
4m	-5.97	82.26	5m	-10.54	85.61	$Z = -0.681, p = .496$
4m	-5.97	88.80	6m	-31.13	88.80	$Z = -3.723, p < .001$
5m	-10.54	85.61	6m	-31.13	88.80	$Z = -3.209, p < .01$

suggests, participants made greater error and thus underestimated the distance for narrower FOVs, and the error for further targets is greater.

Friedman Tests and Wilcoxon Signed-Rank Tests

We performed a Friedman test for each independent variable. First, we found a significant effect of FOV on user distance perception, $\chi^2(2) = 15.57, p < .001$. We performed post-hoc Wilcoxon signed rank tests, comparing each condition pair. We found a significant difference between the 200° and 60° conditions, as well as 110° and 60° conditions. However, we did not find a significant difference between 200° and 110° (see Table 4.2). Our results indicate that restricted FOVs are more conducive to distance compression, whereas the larger FOVs help to reduce error.

Next, we performed a Friedman test on the data for Distance, and found a significant effect, $\chi^2(3) = 41.61, p < .001$. We therefore performed post-hoc Wilcoxon signed rank tests, comparing each condition pair; see Table 4.2. We found significant differences in user error between each target distance, with one exception; 4m was not found to be significantly different than 5m. As expected, greater target distance was conducive to greater user error.

Discussion and Conclusion

The effect of restricted FOV on distance judgement is one of the problems that has different answers among the literature. While some historical studies have suggested that FOV - when combined with other HMD traits (weight and resolution) - does have a significant effect on distance estimation [4, 38], there are other studies that suggest FOV is not a significant factor that causes compression in distance estimation [46]. In our work, we simulated reduced FOVs within one headset, therefore keeping screen resolution and weight constant, finding a significant main effect of FOV such that reduced FOVs resulted in distance compression. Although user error was greater in the 110° condition compared to the 200° condition, we note that these two conditions were not statistically different. Therefore, this implies that newer hardware which boasts a FOV similar to that of natural human eyesight may not provide a benefit in terms of distance estimation in virtual environments. However, our result does not speak to other VR outcomes such as presence, simulator sickness, etc. As we are interested in understanding how humans perceive realistic virtual environments, in an effort to help bridge the gap between VR and the real world, in the next chapter we will focus on understanding how varying horizontal FOV and vertical FOV separately influences the perception of distance in various virtual environments.

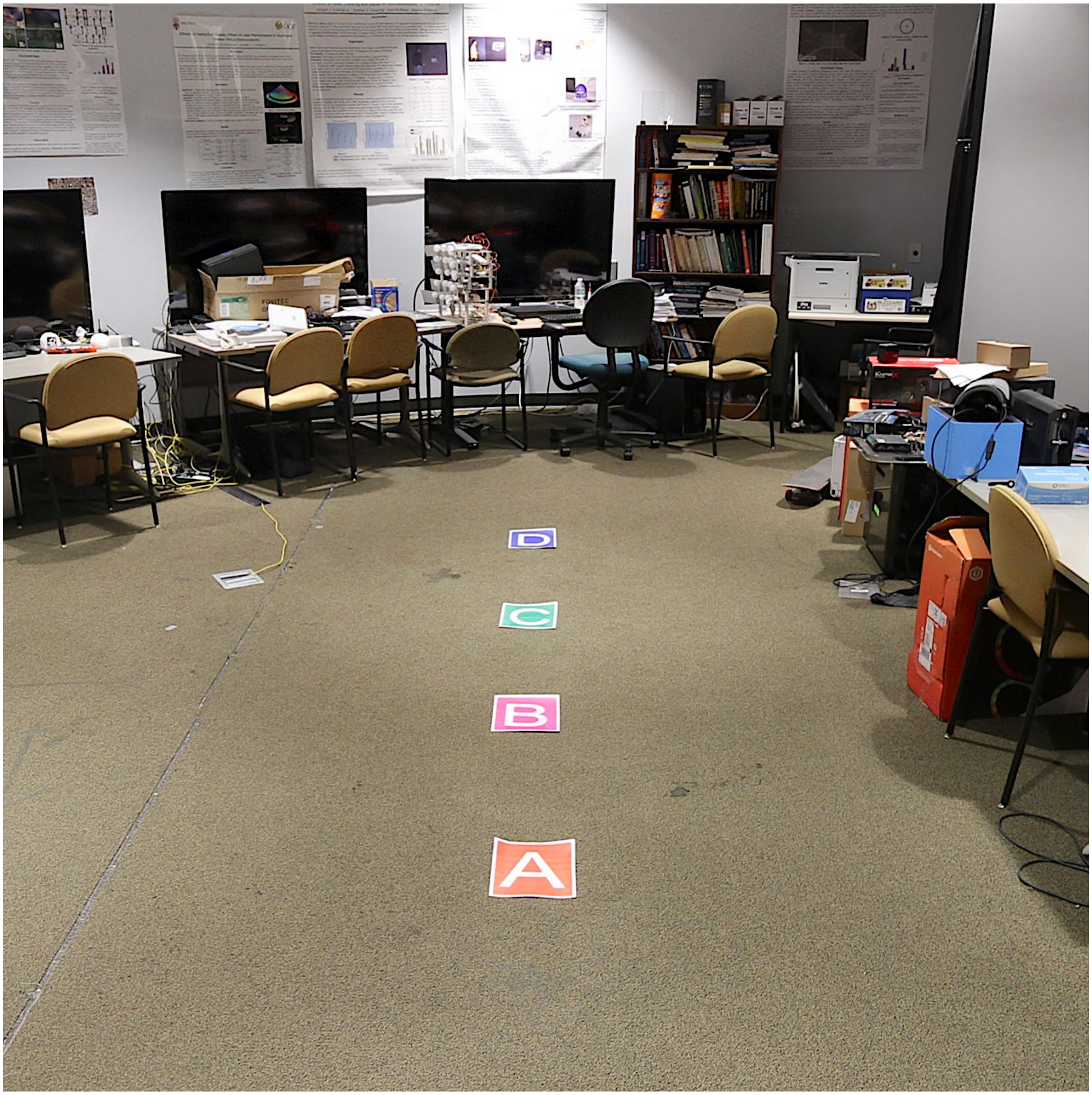


Figure 4.1: Static Environment used for the study

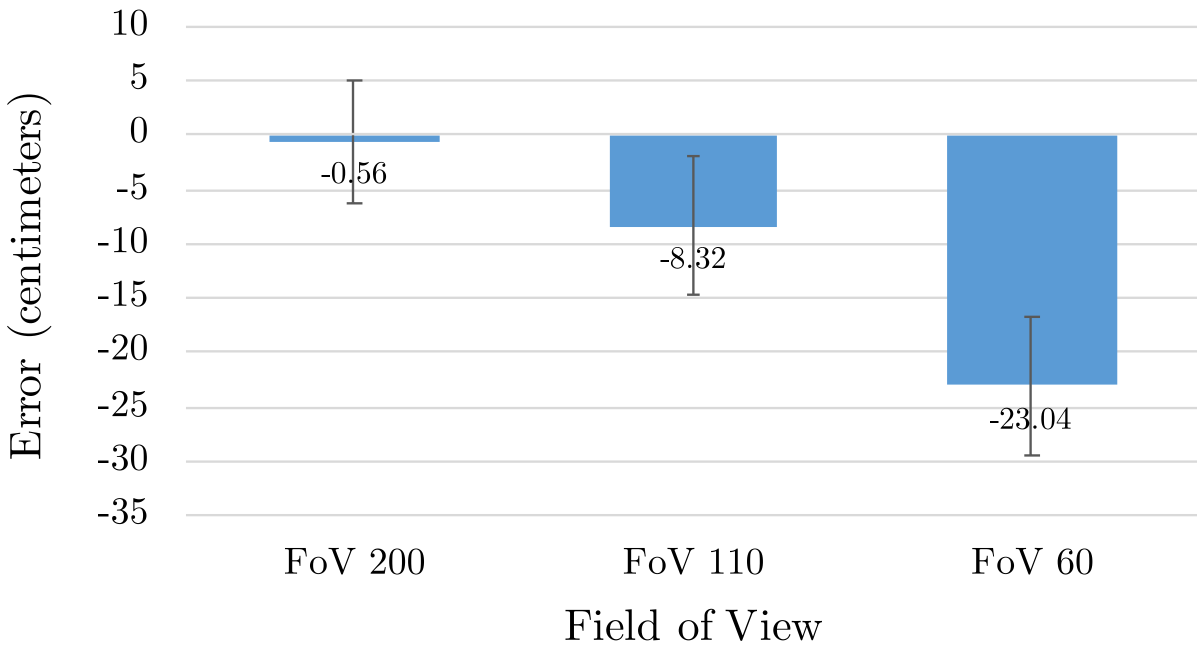


Figure 4.2: Average error by FOV with 95% confidence. Generally, participants underthrew the beanbag to the targets, but were less accurate when their FOV was limited.

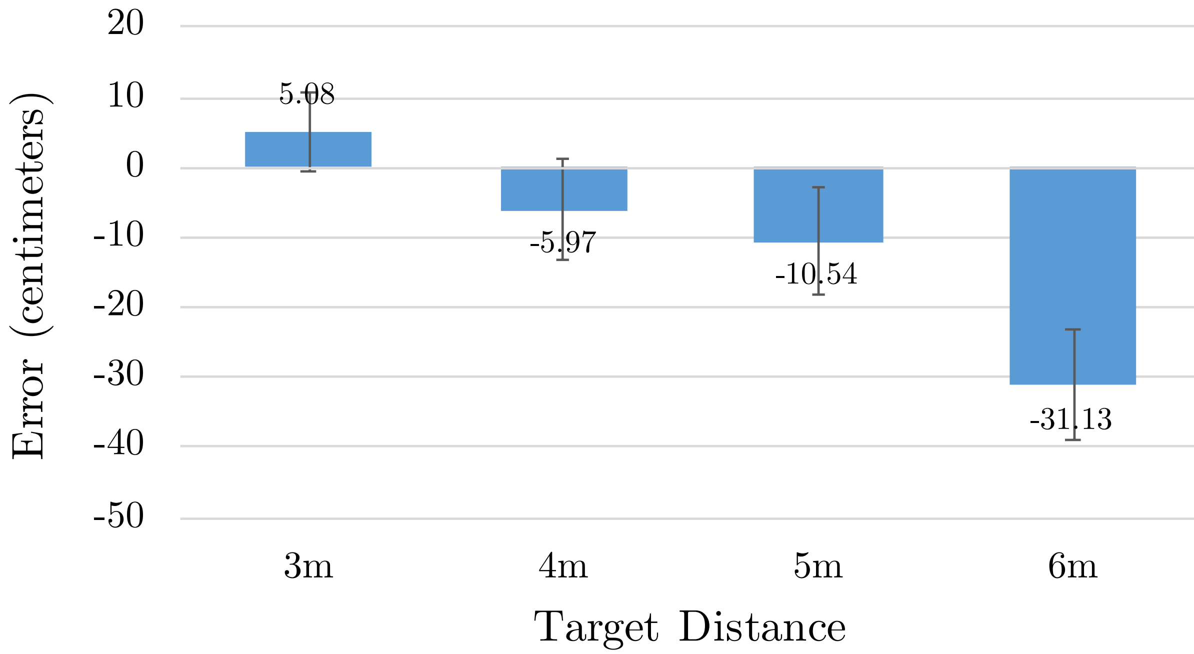


Figure 4.3: Average error by Distance with 95% confidence. Generally, participants were less accurate with farther targets which resulted in greater underthrow.

CHAPTER 5: EFFECTS OF FIELD OF VIEW ON EGOCENTRIC DISTANCE PERCEPTION IN VARIOUS VIRTUAL ENVIRONMENTS[1]

In this chapter, our goal is to understand the direct impact of Horizontal Field of View (HFOV) and Vertical Field of View (VFOV) on user distance perception. To ensure results are general and potential FOV effects are not bounded to one specific environment, we tested varying FOV conditions across multiple environments: indoor/outdoor and cluttered/uncluttered. In doing so, it can be understood if distance perception effects are specific to the FOV or if the environment also influences distance perception. We examined the effects of FOV on egocentric distance judgment while using the same HMD - the Pimax 5K Plus headset, which boasts a horizontal field of view of 165° and a vertical field of view of 110°. We used the Unity3D game engine to programmatically simulate 110° and 45° HFOVs and 35° VFOV in the headset, in addition to the native FOV. This way, we could keep the HMD weight, screen pixel density, latency, and other attributes constant throughout the study and isolate the effect of variation of FOVs. These FOVs were chosen to match those of HTC Vive (110°×110°) and NVIS nVisor ST60 (45°×35°) which have been used in previous research [19, 51, 4, 2]. We found that reduced HFOVS cause significant increases to error, while VFOVS do not have significant impact on error. Further, we found that outdoor environments and uncluttered environments both hinder distance estimations. We make the following contributions to the VR distance underestimation literature in this dissertation:

- A user study protocol that isolates FOV for direct investigation in VEs
- Evidence that HFOV is a significant factor for distance underestimation, whereas VFOV is not

[1]This chapter contains previously published material adapted from the following article: Masnadi, Sina, Kevin Pfeil, Jose-Valentin T. Sera-Josef, and Joseph LaViola. "Effects of Field of View on Egocentric Distance Perception in Virtual Reality." In CHI Conference on Human Factors in Computing Systems, pp. 1-10. 2022. https://doi.org/10.1145/3491102.3517548

- Evidence that presence of items in a VE, and visual boundaries of a VE, provide significant visual anchor to reduce distance underestimation
- Design recommendations and roadmap for future study, identifying potential avenues to further reduce distance compression in VR

The rest of this chapter is comprised as follows: first, we position our work against that of previous findings in the VR distance underestimation literature; then, we describe in detail our user study to directly investigate the effects of FOV on distance underestimation; next, we present the results and findings from our user study, for each main effect and relevant interactions; and finally, we discuss the implications of our findings, highlighting VR design considerations and areas of consideration for future work.

Methods

We conducted a user study to measure distance judgment with various FOVs and different VEs. The following sections describe the user study methods in detail.

Study Design

To evaluate distance perception, we utilized a blind-walking task in which users were asked to walk towards a specified target while keeping their eyes closed. We conducted a $2 \times 2 \times 3 \times 2 \times 4$ mixed-design study: the between-subject factors were the environment characteristics - INDOOR/OUTDOOR (2 levels) and CLUTTERED/UNCLUTTERED (2 levels) - and the within-subject factors were HFOV (3 levels), VFOV (2 levels), and target distance (4 levels).

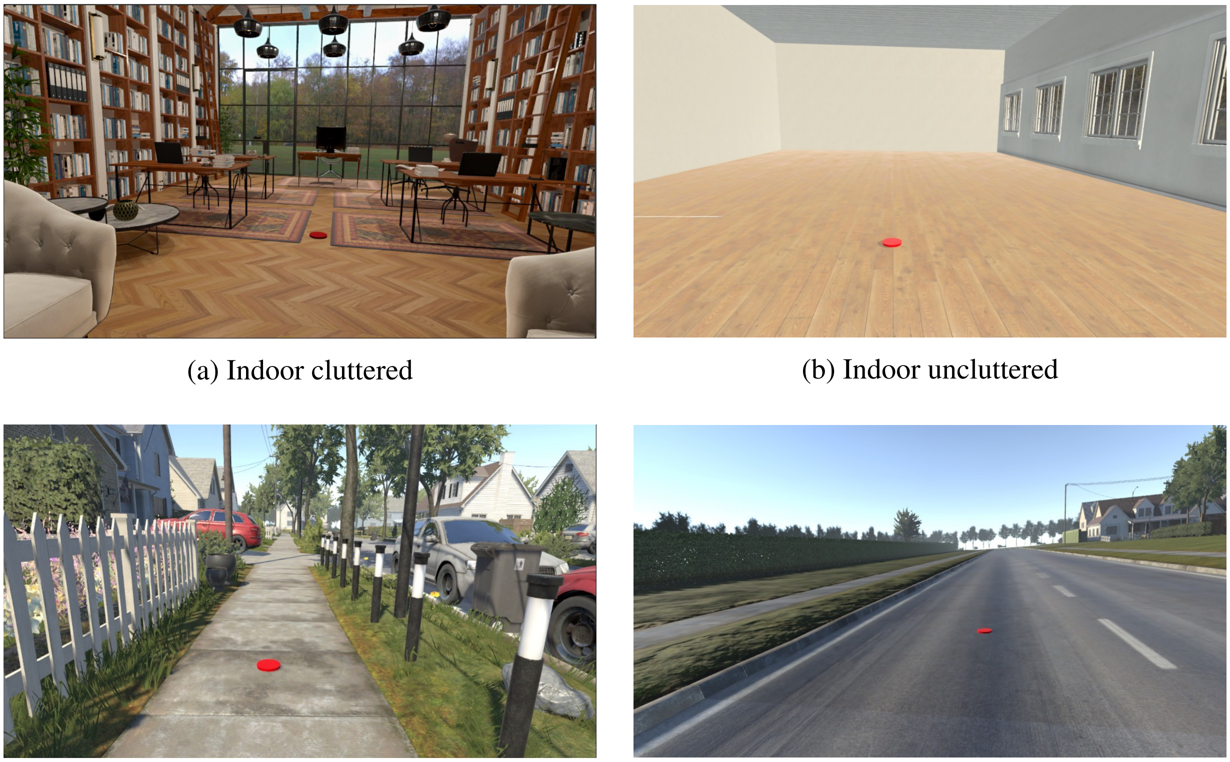
Virtual Environments (Between-Subjects Variables)

We utilized four different environments with each user only seeing one of them. These environments were downloaded from the Unity3D Asset Store[2][3]. Participants were assigned an environment in a random order. The environment conditions were Indoor Cluttered; Indoor Uncluttered; Outdoor Cluttered; and Outdoor Uncluttered (see Figure 5.1). We decided to create combinations of INDOOR/OUTDOOR and CLUTTERED/UNCLUTTERED to represent the types of environments that a user might encounter in VR. All of the environments were designed with realistic elements and real-world scales. The *cluttered indoor* environment (Figure 5.1a) was a 10m$\times$7m library with a 4m high ceiling, bookshelves along two sides of the room, sofas, and five desks. One side of the room was glass facing a yard. The *uncluttered indoor* environment (Figure 5.1b) was an empty 20m$\times$10m room with 4m high ceilings, wood floor, and windows along one side of the room. The *outdoor uncluttered* environment (Figure 5.1c) was located on a 100m long street in daylight with no trees, homes, or cars within the 50m range. There were sidewalks on both sides of the street. The *cluttered outdoor* environment (Figure 5.1d) was on a suburb neighborhood sidewalk in daylight with cars parked along the street and a picket fence on one side. The scenes were displayed to the user using Unity3D.

The user's location in each environment was randomized for each trial. To achieve this, a rectangular boundary was defined for each scene as the *safe area*. The safe area is the area in the VE that it was possible to place the user without overlapping with virtual objects and they could walk to the target without colliding with virtual objects. Before starting a trial, the rotation of the camera and position of the starting point was randomized in a way that the starting point and the targets would

[2] https://assetstore.unity.com/packages/3d/environments/urban/library-interior-archviz-160154; retrieved 2021-12-31

[3] https://assetstore.unity.com/packages/3d/environments/urban/suburb-neighborhood-house-pack-modular-72712; retrieved 2021-12-31



(a) Indoor cluttered

(b) Indoor uncluttered

(c) Outdoor cluttered

(d) Outdoor uncluttered

Figure 5.1: Four different environments were used in this study.

fit in the safe area. None of the two consecutive trials had FOV or target distance in common. In other words every two consecutive trials had a different FOV and a different target distance. Using starting position and rotation randomization minimizes the chance of memorizing the number of steps by the user and also provides more environment variations to mitigate the effect of the environment.

Within-Subjects Independent Variables

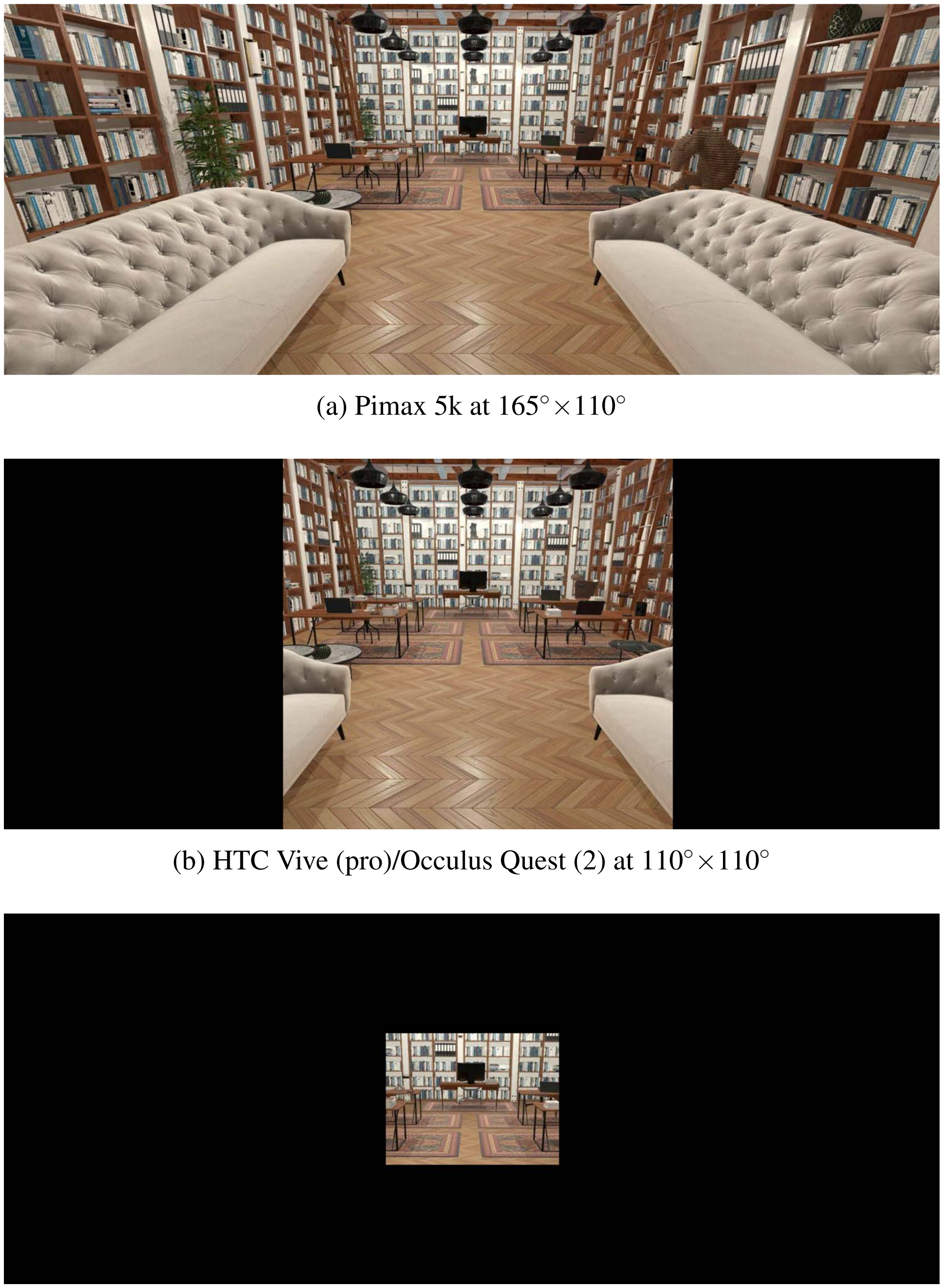
Similar to previous studies, we simulated six different FOV combinations programmatically in the headset [41, 64]. The HFOV levels were 165°, 110°, and 45°, and the VFOV levels were 110°, and 35°. Each FOV level represents the FOV of a real VR HMD: Pimax (165°×110°), HTC Vive (110°×110°), and nVisor ST60 (45°×35°). Figure 5.2 shows an environment with these three HMDs FOVs simulated.

The target distances were 3m, 4m, 5m, and 6m away from the participant. These distances were the exact target distances tested in a previous blind-walking user study [16]. The target was represented as a red cylinder on the ground with a diameter of 10cm and a height of 5cm. The cylinder cast and received shadows to blend in with the scene and provide realistic depth cues to the user. A small cylinder was chosen because we did not want the target indicator to interfere with the user's environment perception, moreover, the users should have been comfortable with stepping on the target without any worry. Figure 5.1 shows the target in different environments.

The combination of HFOV, VFOV, and target distance resulted in 24 different conditions for each user in which we measured blind-walking distances. Each condition was performed 3 times by each user, and the mean error (distance from the target) was recorded. This resulted in 72 trials. The order of the 72 trials was randomized for each user.

Subjects

We recruited a total of 60 participants from the university population, but 4 participants were excluded as they were unable to pass an eye exam. The final participant pool consisted of 56 users (11 female, 45 male) with ages ranging from 18 to 33 (M=22.43, SD=4.38) and heights between 149cm and 199cm (M=173.97, SD=10.26). 31 participants wore glasses or contact lenses. The participants also reported their experience with VR in a scale of 1 (least experienced) to 5 (most experiences) and the result was M=2.39 and SD=1.29.



(a) Pimax 5k at 165°×110°

(b) HTC Vive (pro)/Occulus Quest (2) at 110°×110°

(c) NVIS nVisor ST60 at 45°×35°

Figure 5.2: Simulated FOV for the three HMDs.

Apparatus

We used a Pimax 5k Plus VR headset with a field of view of 165° (horizontal)×110° (vertical). This headset has a resolution of 2560×1440 per eye, a refresh rate of 120hz, and weighs 470g. The headset was connected to an HP Z VR Backpack equipped with an Intel 7820HQ CPU, an NVIDIA Quadro P5200 GPU, and 32GB of memory. We also included a small speaker that rested on the backpack behind the participant's head, to provide auditory feedback during the study (see Procedure). The backpack's total weight was 4.35kg (including the harness and external batteries).

To limit the FOV in Unity 3D we used the canvas feature which can display images 10cm away from the camera on a plane. We used cutouts in a large black rectangle to recreate each of the FOVs. The image within the cutout was unchanged and all the depth cues remained the same. To match the cutouts with the desired FOV, the cutout dimensions were calculated by aligning them to an image with pre-calculated FOV guidelines. The guideline image was placed 2m away from the camera with a dimension of 10m × 10m and canvas cutouts were adjusted to cover the surroundings of the FOV guideline.

We designated an empty area in our closed laboratory to perform this study. The room dimensions were $6m(w) \times 9m(l) \times 3.3m(h)$ and the empty area in the middle of the room was $4m(w) \times 9m(l)$. The furthest target was 6m away from the user and there was a 2m distance between this target and the closest non-study object. Figure 5.3 is a picture of the environment.

A system was developed that allowed us to monitor the user without interfering with their visual display. This means the backpack was not tethered to any display and remote desktop was not possible for this device. Furthermore, remote desktop software would consume resources from the VR rendering system. Due to these limitations, we created a tool to monitor the user's activities and view the headset image on another computer. The tool takes small-scaled images from the

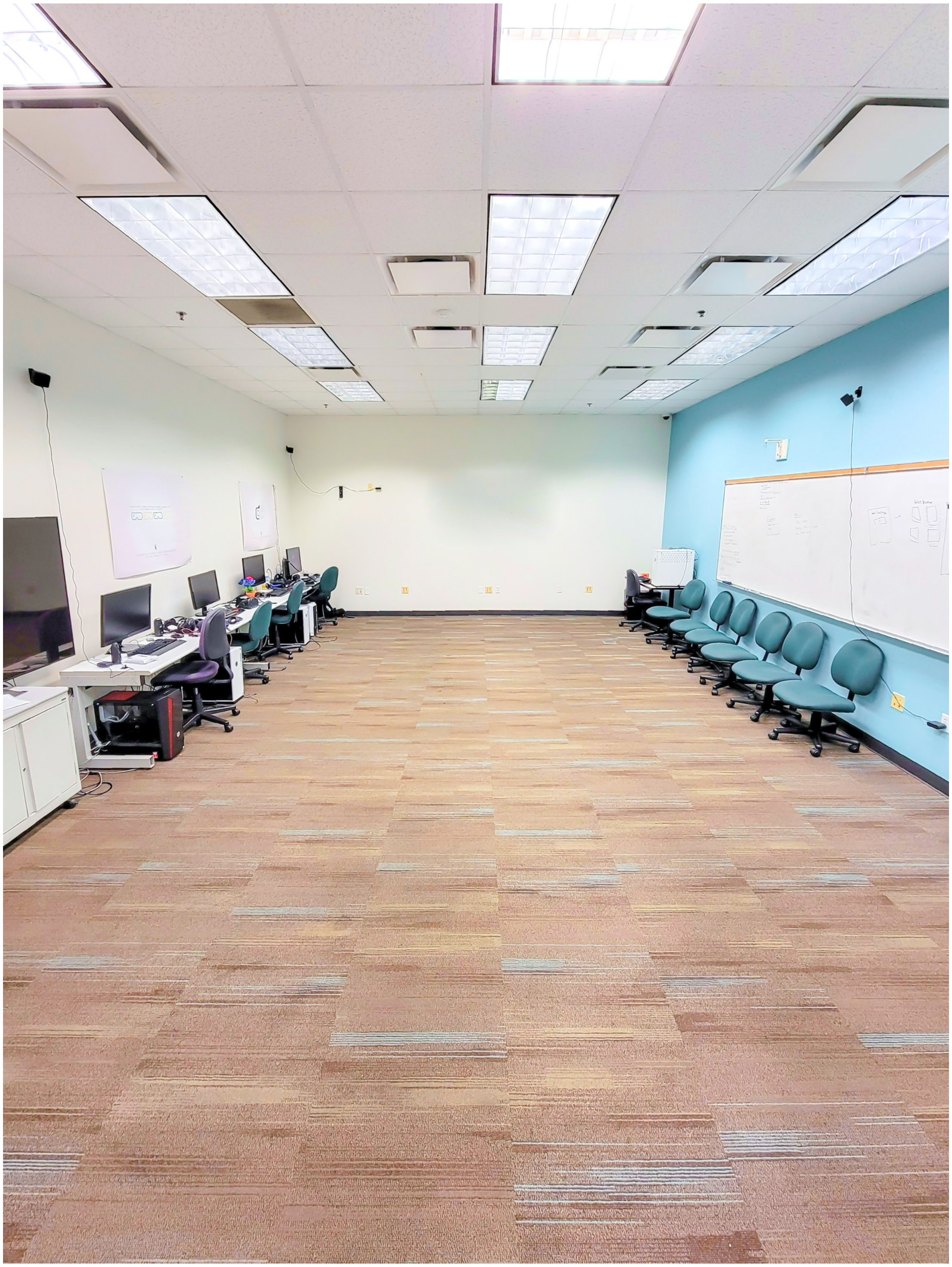


Figure 5.3: The room used for the study.

Figure 5.4: A user wearing the backpack and the HMD.

headset and transmits them to another computer over a WebSocket with no perceivable impact on performance. It also transmits text data to show the researcher the trial information.Our study code is available on Github [4]. It provides a prefab that can be added to any Unity 3D scene to perform the study.

Procedure

Before the study began, the participants were asked to review an informed consent form and were verbally asked for their consent. We measured their vision acuity afterward using a Snellen Chart (see [65]) to ensure that their eyesight was adequate for the study - our participants were required to see better than 20/32 in each eye. If a participant wore corrective lenses, they were required to wear them for the study. If a recruited individual was unable to pass this vision acuity test, they were dismissed. Then, the participants completed a demographic questionnaire (age, gender, and VR experience).

We described the task and objective of blind-walking to the user and showed them the headset and backpack's adjustments. The participant was asked to wear the backpack and adjust the harness and buckles. Then, we asked the participant to wear the headset and make adjustments to get it comfortable and snug on their head. Figure 5.4 shows a user wearing the HP backpack and the Pimax HMD. After the adjustments, we proceeded to collect data.

Before each trial, the FOV of the headset and the target location was changed automatically from a pre-processed sequence of trials. The participant looked at the environment and estimated their distance to the target. They then closed their eyes and let the researcher know that they are ready. The researcher started the walk procedure by pressing a key on a wireless keyboard which made the

[4] https://github.com/anonymous

environment invisible (black) to the user, and a faint computer voice from the backpack was played, which told the participant “go”. This was to simulate “blindfolding” the user, as per previous experiments. The user started to walk and stopped when they thought they reached the target and let the researcher know verbally. The researcher then pressed a button on the keyboard to record the user’s location, play a faint computer voice that said “done” to let the user know they can open their eyes, and reveal a *guidance arrow* under the participant’s feet. To navigate the user back to the starting position we used a guidance arrow which was always fixed under their feet and pointed to the start location. The user should have walked towards the arrow’s direction. When they reached the start location, another arrow (alignment arrow) showed them the correct direction; the user had to align the guidance arrow with the room direction arrow. Once aligned, a green arrow confirmed the alignment. The participant let the researcher know when they completed the alignment; the researcher then pressed a key on the keyboard, such that the VE would then reappear. The next trial then began.

Due to the COVID-19 pandemic, we used the guidance arrow to keep researchers and participants at a safe distance from each other. In the past studies, the researcher had to get close to the user to navigate them back to the starting point. The arrow was designed to stay under the user’s feet to keep its position relative to the user, therefore, avoiding giving feedback to the user about the distance that they have walked to get back to the starting point. Moreover, by avoiding researcher-to-participant verbal communication, we eliminated the potential for the user to receive audio cues based on researcher location.

If the user stopped before the target, the distance from the user to the target was recorded as a negative value; if they stopped past the target, the distance was recorded as a positive value. If they walked to the side of the target, their location was transposed to align it with the line from the start position to the target. The study took one hour and once the study was completed, the participants received $10 USD in cash.

Hypotheses

Research in the past three decades has resulted in conflicting evidence for the identification of FOV being a significant factor that causes distance underestimation in VR [4, 1], but the more recent works suggest that modern technology eliminates this problem - perhaps due to FOV improvements [51]. Similar studies that focused on AR devices have pointed to reduced FOVs contributing to underestimation [36, 64], and we suspect that this finding translates to VR as well. In addition, we note that the environment also influences perception of distance. Creem-Regehr et al. noted that indoor environments are more conducive to more accurate distance judgements than outdoor environments [2], and though there is uncertainty about environment clutteredness providing visual cues which users can use to enhance estimations, some designers add furniture and other objects into their environments, seemingly to improve user perception of distance [66, 67]. We thus conducted our study with the above parameters, hypothesizing the following:

H1: Participants will more accurately estimate distances with wider HFOVS.

H2: Participants will more accurately estimate distances with taller VFOVS.

H3: Participants will more accurately estimate distances when viewing cluttered environments.

H4: Participants will more accurately estimate distances when viewing indoor environments.

Results

The results of our study and the ANOVA analysis of the data are presented below. We report the measured errors in cm.

A Shapiro-Wilks test showed the data was normally distributed ($p = .058$). We planned on per-

Table 5.1: Descriptive statistics of average user error, by FOV and Target Distance

FOV	**Target**	**Error (centimeters)**
$165° \times 110°$	3 meters	M=-40.8, SD=7.7
	4 meters	M=-62.3, SD=8.7
	5 meters	M=-72.4, SD=96.3
	6 meters	M=-82.5, SD=12.4
$165° \times 35°$	3 meters	M=-40.4, SD=7.5
	4 meters	M=-53.0, SD=10.5
	5 meters	M=-69.1, SD=12.6
	6 meters	M=-88.9, SD=13.7
$110° \times 110°$	3 meters	M=-45.6, SD=7.4
	4 meters	M=-71.6, SD=7.6
	5 meters	M=-87.7, SD=12.0
	6 meters	M=-99.4, SD=13.8
$110° \times 35°$	3 meters	M=-42.8, SD=6.7
	4 meters	M=-60.0, SD=10.0
	5 meters	M=-81.1, SD=11.5
	6 meters	M=-84.0, SD=13.6
$45° \times 110°$	3 meters	M=-46.4, SD=8.3
	4 meters	M=-61.2, SD=10.0
	5 meters	M=-83.4, SD=10.2
	6 meters	M=-92.4, SD=14.0
$45° \times 35°$	3 meters	M=-42.5, SD=8.0
	4 meters	M=-60.3, SD=10.2
	5 meters	M=-83.6, SD=12.0
	6 meters	M=-100.1, SD=14.0

forming pair-wise t-tests on the main effects in case of a significant omnibus test. Since we had multiple comparisons, to control the type I errors we used a Bonferroni correction.

We performed the analysis on INDOOR/OUTDOOR $\times$ CLUTTERED/UNCLUTTERED as the between-subject factors. The within-subject factors were DISTANCE, HFOV, and VFOV. Table 5.1 shows the descriptive statistics of average user error by FOV and distance and Figure 5.7 shows the plot of average error by FOV.

Repeated Measures ANOVA Results

In this section, we describe the results of a repeated measures ANOVA.

Main Effect of HFOV

We found a significant main effect of HFOV ($F_{2,104} = 6.428, p = .002, \eta_p^2 = .110$) on distance judgements. Post-hoc comparisons using a Bonferroni adjustment revealed a statistically significant difference between 165° (M = -63.7, SD = 9.6) and 45° (M = -71.2, SD = 9.7), $p = .038$, as well as a significant difference between 165° and 110° (M = -71.5, SD = 9.3), $p < .001$, such that participants were more accurate with their distance estimations with the larger HFOV conditions. Figure 5.5 shows the error mean on the three different HFOVs.

Main Effect of VFOV

We did not find a significant main effect of VFOV ($F_{1,52} = 1.669, p = .202, \eta_p^2 = .031$) on distance judgements. Figure 5.6 shows the error mean on the two different VFOVs.

HFOV × VFOV Effect

We found a significant interaction effect between HFOV and VFOV, $F_{2,104} = 3.260, p = .042, \eta_p^2 = .059$. A post-hoc comparison using a Bonferroni adjustment revealed, when the HFOV was 110°, that the 110° level of VFOV (M = -76.1, SD = 9.3) performed significantly worse than the 35° level (M = -67.0, SD = 9.7), $p = .007$.

Main Effect of Clutteredness

We found a significant main effect of Clutteredness on distance judgements, $F_{1,52} = 4.333, p = .042, \eta_p^2 = .077$, such that the participants had greater underestimation in uncluttered environments ($M = -88.5, SD = 13.4$) compared to cluttered environments($M = -49.1, SD = 13.4$).

Main Effect of Indoor/Outdoor

We found a significant main effect of environment type, $F_{1,52} = 4.121, p = .042, \eta_p^2 = .073$. The participants tended to have a larger underestimation of distances in outdoor environments ($M = -88.0, SD = 13.4$) compared to the indoor environments ($M = -49.6, SD = 13.4$). Figure 5.8 shows the mean error categorized by environment type.

Clutteredness × Indoor/Outdoor Effect

We did not find a significant interaction between CLUTTEREDNESS × INDOOR/OUTDOOR, $F_{1,52} = .904, p = .904, \eta_p^2 = .017$ which shows independent effect of INDOOR/OUTDOOR and CLUTTERED/UNCLUTTERED on distance judgement within our selected environments.

Main Effect of Distance

We found a significant main effect of Distance, such that the further the target, the greater the underestimation, $F_{3,156} = 14.951, p < .001, \eta_p^2 = .365$. Figure 5.9 shows the plot of average error by target distance.

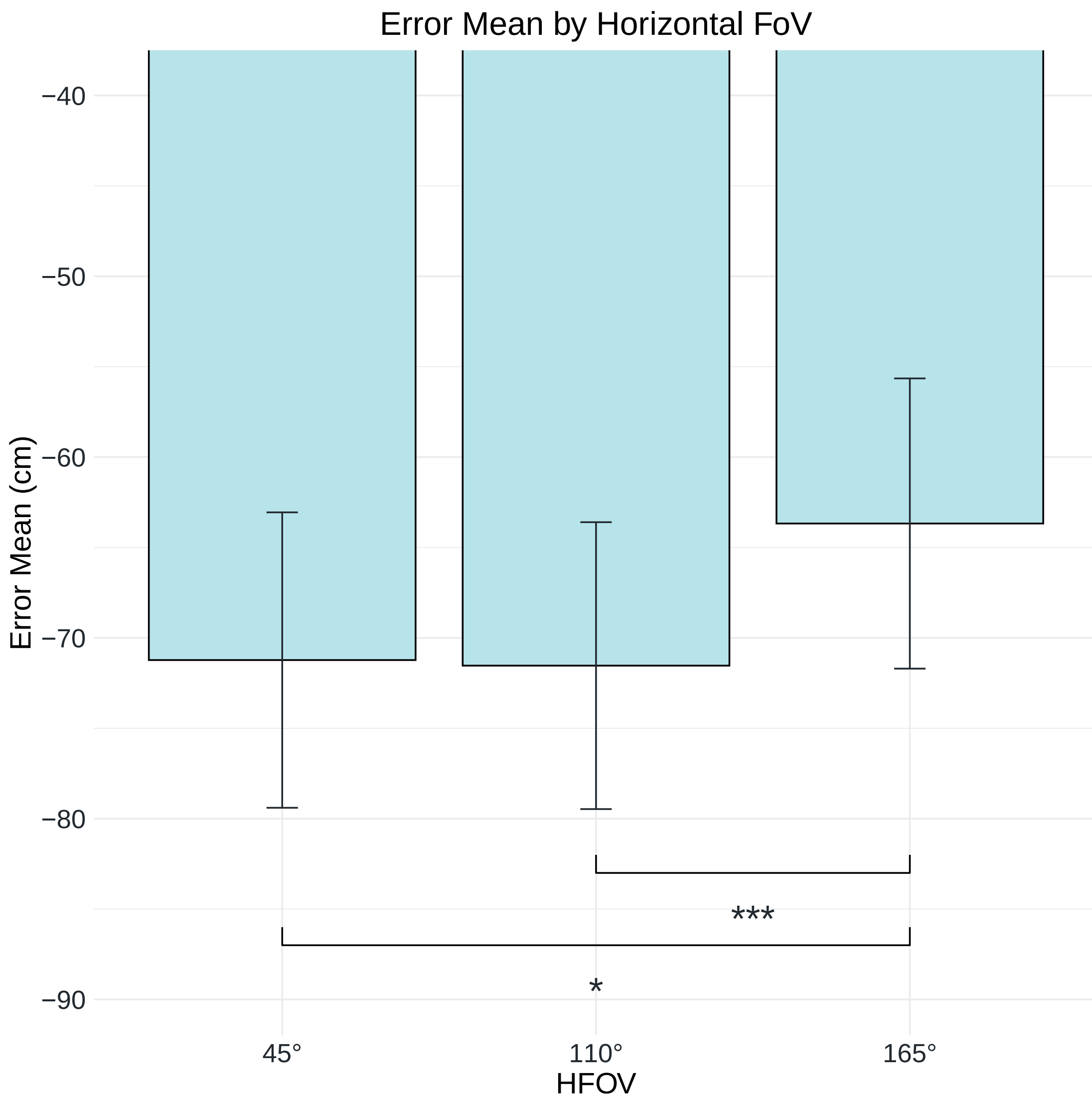


Figure 5.5: Mean error of different horizontal FOVs (error 95% CI).
* = $p < .05$; ** = $p < .01$; *** = $p < .001$

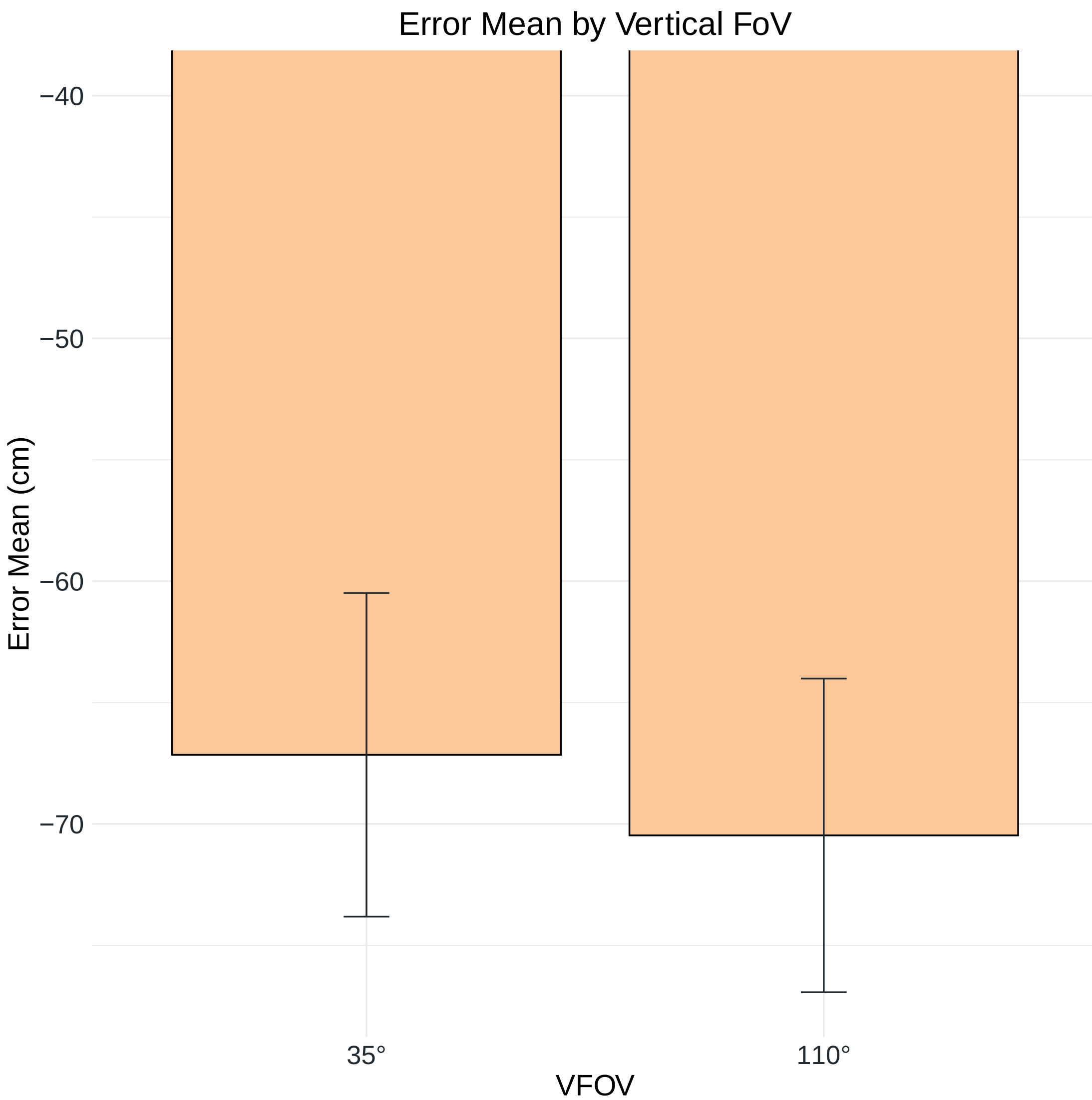


Figure 5.6: Mean error of different vertical FOVs (error 95% CI).

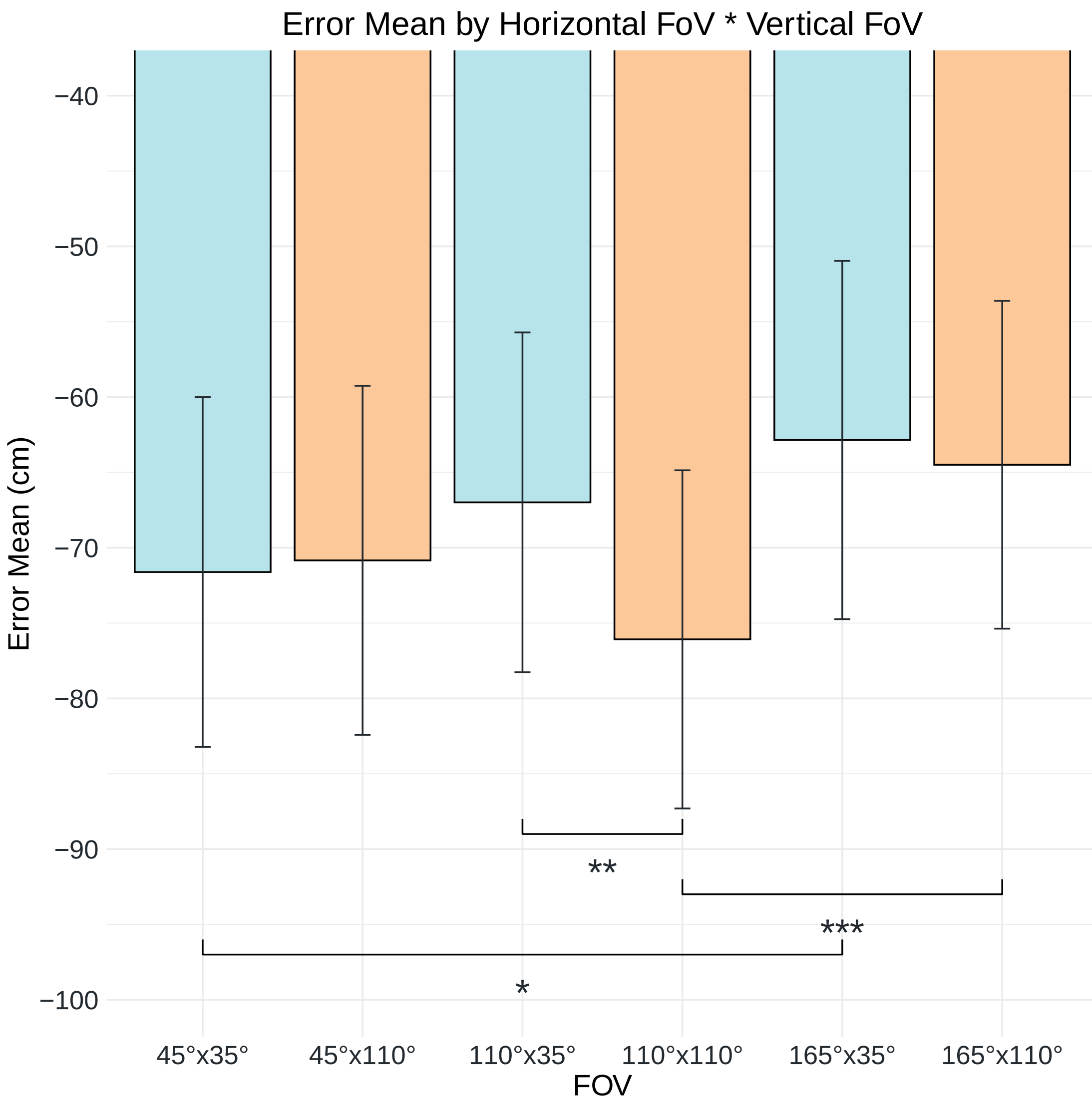


Figure 5.7: Mean error of different FOV combinations (error 95% CI).
* = $p < .05$; ** = $p < .01$; *** = $p < .001$

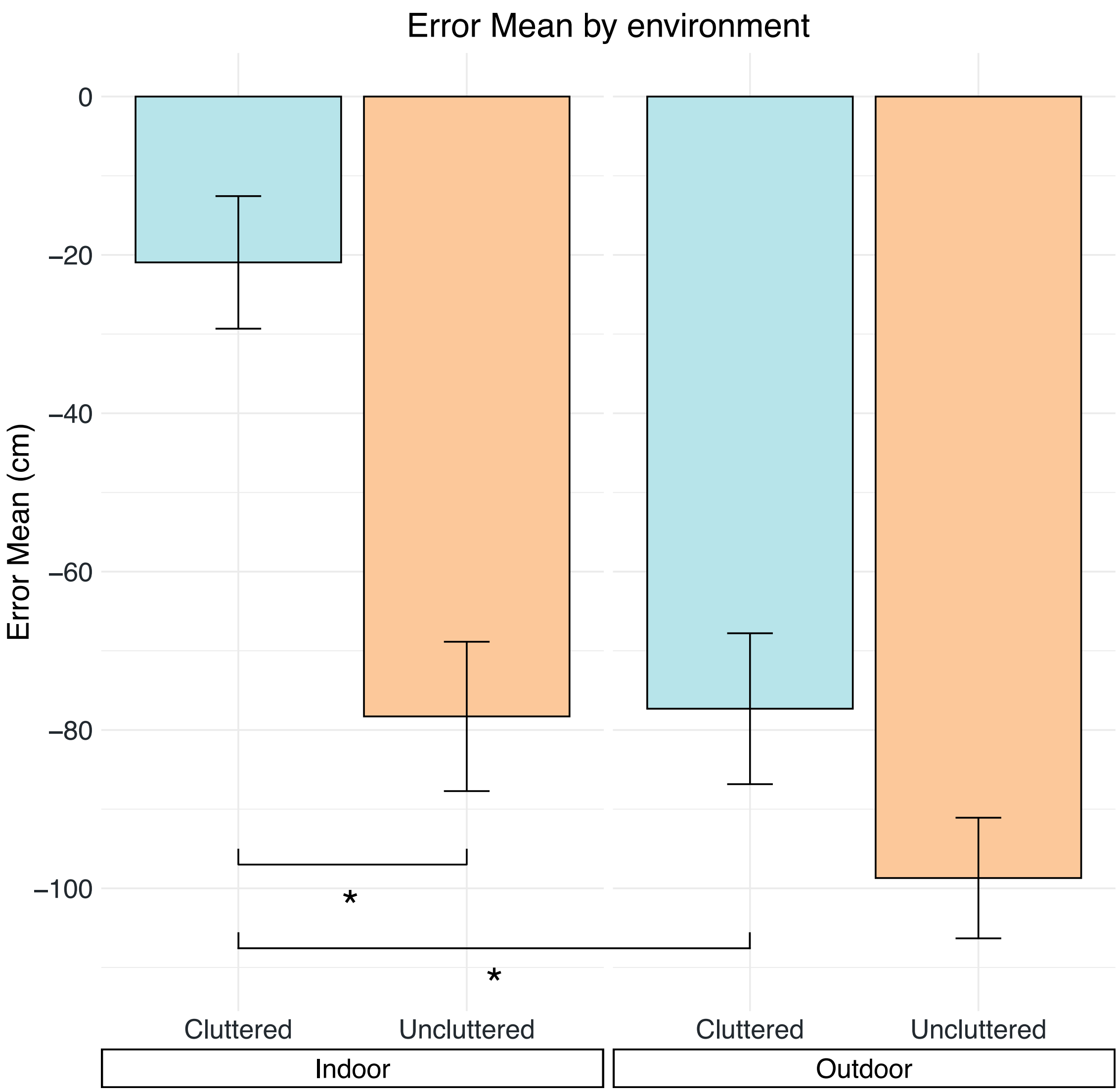


Figure 5.8: Mean error of different Environments (error 95% CI).
* = $p < .05$; ** = $p < .01$; *** = $p < .001$

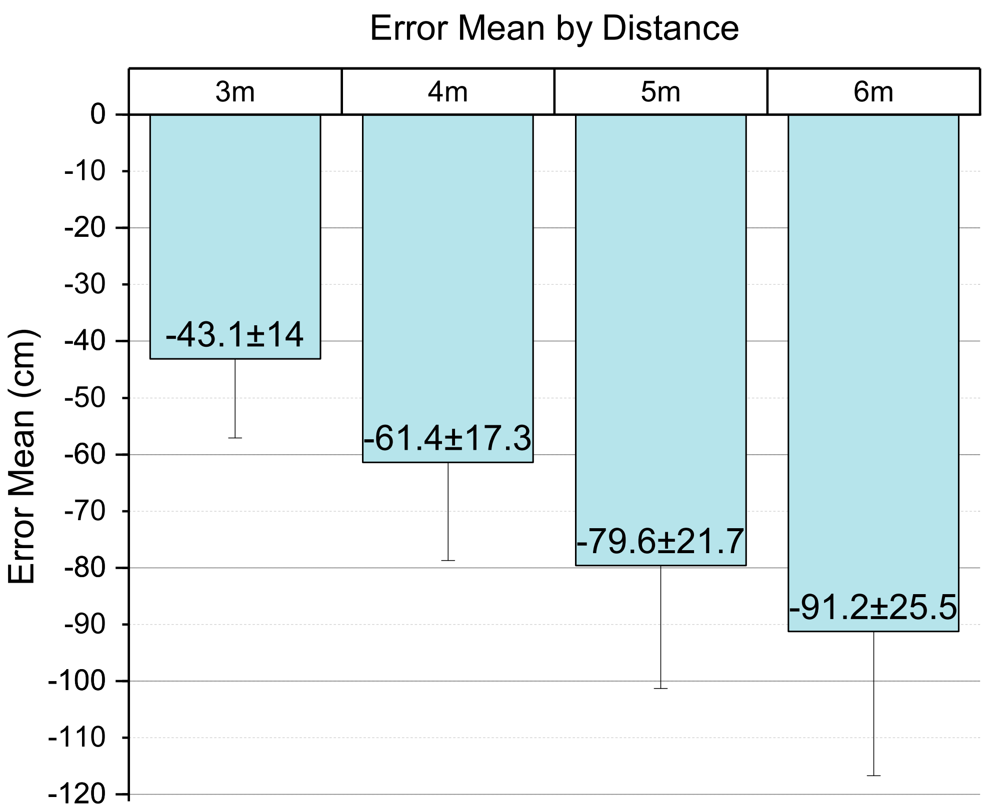


Figure 5.9: Mean error of different Distances (error 95% CI).

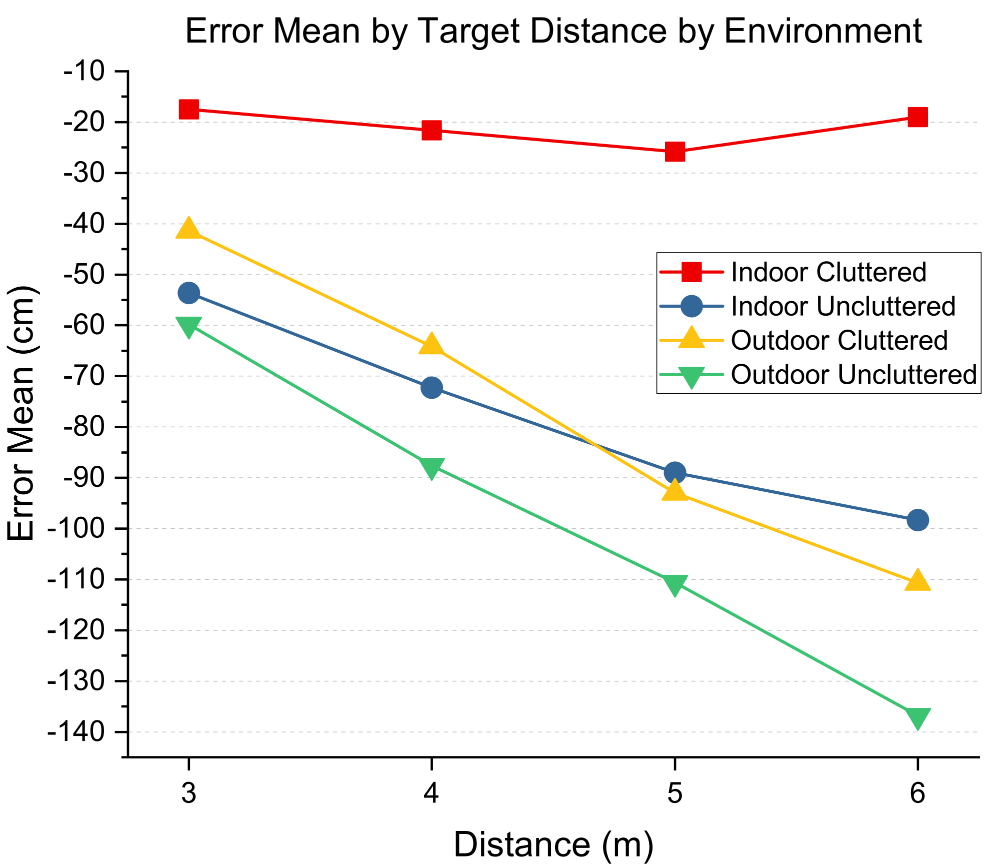


Figure 5.10: Mean error in different Environments by Distance.

DISTANCE × HFOV *Effect*

We did not find a significant interaction effect between DISTANCE and HFOV, $F_{6,312} = 1.002, p = .424$.

DISTANCE × VFOV *Effect*

We did not find a significant interaction effect between DISTANCE and VFOV, $F_{3,156} = .637, p = .592$.

DISTANCE × *Indoor/Outdoor Effect*

We found a significant interaction effect between DISTANCE and INDOOR/OUTDOOR, $F_{3,156} = 7.766, p < .001$). In all environments, participants distance judgement degraded with increasing target distance, except for the indoor cluttered. The indoor cluttered environment had similar error for all four distances while the outdoor uncluttered environment had a sharp decline and the largest mean error (Figure 5.10).

DISTANCE × CLUTTEREDNESS *Effect*

We did not find a significant interaction effect between DISTANCE and CLUTTEREDNESS, $F_{3,156} = 1.859, p = .139$. This, in conjunction with the significant interaction between DISTANCE and INDOOR/OUTDOOR, suggests that the bounding walls of our selected indoor environments were also used to help participants make distance judgement calls for the further distances.

Discussion

Generally, we find that by expanding HFOV, user perception of distance becomes more accurate. As more of the environment geometry becomes visible to the user, so too do the static objects and features of that environment, which may provide a frame of reference. At the very least, light from wider FOVs stimulate the periphery, which has been shown to improve distance judgements [44]. In this section, we discuss the implications of our results.

H1: Horizontal Field of View Needs Widening

Our results indicate that wider HFOVs yield more accurate estimations of short-range distances in VR; H1 is supported. Where previous work did not find FOV to be a significant factor [38, 39], our work is the first to isolate HFOV while keeping all other apparatus attributes constant, and it does show how FOV is a main factor to be considered. This finding parallels that of Buck et al., who used a variety of devices to conduct a similar study [33], but our work was able to achieve this result while keeping other potential factors (weight, screen resolution, etc.) constant. Our results also imply that the current, differing, commercial HMDs lend themselves to varying perception of a given VE. Where previous work found that desktop display size directly affects task performance [68], and television screen size affects sense of presence in video games [69], it now follows that VR HMD HFOV may also directly affect performance in VR applications, though our current study does not confirm this directly. Our selected apparatus, the Pimax VR headset, has a maximum HFOV of 165°, but we note, however, that even with an HFOV of 165°, our participants still made significant errors in our experiment. It is clear that hardware improvements must still be made to maximize FOV, in an effort to minimize distance underestimation. The limits of human vision reaches approximately 220° horizontally; as such, we expect VR hardware developers to continue progressing the limits of HMD FOV to achieve this maximum. We expect this technological progression to be expensive, but one area of opportunity to reduce costs is the focus on VFOV.

H2: Necessary Vertical Field of View Maximum Reached?

One unexpected result of our study was that VFOV did not have a significant effect on distance judgments; H2 is thus not supported. The 2 levels of VFOV were so vastly different that we anticipated to show how taller FOVs were superior to shorter ones, but it seems that this is not necessarily true. Current hardware may already support the levels of VFOV that are necessary to accurately perceive a given VE, and as such we would expect hardware designers to strictly focus on HFOV extensions. However, although we have shown how distance estimation does not improve with taller FOV, it is likely the case that other metrics not measured in our study, such as task performance, presence, and enjoyment, could improve with the extension of VFOV. Our study strictly speaks to distance perception. However, we must consider the significant interaction effect between HFOV and VFOV. This unexpected result happened to occur when the displayed FOV was square, whereas all other FOV combinations in our study were rectangular. While we are unaware of any literature that might explain this finding, it could be in part due to natural human eyesight *not* having equal horizontal and vertical angles.

H3: Environment Objects Provide Significant Anchor

We found a significant difference between cluttered and uncluttered environments such that the participants tended to underestimate distances significantly in uncluttered environments versus cluttered ones. This shows that environment clutteredness and the presence of familiar objects that the user can use to grasp a sense of scale in the environment affects the perception of distance; hypothesis H3 is supported. This improvement in distance judgement in cluttered environments may be related to the number of objects present in the scene and the visual depth cues they provide to the users. For example, in the cluttered indoor scene, which had the most accurate perception of distance among all environments, there are numerous objects around the room which a user can use to determine their relative and egocentric distance with little effort, while in the uncluttered environments only a few visual cues are available which are not located in the near-field of the user. While there is ongoing discussion regarding the direct effects of static environmental elements providing a reliable visual anchor [67, 70], our results indicate that these attributes do indeed make a significant difference, for egocentric distance judgements.

H4: Natural Environment Bounds Provide Significant Anchor

Our results also revealed that being in an indoor environment significantly improves distance judgment, and this is most likely due to the walls of the indoor space providing some visual cues regarding the environment size. Based on this result we can accept hypothesis H4. These findings align with those of Creem-Regehr et al. on outdoor vs indoor environments [2], but counter those of Kelly et al. [51]. We find that this effect of being enclosed in a walled environment, and familiarity with the building blocks of an indoor environment, does substantially enhance one's ability to judge distances regarding that environment.

Limitations and Future Work

In this section we acknowledge our study limitations. Although our results are applicable to the VR community, we cannot claim that our results generalize to AR scenarios. Although previous work in that field does suggest that FOV is a significant factor [36], more work is necessary to confirm this claim. As researchers plan on using AR devices for multiple daily life scenarios, including vision correction [31, 71], it is important to study the effects of FOV for these devices as well.

Further, we chose two levels for VFOV (110° and 35°) which have a large gap, and defining finer gaps between more levels of VFOV might provide more insight about the effect of VFOV on distance judgment. We also note that, although 110° is very tall, it does not represent the natural limits of human vision. It may still be possible that accommodating the maximum VFOV would help to minimize distance underestimation, but we cannot confirm or deny this possibility now.

In this study we used four different environments to represent combinations of indoor or outdoor, and cluttered or uncluttered environments. However, an elaborated investigation of different environment conditions will provide more insight about the environment effect to the field. Our cluttered conditions had various items dispersed in them, and these items were not the same across the 2 cluttered environments. As such, our study cannot directly speak to any effect of *types* of objects found in a scene. There is some level of ambiguity to human avatars, vehicles, furniture, etc., and it is possible that different categories of "clutter" provide a user with varying visual cues. More work should be conducted to help identify *which* clutter would help reduce distance underestimation.

We also hesitate to generalize our findings to all potential VR populations. The participants of this study were from recruited from the student body of our local university, and this limited the age group of the users and therefore restricts the results of the study.

Another limitation of our work is the lack of comparison with real-world environments. Since it has been shown multiple times in the previous studies that people tend to underestimate distances in VEs compared to the real world, we decided to focus on the VEs themselves and compare them to each other and the effect of FOV in each of them. Our future work will replicate our protocol with a focus on comparing VR to the real world.

One other aspect that should be investigated in the future is the user's gaze and the areas that the user is using in a scene to identify and estimate distances. The area that user looks at can be identified using a convex-hull algorithm applied to the gaze points [72].

We investigated targets in the medium-field, while a further examination is necessary to conclude the effects of FOV in the near-field and far-field. Since the evaluation techniques used for near-field and far-field are different from blind-walking, we decided to focus on evaluating using a single evaluation method.

Conclusion

In this chapter, we showed through an action-based assessment (blind-walking) that wider HFOV results in more accurate distance judgment. We also showed that VFOV did not have a significant effect on distance perception. The results indicated that using cluttered environments improves the perception of distance comparing to uncluttered environments. The context of the environment was a significant factor, showing that users performed better in indoor environments in the distance judgment task while greater underestimation was seen in outdoor environments. These trade-offs may need to be considered when the perception of distance is of importance in a VR system design.

CHAPTER 6: EFFECTS OF CLUTTER ON EGOCENTRIC DISTANCE PERCEPTION

In the last chapter we talked about the differences between cluttered and uncluttered environments. The results of the study discussed in the last chapter showed that participants tend to underestimate distances greater in uncluttered environments compared to cluttered environments. In this chapter we focus on the causes of this phenomenon. The definition of clutter can be different depending on the context. However there is no single definition for clutter, in this chapter we defined the clutter as a combination of number of objects in the scene.

Methods

We conducted a user study to measure distance judgment with various levels of clutter in different VEs. The following sections describe the user study methods in detail.

Study Design

To evaluate distance perception, we utilized a blind-walking task in which users were asked to walk towards a specified target while keeping their eyes closed. We conducted a $2 \times 2 \times 3 \times 3 \times 4$ mixed-design study: the between-subject factors were the environment characteristics - INDOOR/OUTDOOR (4 levels) - and the within-subject factors were CLUTTER-LEVEL (3 levels), FOV (3 levels), and target distance (4 levels).

Virtual Environments (Between-Subjects Variables)

We used four different environments where each participant only saw one of them. These environments were downloaded from the Unity3D Asset Store[1][2][3][4]. Participants were assigned an environment in a round robin order. The environment conditions were Indoor1, Indoor2, Outdoor1 and Outdoor2. For each scene we designed three levels of clutter: 1:uncluttered, 2:semi-cluttered, and 3:cluttered. A higher level scene has more objects comparing to a lower in the same environment. All of the environments were designed with realistic elements and real-world scales. The *Indoor1* environment (Figure 6.1) was a 10m$\times$7m library with a 4m high ceiling, bookshelves along two sides of the room, sofas, and five desks. The *Indoor2* environment (Figure 6.2) was a 10m$\times$5m apartment living room with 3m high ceilings, carpet floor, and windows along one side of the room. The *Outdoor1* environment (Figure 6.3) was on a sidewalk on a suburb neighborhood in daylight with cars parked along the street and a picket fence on one side. The *Outdoor2* environment (Figure 6.4) was located on an island in daylight with trees, wooden cottages, barrels, ropes, and wooden boxes around the walking area. Unity3D was used to display the scenes to the user using.

The position and rotation of the user in the virtual environment was randomized for each trial. We used a rectangular boundary for each scene as the *safe area*. In the VE, within the safe area, it was possible to place the user and the target so that the user could walk towards it without colliding with virtual objects. On each trial, the camera's rotation and position, which represents the starting point, was randomized in a way that the *starting point* and the targets would fit in

[1] https://assetstore.unity.com/packages/3d/environments/urban/library-interior-archviz-160154; retrieved 2022-06-12

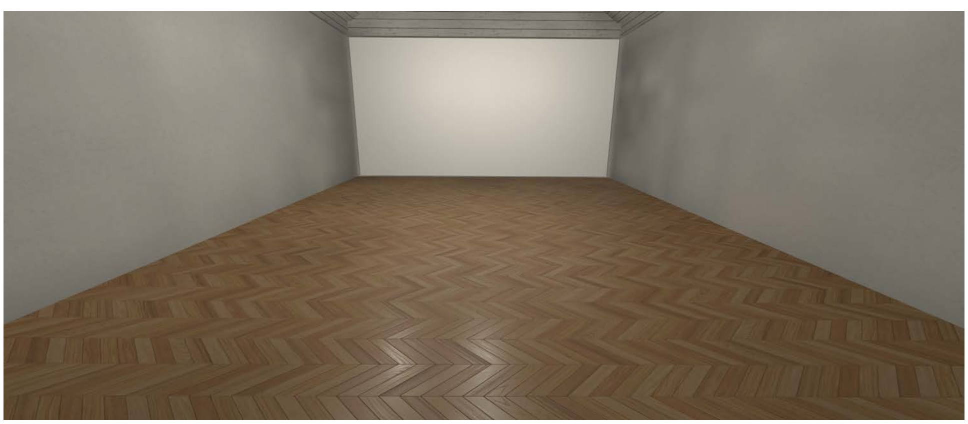
[2] https://assetstore.unity.com/packages/3d/environments/urban/suburb-neighborhood-house-pack-modular-72712; retrieved 2022-06-12

[3] https://assetstore.unity.com/packages/3d/props/apartment-kit-124055; retrieved 2022-06-12

[4] https://assetstore.unity.com/packages/3d/environments/pirates-island-14706; retrieved 2022-06-12

(a) Indoor1 cluttered

(b) Indoor1 semi-cluttered



(c) Indoor1 uncluttered

Figure 6.1: Three levels of clutter for the Indoor1 environment were used in this study.

(a) Indoor2 cluttered

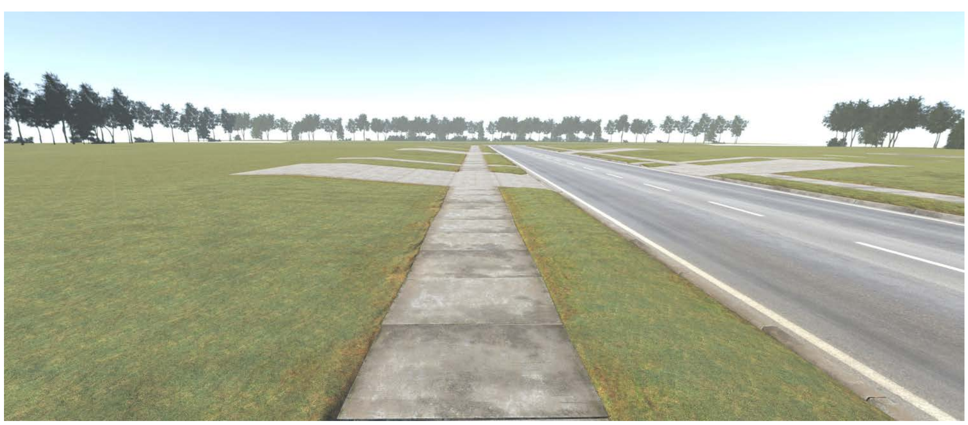
(b) Indoor2 semi-cluttered

(c) Indoor2 uncluttered

Figure 6.2: Three levels of clutter for the Outdoor1 environment were used in this study.

(a) Outdoor2 cluttered

(b) Outdoor2 semi-cluttered



(c) Outdoor2 uncluttered

Figure 6.3: Three levels of clutter for the Outdoor1 environment were used in this study.

(a) Outdoor2 cluttered

(b) Outdoor2 semi-cluttered

(c) Outdoor2 uncluttered

Figure 6.4: Three levels of clutter for the Outdoor1 environment were used in this study.

the safe area. None of the two consecutive trials had any clutter level, FOV, or target distance in common. In other words every two consecutive trials had a different clutter level, a different FOV, and a different target distance. The starting point randomization minimizes the chance of the user memorizing the number of steps. It also mitigates the effect of the environment by providing more environment variations to the user.

Within-Subjects Independent Variables

We simulated three different FOVs programmatically in the HMD. The FOV levels were $165° \times 110°$, $110° \times 110°$, and $45° \times 35°$. Each FOV level represents the FOV of a real VR HMD: Pimax 5K ($165° \times 110°$), HTC Vive/Oculus Quest ($110° \times 110°$), and nVisor ST60 ($45° \times 35°$). Figure 5.2 shows an environment with these three HMDs FOVs simulated.

The target distances were 3m, 4.5m, and 6m away from the participant. Figure 6.5 shows these three targets in an environment. These range of the distances were the range that was tested in a previous blind-walking user study [16]. Instead of 3m, 4m, 5m, and 6m, we simplified them to three target distances to keep the number of trials a user performs lower and preventing fatigue and learning effect during the study. The target was represented as a red cylinder on the ground with a diameter of 10cm and a height of 5cm. The cylinder cast and received shadows to blend in with the scene and provide realistic depth cues to the user. The target object specifications matched the previous study [73].

The combination of clutter level, FOV, and target distance resulted in 27 different conditions for each user in which we measured blind-walking distances. Each condition was performed 3 times by each user, and the mean error (distance from the target) was recorded. This resulted in 81 trials. The order of the 81 trials was randomized for each user.

Figure 6.5: All three targets are displayed in an environment. The camera is located at the user's point of view.

Subjects

We recruited a total of 24 participants from the university population (6 female, 18 male) with ages ranging from 18 to 34 (M=22.54, SD=3.94) and heights between 152cm and 210cm (M=175.26, SD=13.10). 12 participants wore glasses or contact lenses. The participants also reported their experience with VR in a scale of 1 (least experienced) to 5 (most experiences) and the result was M=2.31 and SD=1.05.

Apparatus

For this study, we used a Pimax 5k Plus VR headset. This headset has a field of view of 165° (horizontal)×110° (vertical) and resolution of 2560 × 1440 per eye. It has a refresh rate of 120hz, and weighs 470g. A HP Z VR Backpack with an Intel 7820HQ CPU, an NVIDIA Quadro P5200 GPU, and 32GB of memory was used to drive the headset. A small speaker on the backpack behind the participant's head was installed to provide auditory feedback during the study (see Procedure). The total weight of the backpack, including the harness and external batteries, was 4.35kg .

Similar to Chapter 5, a canvas in Unity3D was used to limit the user's FOV. The canvas was positioned 1cm away from the cameras and it was separately calibrated for each of the stereo cameras. A cutout in a black plane in the canvas limited the FOV so that the cutout part match the desired FOV. A guideline image was placed 2m away from the camera with a dimension of 10m × 10m and canvas cutouts were adjusted to cover the surroundings of the FOV guideline. The stereo vision and depth cues remained unchanged for the visible FOV.

An empty area in our closed laboratory was designated to perform this study. The room dimensions were $6m(w) \times 9m(l) \times 3.3m(h)$ and the empty area in the middle of the room was $4m(w) \times 9m(l)$. There was a 2m distance between the targets and the closest non-study object. Figure 6.6 shows

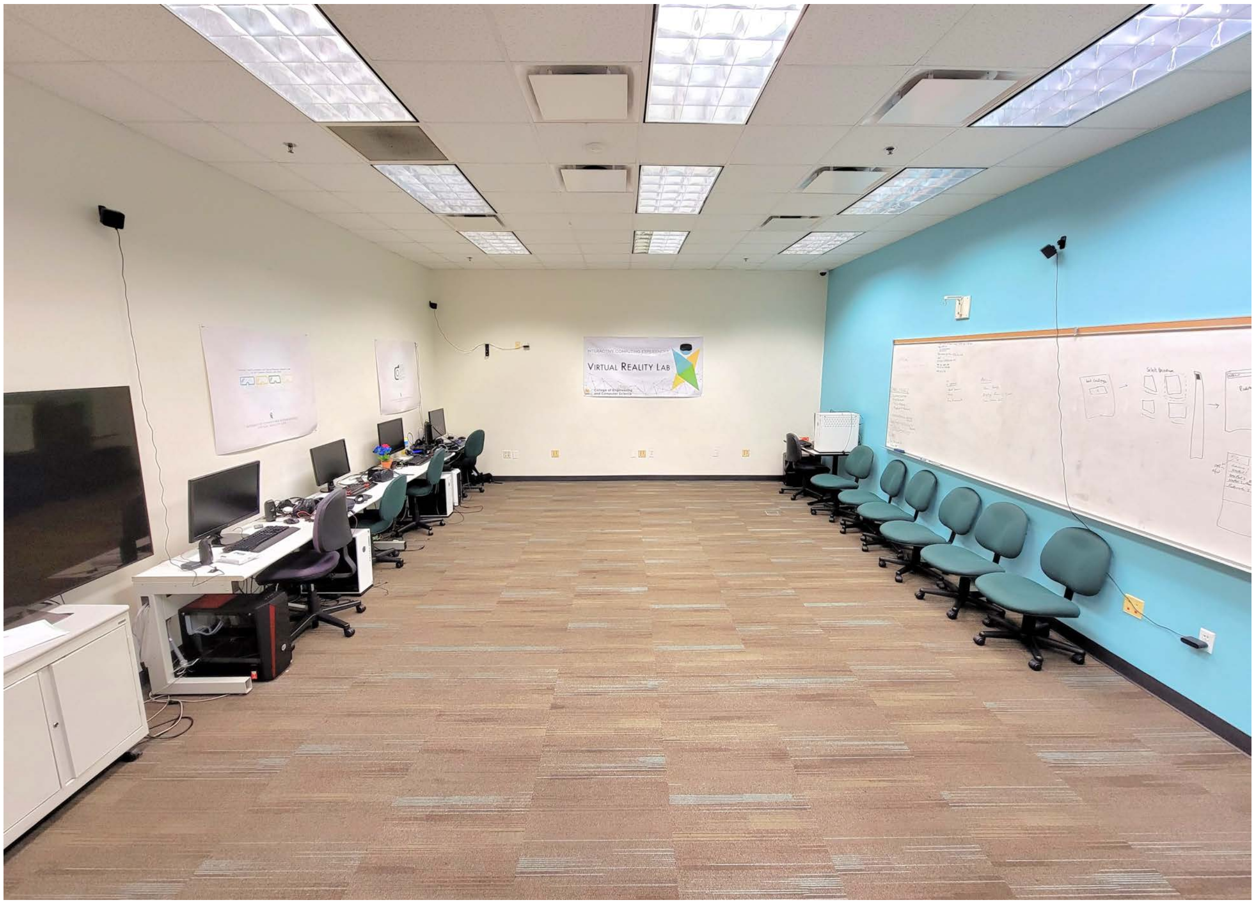


Figure 6.6: The room used for the study

the laboratory environment.

Procedure

Before the study began, the participants were asked to review an informed consent form and were verbally asked for their consent. We measured their vision acuity afterward using a Snellen Chart (see [65]) to ensure that their eyesight was adequate for the study - our participants were required to see better than 20/32 in each eye. If a participant wore corrective lenses, they were required to

Figure 6.7: A user wearing the backpack and the HMD.

wear them for the study. If a recruited individual was unable to pass this vision acuity test, they were dismissed. Then, the participants completed a demographic questionnaire (age, gender, and VR experience).

We described the task and objective of blind-walking to the participant and showed them the adjustments on the headset and the backpack. The participant was asked to wear the backpack and adjust the straps to fit them. Then, the participant was asked to wear the headset and adjust the straps on it to get it comfortable and snug on their head. After the adjustments, we proceeded to collect data. Figure 6.7 shows a user wearing the HP backpack and the Pimax HMD.

On each trial, the clutter level, the FOV of the headset, and the target location was changed automatically from a pre-processed sequence of trials. After the participant looked at the environment and estimated their distance to the target, they closed their eyes and let the researcher know that they were ready. The researcher started the walk procedure by pressing a key on a wireless keyboard which made the environment invisible (black) to the participant, and a faint computer voice from the backpack was played, which told the participant "go". The participant started to walk and stopped when they thought they reached the target and let the researcher know verbally. The researcher then recorded the participant's location by pressing a button on the keyboard. At the same time a faint computer voice that said "done" was played on the backpack to let the participant know they can open their eyes, and a *guidance arrow* war revealed under the participant's feet to navigate the participant back to the starting position. The guidance arrow was fixed under the participant's feet and pointed to the start location. When they reached the start location by walking towards the guidance arrow's direction, another arrow (alignment arrow) showed them the correct direction. The participant had to align the guidance arrow with the alignment arrow which aligned them with the physical room. A green arrow confirmed the alignment to notify the user of a correct alignment. The participant verbally let the researcher know when they completed the alignment and the researcher then pressed a key on the keyboard which made the VE reappear and started the next trial.

After 40 trials, the participants were asked to take a five minute break, by taking off the headset and sitting on a chair. The participants continued the study until they finished the 81 trials after the break.

The guidance arrow helped us to keep the researchers and participants at a safe distance from each other during the COVID-19 pandemic. Moreover, by avoiding verbal communication by the researcher, we eliminated the potential of receiving audio cues based on researcher's location by the participant.

A negative value was recorded for the distance perception error if the user stopped before the target and if a positive value was recorded if they stopped past the target. If they walked to the side of the target, their location was transposed to align it with the line from the start position to the target. The study took one hour and the participants received $10 USD in cash once the study was completed.

Hypotheses

Research in the past three decades has resulted in conflicting evidence for the identification of FOV being a significant factor that causes distance underestimation in VR [4, 1], but the more recent works suggest that modern technology eliminates this problem - perhaps due to FOV improvements [51]. Similar studies that focused on AR devices have pointed to reduced FOVs contributing to underestimation [36, 64], and we suspect that this finding translates to VR as well. In addition, we note that the environment also influences perception of distance. Creem-Regehr et al. noted that indoor environments are more conducive to more accurate distance judgements than outdoor environments [2], and though there is uncertainty about environment clutteredness providing visual cues which users can use to enhance estimations, some designers add furniture and other objects into their environments, seemingly to improve user perception of distance [66, 67]. We thus conducted our study with the above parameters, hypothesizing the following:

H1: Participants will more accurately estimate distances in more cluttered environments.

H2: Participants will more accurately estimate distances when viewing indoor environments.

H3: Participants will more accurately estimate distances with wider FOVs.

Data Analysis Approach

A Shapiro-Wilks test showed the data was not normally distributed ($p < .01$). To run a repeated-measures ANOVA on our data we transformed the data using ARTool [55]. In the event of a significant omnibus test, we planned on conducting pair-wise t-tests on the main effects. Since we had multiple comparisons, we controlled for Type I errors using Holm's Sequential Bonferroni Adjustment [56].

Results

In this section we will present the results of this study and the ANOVA analysis.

Repeated Measures ANOVA Results

After transforming the data using the ARTool [55], we conducted a 4x3x3x3 repeated-measures ANOVA.

We found a significant main effect of FOV, distance, and environment; but we did not find a main

Table 6.1: Repeated Measures ANOVA results. The measured errors are reported in cm.

Effect on Error	**ANOVA Result**
Main Effects	
Clutter	$F(2,55) = 3.42, p < .05, \eta_p^2 = .048$
FOV	$F(2,55) = 19.00, p < .001, \eta_p^2 = .218$
Distance	$F(2,55) = 135.88, p < .001, \eta_p^2 = .666$
Environment	$F(3,75) = 7.88, p < .001, \eta_p^2 = .258$
Interaction Effects	
Clutter×FOV	$F(4,53) = 1.87, p = .115, \eta_p^2 = .027$
Clutter×Distance	$F(4,53) = .86, p = .487, \eta_p^2 = .013$
Clutter×Environment	$F(6,112) = .54, p = .777, \eta_p^2 = .023$
FOV×Distance	$F(4,53) = 2.92, p < .05, \eta_p^2 = .041$
FOV×Environment	$F(6,112) = 1.36, p = .235, \eta_p^2 = .057$
Distance×Environment	$F(6,112) = 6.08, p < .001, \eta_p^2 = .212$
Clutter×FOV×Distance	$F(8,49) = 1.34, p = .223, \eta_p^2 = .019$
Clutter×FOV×Environment	$F(12,165) = 1.93, p < .05, \eta_p^2 = .078$
Clutter×Distance×Environment	$F(12,165) = 1.62, p = .086, \eta_p^2 = .067$
FOV×Distance×Environment	$F(12,165) = .60, p = .839, \eta_p^2 = .026$
Clutter×FOV×Distance×Environment	$F(24,153) = 1.83, p < .05, \eta_p^2 = .075$

effect of clutter. We did find an interaction effect between clutter and FOV. Table 6.1 shows the results of the omnibus test.

Discussion and Future Work

The results of our study provide insight into distance perception in different levels of clutter in varying FOVs. The following section details the implications of our findings.

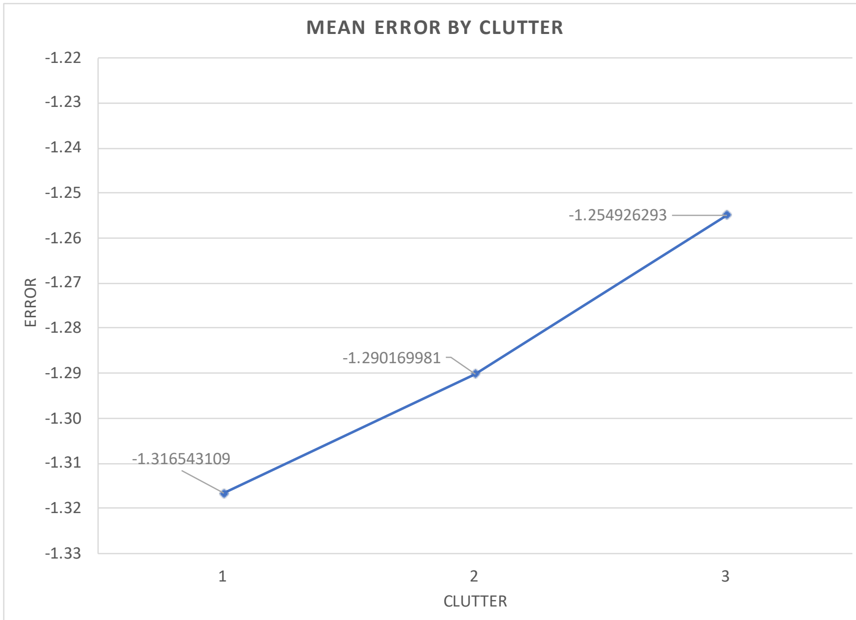


Figure 6.8: Mean error (m) of different clutter levels.

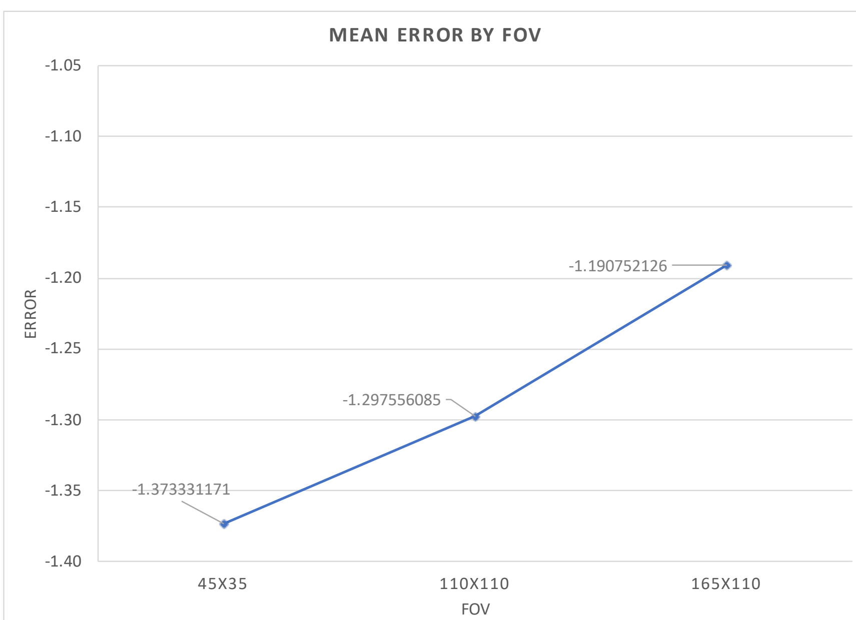


Figure 6.9: Mean error (m) of different FOVs.

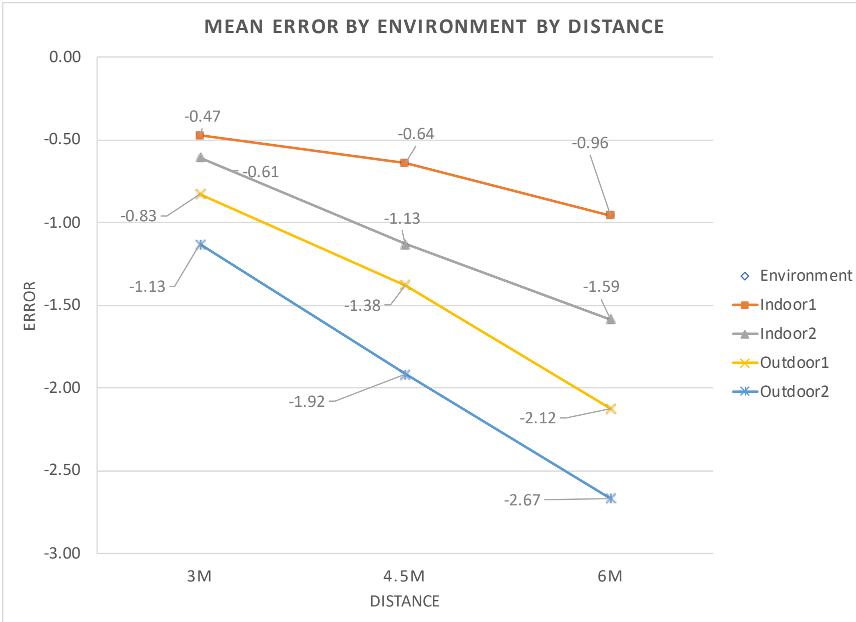


Figure 6.10: Mean error (m) of different distances in each environment.

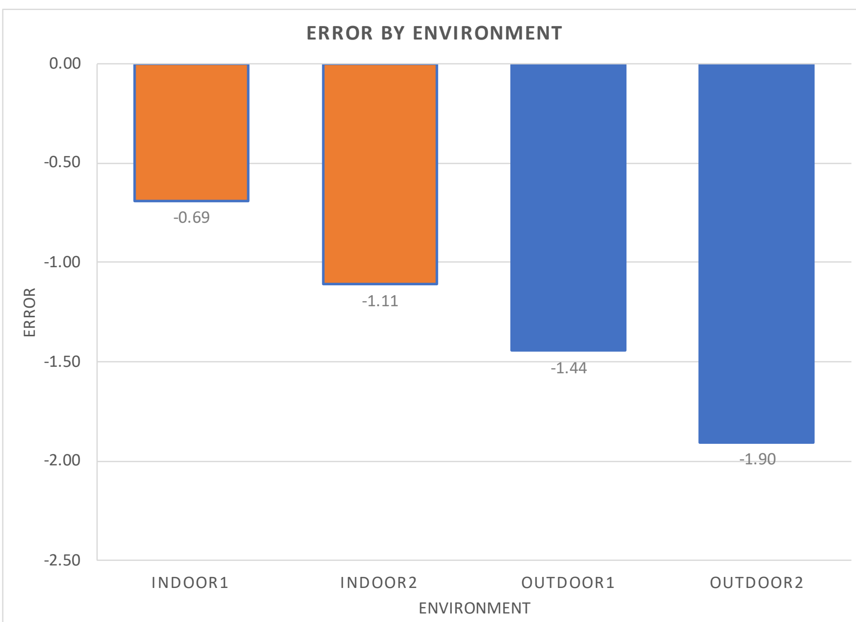


Figure 6.11: Mean error (m) in each environment.

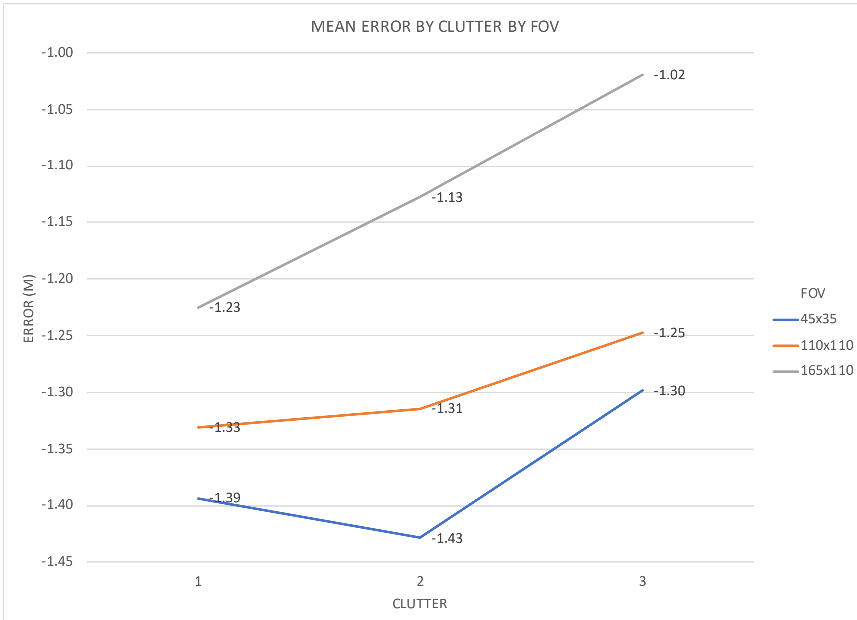


Figure 6.12: Mean error (m) by clutter over each FOV.

Main effect of clutter

We did not found a significant main effect of clutter ($p < .05$). The results showing that higher clutter in the environment results in more accurate estimation of distances and less underestimation (6.8). The pairwise comparison with Bonferroni adjustments showed significant difference between cluttered and uncluttered ($p < .05$), however, there was no significance difference between semi-clutter and uncluttered, and semi-cluttered and cluttered.

Distances are Underestimated with narrower FOVs

We found a significant main effect of FOV. The $165° \times 110°$ showed the least distance underestimation and most accurate results among the three FOVs. As the FOV decreased, the distance estimation deteriorated, where the narrowest FOV resulted in the highest error and higher underestimation of distances. Figure 6.9 shows the error by FOV. The pairwise comparison with Bonferroni adjustments showed significant difference between $165^\circ \times 110^\circ$ and $1110^\circ \times 110^\circ$ and ($p < 001$)also between $165^\circ \times 110^\circ$ and $45^\circ \times 35^\circ$ ($p < 001$). But the difference between $110^\circ \times 110^\circ$ and $45^\circ \times 35^\circ$ was not significant ($p = .085$).

We did not find a significant interaction effect of Clutter×FOV. This shows that clutter and FOV independently affects the perception of distance factor. Figure 6.12 shows the improvement of perception of distance when FOV and clutter increases.

Discussion and Future Work

In this chapter we presented through a blind-walk user study that existence of clutter in VEs improves perception of distance. We also found that perception of distance improved with wider FOVs.

H1: Clutter in Virtual Environments

The results of out study indicates that increasing clutter in a VE improves the perception of distance and mitigates the distance underestimation. We have preciously shown in Chapter 5 that clutter improves perception of distance, but unlike the previous study in which the cluttered and uncluttered environment were completely different environments, in this study we varied the clutter level within the same environment. To generalized our idea, we applied this idea to four different environments.

This result reveals that regardless of being in an indoor environment or an outdoor environment, introducing clutter to the environment and adding objects to the scene will improve the perception of distance.

We defined clutter by the number of objects in the scene, however a definition of clutter based on the overall contrast of the scene, total length of the edges, and also using information theory [74] can provide a better understanding of clutter in different contexts in future work.

H2: Indoor vs Outdoor Environments

In the study reported in this chapter and also the study discussed in Chapter 5, we concluded that users perform better in indoor environments versus outdoor environments in the distance perception assessment task. This can be because of the familiarity of the indoor environments and mostly because many people are used to the environment of their home and perform daily tasks in indoor environments; However, further investigation is needed to reveal underlying causes of this difference.

H3: FOV of the HMD

We investigated at FOV at three different angles ($165^\circ\times110^\circ$, $110^\circ\times110^\circ$, and $45^\circ\times35^\circ$). Our results shows significant difference of the widest FOV with the other two FOVs. This is mostly because the $165^\circ\times110^\circ$ is the only FOV that stimulates the far-periphery area of the eye which is above 120°.

Conclusion

In this chapter, we showed through a blind-walking assessment that wider FOVs in VEs results in more accurate distance judgment. We also showed that Clutter did not have a significant effect on distance perception. However, the significant interaction effect of FOV and clutter showed that exposing the periphery to more clutter results in more accurate distance perception and less underestimation. The context of the environment was a also significant factor, showing that users performed with greater underestimation in outdoor environments less underestimation was seen in indoor environments.

CHAPTER 7: DISCUSSION AND FUTURE WORK

In this dissertation, through multiple studies, we demonstrated that wider FOVs, existence of clutter, and being in indoor environments improves the perception of distance in head-mounted displays. We showed the evidence using action based assessment techniques on video see-through, 360° static, and virtual environments.

In this chapter we will indicate directions for future research and improvement on the perception of distance in head-mounted displays.

On Assessment Techniques

In this dissertation, we presented two studies base on a blind-throwing and two studies based on a blind-walking task. Our research is based on the distance perception literature, which uses blind walking as the major assessment. Because of the COVID-19 pandemic, we opted to use the blind throwing method to provide for safe social distancing for both the participant and the experimenter. We were also able to avoid tripping over HMD cords thanks to this strategy. Despite the fact that blind throwing has been proven to be comparable to blind walking [16], a direct comparison between the two is not possible. To get past this limitation, we created the guidance arrow, which allows the user to freely move around the environment without the involvement of the experimenter. During the COVID-19 pandemic, this instrument allowed us to apply the blind walking evaluation while maintaining the researcher and participant at a safe distance. However, future research should look into alternatives to blind walking and blind throwing, because walking may not always be feasible for participants, and throwing brings more variance into the data. Furthermore, both blind throwing and blind walking protocols limit the lengths that can be employed in a study due to physical limitations and safety concerns. As a result, unlike Gagnon et al. [24], our findings cannot be generalized over large distances, and verbal estimation should be utilized in conjunction with other data collection methods.

We studied targets in the medium-field, but further research is needed to determine the impact of FOV in the near-field and far-field. Since the evaluation techniques used for near-field and far-field are different from blind-walking and blind-throwing, we decided to focus on evaluating using a single evaluation method. In future, elaborated studies with more participants on near-field, medium-field, and far-field distances can provide insight to this research area.

On the Perception of Distance in VST HMDs

When compared to real-world viewing, the findings of our experiments revealed a significant difference in participants' distance estimation when using the VST device. We discovered that using the ZED Mini pass-through camera made distance estimation worse. A few factors have changed as a result of the addition of the ZED Mini. Because the ZED Mini is 63g, it accounts for 11% of the total device weight, which was attached to the frontmost part of the headset, the device weight (and thus weight distribution) immediately changed. A VST camera also introduced parallax effect, which causes images to be rendered with an offset to the user's eyes. The FOV is reduced when the HMD is used as a VST device. The Vive's usual FOV is around 110 degrees horizontally and vertically, however the ZED Mini decreased it to 90 degrees horizontally and 60 degrees vertically. A more compact camera system with wider FOV and higher resolution can overcome this limitations in future work. Moreover, experimenting with a parallax-free VST HMD [75, 76] will provide additional insight to understanding the contributing factors to distance underestimation in VST HMDs. Although our participants were exposed to the camera's delay, we do not expect it to have influenced our results due to the blind nature of the study.

However, we must be aware that an increased FOV might have a significant trade-off concerning simulator sickness. While our study did not assess this (e.g. through use of the Simulator Sickness Questionnaire [60]), previous research indicates that a reduced FOV helps to prevent users from experiencing discomfort when navigating an environment [61]. However, the reported discomfort might be caused by other factors such as latency, and requires further investigation.

On the Effect of FOV on Perception of Distance

One of the issues with conflicting responses in the literature is the influence of reduced FOV on distance judgment. While some past research have claimed that FOV has a substantial influence on distance estimation when paired with other HMD features (weight and resolution)[4, 38], other studies have found that FOV is not a significant component that causes compression in distance estimation [46]. We simulated limited FOVs within one headset, maintaining screen resolution and weight of the headset constant, and discovered a significant main effect of FOV, such that reduced FOVs resulted in greater distance underestimation.

Generally, we find that by expanding HFOV, user perception of distance becomes more accurate. As more of the environment geometry becomes visible to the user, so too do the static objects and features of that environment, which may provide a frame of reference. At the very least, light from wider FOVs stimulate the periphery, which has been shown to improve distance judgements [44]. In this section, we discuss the implications of our results.

One surprising finding from our investigation was that VFOV had no influence on distance estimations. Current hardware may already provide the levels of VFOV required to reliably perceive a particular VE, therefore we would inform hardware makers to focus on expanding the HFOV in newer headsets. We also note that, although 110° is very tall, it does not represent the natural limits of human vision at 135°. It might be possible that using the maximum human vision VFOV would help to improve the perception of distance in HMDs, but further investigation is required to prove or disapprove this statement.

Although our findings are relevant to the VR applications, we cannot claim that they are applicable to AR scenarios. While our study on VST HMDs suggests that FOV is a significant factor affecting the perception of distance, more research is required to confirm this claim. As researchers intend to use AR devices for a variety of everyday life scenarios, including vision correction tools [31, 71], it is critical to investigate the effects of FOV for these devices as well.

One other aspect that should be considered when investigating FOV effects on perception of distance is embodiment and body ownership [77, 78, 79]. As the presence of an avatar that is matching the user's size would give them a point of reference in the environment and using a tall VFOV would make the avatar visible to the user in most situations in contrast with a short VFOV.

On the Effect of Indoor/Outdoor on Perception of Distance

In total we used eight different environments to represent four indoor and four outdoor environments. An indoor environment is defined by any environment enclosed by walls and a ceiling and an outdoor environment does not have the mentioned characteristics. However, an elaborated investigation of different environment conditions will provide more insight about the environment effect to the field.

On the Effect of Clutter on Perception of Distance

We recruited 24 people to investigate the effect of clutter on perception of distance in VEs. The results shows that increasing clutter in a virtual environment significantly improves perception of distance. Moreover, in this study, users perception of distance was worse in outdoor environments comparing to indoor environments.

Although, a definition of clutter is introduced, the definition of clutter is depending on the context. We defined clutter by the number of objects in the scene. Moreover, we defined the levels of clutter in the scene relative to each other. While these levels were designed to satisfy our definition of clutter, they were limited to the constraints defined in this definition and one can argue against it. To provide a better assessment for these scenes clutter level, they can be categorized using human input (such as Mechanical Turk) in a future work. Utilizing human input will provide labeled data for clutter which can be used in combination with machine learning techniques to build a classifier to rate an arbitrary scene with its level of clutter and being a suitable environment in critical tasks that are reliant on accurate perception of distance.

Our cluttered conditions had various items dispersed in them, and these items were not the same across the two cluttered environments. As such, our study cannot directly speak to any effect of *types* of objects found in a scene. There is some level of ambiguity to human avatars, vehicles, furniture, etc., and it is possible that different categories of "clutter" provide a user with varying visual cues. More work should be conducted to help identify *which* clutter would help reduce distance underestimation.

One other aspect to be considered in the definition of clutter is distinguishing the linear perspective effect from clutter. As linear perspective is a significant visual cue that can help with perception and estimation of distance, identifying its effect separate from the clutter will help to better understanding this problem.

On the Applications of Eye-tracking

Eye-tracking technology can be utilized in understanding the visual cues used by the user and also their thinking path. By tracking the user's gaze, the objects and the parts of the scene that are used by the user to estimate the distance can be identified. Moreover, in the case of the effects of FOV, different FOVs can be compared to each other by identifying users gaze movements patterns accompanied by their head movements. Because it might be possible that despite finding similarities between taller and shorter VFOV, users spend more time with their gaze movements and head rotation in order to estimate the distances in the shorter VFOV conditions. Eye-tracking can also be used for keeping the limited FOV box locked to the user's gaze in order to prevent exposing the scene to unwanted areas of the retina and studying the way that different areas of the eye help the perception of distance and other factors in representation of the environment. However, it is important to note that eye-tracking systems are still limited because of their latency and jittering.

Investigating the perception of distances using eye-tracking can provide insights to this field which can be used for creating user friendly and intuitive VR and AR systems.

Conclusion

It has been a long-studied topic in the HCI field whether people underestimate, overestimate, or accurately judge distance in virtual environments. In the past two decades, researchers have studied the perception of distance in VEs and the real world, and a common finding among this research is that distances in VEs are greatly underestimated by users. Researchers have identified a variety of factors that affect the perception of distance such as FoV, weight of the HMD, presence of a self avatar, camera position, and display resolution.

In this dissertation, we demonstrated through multiple studies that more restricted FOV results in greater distance underestimation while wearing an HMD. We initially tested our theory by comparing real-world distance perception with a video see-through head mounted display and a fake headset. Since, the result of the fake headset and VST HMD was similar and significantly different from the real world we decided to further investigate the effects of FOV on egocentric distance perception.

We showed in various virtual environments that wider horizontal field of view results in more accurate distance judgment. We also showed that vertical field of view did not have a significant effect on distance perception. The results indicated that using cluttered environments improves the perception of distance comparing to uncluttered environments. The context of the environment was a significant factor, showing that users performed better in indoor environments in the distance judgment task while greater underestimation was seen in outdoor environments. These trade-offs may need to be considered when the perception of distance is of importance in a VR system design.

Modern VST HMDs currently exhibit reduced FOVs, and we thus question if these devices can be used continuously in daily life, in their current state. We anticipate future devices will provide wider FOVs which at least results in better distance perception.

However, our results do not speak to other VR outcomes such as presence, simulator sickness, etc. Towards understanding how humans perceive realistic virtual environments, in an effort to help bridge the gap between VR and the real world, further investigation is required to understand how varying FOV, clutter, indoor/outdoor and other physical and environment conditions in head-mounted displays influences these other subjective outcomes.

APPENDIX A: IRB APPROVAL LETTERS

Institutional Review Board
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Office of Research
12201 Research Parkway
Orlando, FL 32826-3246

UNIVERSITY OF CENTRAL FLORIDA

APPROVAL

July 27, 2021

Dear Sina Masnadi:

On 7/27/2021, the IRB reviewed the following submission:

Type of Review:	Initial Study
Title:	Distance Perception in Virtual Reality and Real World
Investigator:	Sina Masnadi
IRB ID:	STUDY00003200
Funding:	None
Grant ID:	None
IND, IDE, or HDE:	None
Documents Reviewed:	• review, Category: Faculty Research Approval; • consent, Category: Consent Form; • demographics, Category: Survey / Questionnaire; • measurements, Category: Other; • protocol, Category: IRB Protocol; • recruitment, Category: Recruitment Materials; • VR environment, Category: Other

The IRB approved the protocol from 7/27/2021.

In conducting this protocol, you are required to follow the requirements listed in the Investigator Manual (HRP-103), which can be found by navigating to the IRB Library within the IRB system. Guidance on submitting Modifications and a Continuing Review or Administrative Check-in are detailed in the manual. When you have completed your research, please submit a Study Closure request so that IRB records will be accurate.

If you have any questions, please contact the UCF IRB at 407-823-2901 or irb@ucf.edu. Please include your project title and IRB number in all correspondence with this office.

Sincerely,

Katie Kilgore

Katie Kilgore
Designated Reviewer

UCF
UNIVERSITY OF CENTRAL FLORIDA

Institutional Review Board
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IRB00001138, IRB00012110
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APPROVAL

June 2, 2022

Dear Sina Masnadi:

On 6/2/2022, the IRB reviewed the following submission:

Type of Review:	Modification / Update
Title:	Distance Perception in Virtual Reality and Real World
Investigator:	Sina Masnadi
IRB ID:	MOD00002978
Funding:	None
Grant ID:	None
IND, IDE, or HDE:	None
Documents Reviewed:	None

The IRB approved the minor modification on 6/2/2022.

In conducting this protocol, you are required to follow the requirements listed in the Investigator Manual (HRP-103), which can be found by navigating to the IRB Library within the IRB system. Guidance on submitting Modifications and a Continuing Review or Administrative Check-in are detailed in the manual. When you have completed your research, please submit a Study Closure request so that IRB records will be accurate.

If you have any questions, please contact the UCF IRB at 407-823-2901 or irb@ucf.edu. Please include your project title and IRB number in all correspondence with this office.

Sincerely,

Kamille C. Birkbeck

Kamille Birkbeck
Designated Reviewer

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