# Effects of Field of View on Egocentric Distance Perception in Virtual Reality

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## ABSTRACT

We performed a mixed-design study with 56 participants to compare the effect of horizontal FOV (HFOV) and vertical FOV (VFOV) on egocentric distance perception in four different realistic virtual environments (VEs). We also compared VE attributes of indoor/outdoor and cluttered/uncluttered. The participants blind-walked towards four different targets at 3m, 4m, 5m, and 6m distance while wearing a backpack computer and a wide FOV head-mounted display (HMD). The combinations of 165°, 110° and 45° HFOVs, and 110° and 35° VFOVs was simulated in the same HMD. The results indicated more accurate distance judgement with larger HFOV with no significant effect of VFOV. 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 highlight that the environment is important in distance-critical VR applications and wider HFOV should be considered for an improved distance judgment.

## CCS CONCEPTS

• **Human-centered computing → HCI theory, concepts and models**; *User studies*; *Empirical studies in HCI*.

## KEYWORDS

field of view, FOV, distance perception, virtual reality, VR, virtual environment, clutter, indoor, outdoor, horizontal FOV, vertical FOV

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## 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 [3, 5, 34]. 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, HMDs of the past such as the nVisor SX[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. In this work we conducted such a study.

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

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[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

effect of variation of FOVs. These FOVs were chosen to match those of HTC Vive (110°×110°) and NVIS nVisor SX60 (45°×35°) which have been used in previous research [3, 12, 15, 41]. 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 paper:

- 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
- 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 the paper 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.

## 2 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 [7, 27, 37, 41]. 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.

### 2.1 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 [2, 14, 40]. It has been shown that the parallax effect does not affect the distance judgment blind-walking task [12]. Motion parallax is the displacement of image parts relative to each other when the observer moves or the objects move. 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 [18]. In our study, the environment was static, but participants could make subtle movements before their tasks began. 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 [30]. Vaziri et al. also observed the same underestimation of distances in a video see-through HMD [38, 39].

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. [4] and Loftus et al. [23] showed that using different FOVs did not show any impact on distance perception; however, Buck et al. [2], Jones et al. [11, 13], and Li et al. [20–22] found a significant effect of FOV on distance perception. More recent studies that used wider FOVs are inclined towards the significant effect of FOV [5, 34], but this effect was not isolated. In a more recent study, Masnadi et al. found that employing wider FOVs results in a more accurate perception of distances [25], but their work used static 360° images at 3 different pre-defined heights. In our work, we used one device and manipulated HFOV and VFOV in an egocentric VE using software, thus isolating the effects of FOV on distance perception.

Wu et al. [42] found that in the real world, increasing FOV improves distance judgment, whereas Knapp and Loomis [16] 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. In our study we used a real HMD with a wide field of view and a portable computer with a backpack attachment. This lets the participant view a VE and move around freely which eliminates the chance of the headset being pulled by its cable. The backpack computer solution is becoming more popular in the more recent work [38, 39]. 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° × 40° and 48° × 56°) was used throughout the study [11]. 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.

### 2.2 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 [28]. We opted to not show a self-avatar in the VE to isolate the factors we have considered for this study. 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 [19]. Additionally, Kunz et al. found that the quality of the VE's graphics affects users' ability to accurately judge distance [17]. Vaziri et al. showed that level of graphical detail provided in a VE is important for distance judgement [38]. Creem-Regehr et al. [3] revealed larger underestimations in outdoor VEs compared to indoor VEs, however, in our study we also investigate the effect of being cluttered or uncluttered in these 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 [1].

### 2.3 Evaluation Techniques

To evaluate distance perception error, researchers employed different methods such as verbal estimation, blind-throwing, timed imagined walking, and blind-walking [34]. Previous work has shown that verbal estimation leads to larger error as the distance to the target grows further away [17, 24, 34]. *Blind throwing* involves showing the user the target and removing their vision before they throw an object at where they believe the target is. It has been shown that blind throwing results are on par with the blind-walking task [33, 35]. *Timed imagined walking* follows a similar procedure where the participant is shown the target and blindfolded, but instead of walking, they imagine moving towards a target and let the researcher know when they reach they have reached the target in their mind [8, 32]. We decided to employ the most popular method which is *blind walking*, a procedure similar to the timed imagined walking but with the participant physically walking towards the target until they believe they have reached the goal [7, 27, 37, 41]. 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.

## 3 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.

### 3.1 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).

### 3.2 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[3][4]. Participants were assigned an environment in a random order. The environment conditions were Indoor Cluttered; Indoor Uncluttered; Outdoor Cluttered; and Outdoor Uncluttered (see Figure 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 1a) was a 10m×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 1b) was an empty 20m×10m room with 4m high ceilings, wood floor, and windows along one side of the room. The *outdoor uncluttered* environment (Figure 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 1d) was on a suburb neighborhood sidewalk in daylight with

**(a) Indoor cluttered**

**(b) Indoor uncluttered**

**(c) Outdoor cluttered**

**(d) Outdoor uncluttered**

**Figure 1: Four different environments were used in this study.**

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

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

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 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.

## 3.3 Within-Subjects Independent Variables

Similar to previous studies, we simulated six different FOV combinations programmatically in the headset [11, 25]. 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 SX60 (45°×35°).

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 [35]. 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 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.

## 3.4 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.

## 3.5 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 $2560 \times 1440$ 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).

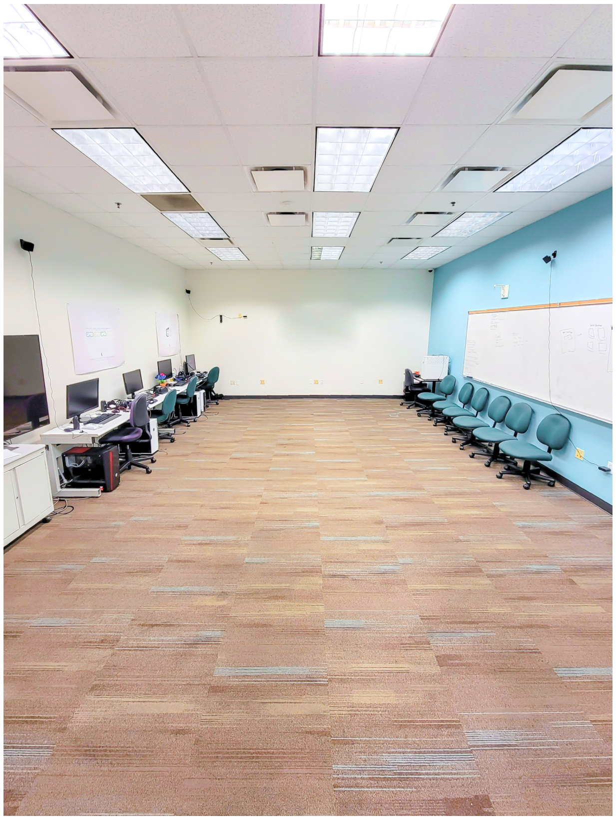

**Figure 2: The room used for the study**

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. 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 2 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

**Figure 3: A user wearing the backpack and the HMD.**

and view the headset image on another computer. The tool takes small-scaled images from the 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 [5]. It provides a prefab that can be added to any Unity 3D scene to perform the study.

## 3.6 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 [36]) 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 3 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 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.

## 3.7 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 [34, 41], but the more recent works suggest that modern technology eliminates this problem - perhaps due to FOV improvements [15]. Similar studies that focused on AR devices have pointed to reduced FOVs contributing to underestimation [25, 30], 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

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[5] https://github.com/sina-masnadi/EgocentricDistanceStudy

**Table 1: Descriptive statistics of average user error, by FOV and Target Distance**

| FOV | Target | Error (centimeters) |
|---|---|---|
| 165° × 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° × 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° × 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° × 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° × 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° × 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 |

judgements than outdoor environments [3], 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 [29, 31]. 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.

# 4 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 performing 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 a Bonferroni correction.

We performed the analysis on *INDOOR/OUTDOOR* × CLUTTERED/UNCLUTTERED as the between-subject factors. The within-subject factors were DISTANCE, HFOV, and VFOV. Table 1 shows the descriptive statistics of average user error by FOV and distance and Figure 6 shows the plot of average error by FOV.

## 4.1 Repeated Measures ANOVA Results

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

### 4.1.1 *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 4 shows the error mean on the three different HFOVS.

### 4.1.2 *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 shows the error mean on the two different VFOVS.

### 4.1.3 *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), $p = .007$.

### 4.1.4 *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($M = -49.1, SD = 13.4$).

### 4.1.5 *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 7 shows the mean error categorized by environment type.

### 4.1.6 *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.

### 4.1.7 *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 8 shows the plot of average error by target distance.

### 4.1.8 *DISTANCE × HFOV Effect.*

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

### 4.1.9 *DISTANCE × VFOV Effect.*

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

### 4.1.10 *DISTANCE × INDOOR/OUTDOOR Effect.*

We found a significant interaction effect between DISTANCE and INDOOR/OUTDOOR,

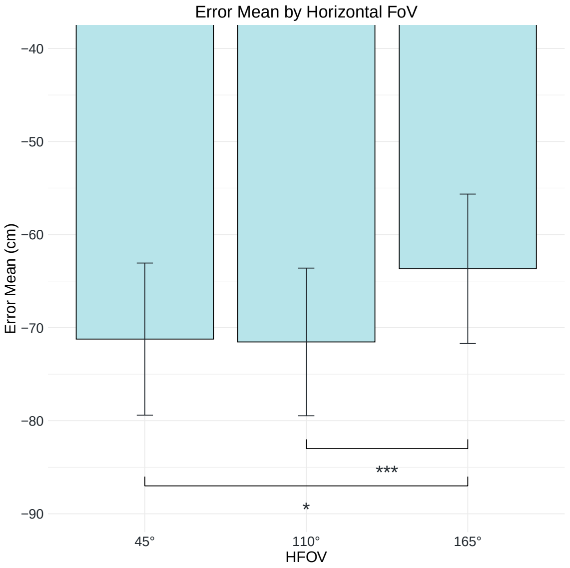

**Figure 4: Mean error of different horizontal FOVs (error 95% CI).**
$^{*} = p < .05$; $^{**} = p < .01$; $^{***} = p < .001$

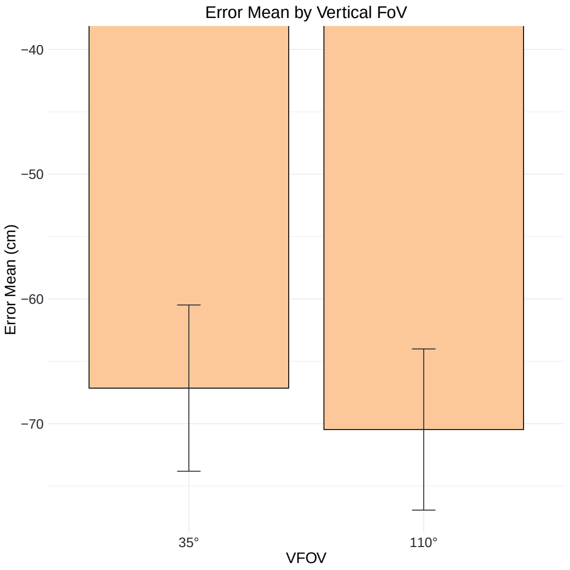

**Figure 5: Mean error of different vertical FOVs (error 95% CI).**

$F_{3,156} = 7.766, p < .001$). Participants exhibited comparable error for the further targets (5m and 6m) for all of the environment, except for the indoor cluttered environment. The indoor cluttered environment had similar error for all four distances. We did not find an interaction effect between DISTANCE, INDOOR/OUTDOOR, and CLUTTEREDNESS, however, the difference between the errors of 5m and 6m for the indoor cluttered environment was significantly different than the other environments ($p < 0.05$ for all of them).

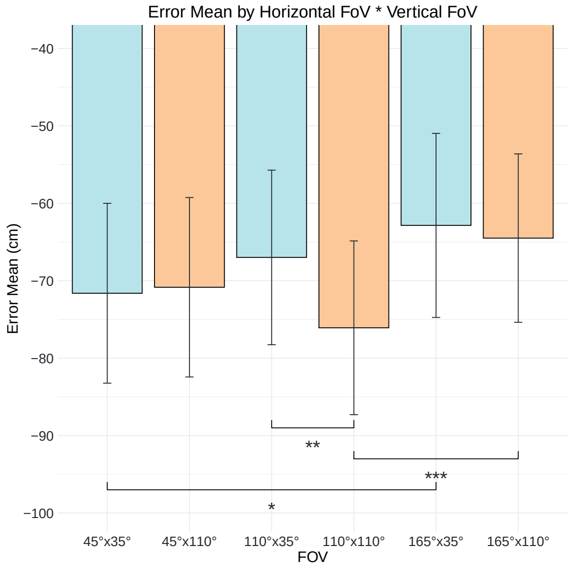

**Figure 6: Mean error of different FOV combinations (error 95% CI).**
$^{*} = p < .05$; $^{**} = p < .01$; $^{***} = p < .001$

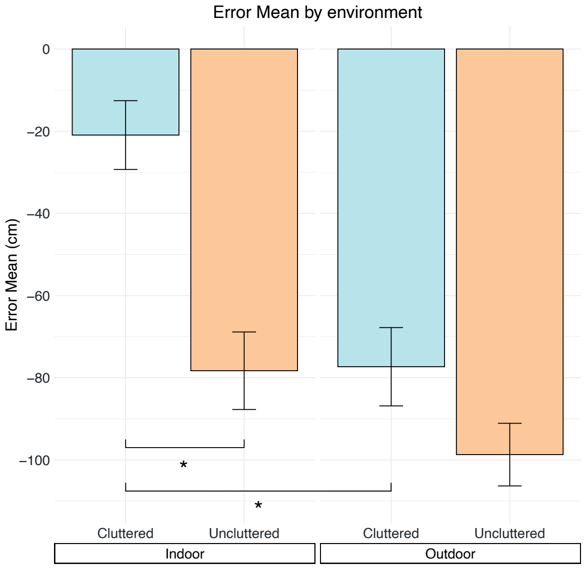

**Figure 7: Mean error of different Environments (error 95% CI).**
$^{*} = p < .05$; $^{**} = p < .01$; $^{***} = p < .001$

The outdoor uncluttered environment had the sharpest decline and the largest mean error (Figure 9).

*4.1.11 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

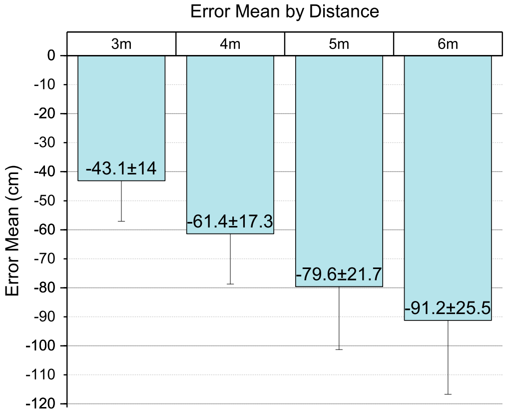

**Figure 8: Mean error of different Distances (error 95% CI).**

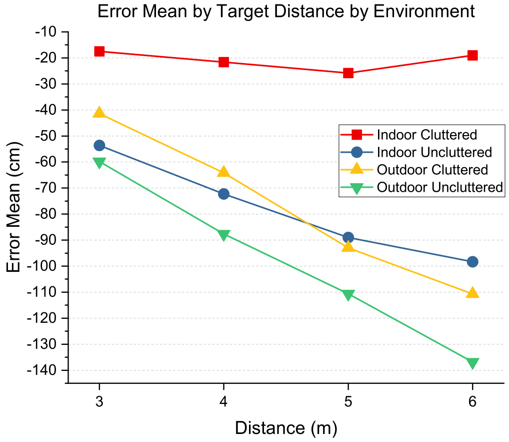

**Figure 9: Mean error in different Environments by Distance.**

used to help participants make distance judgement calls for the further distances.

## 5 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 [21]. In this section, we discuss the implications of our results.

### 5.1 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 [4, 23], 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 [2], 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 [6], and television screen size affects sense of presence in video games [9], 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.

### 5.2 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 two 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.

### 5.3 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 - or 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 [10, 29], our results indicate that these attributes do indeed make a significant difference, for egocentric distance judgements.

### 5.4 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 [3], but counter those of Kelly et al. [15]. 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.

### 5.5 Limitations and Future Work

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 [30], more work is necessary to confirm this claim. As researchers plan on using AR devices for multiple daily life scenarios, including vision correction [26, 43], 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.

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. In future work, we will recruit more participants in order to perform an elaborated study on near-field, medium-field, and far-field distances. Moreover, we want to experiment with other INDOOR/OUTDOOR and CLUTTERED/UNCLUTTERED environments to further investigate the effects shown in this study. The number of objects in the user's field of vision is also another factor that needs further investigation; This can be a part of a study focusing on clutter and the definition of clutter in controlled virtual environments.

## 6 CONCLUSION

In this paper, 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.

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