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# The Effects of Head-Centric Rest Frames on Egocentric Distance Perception in Virtual Reality

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# THE EFFECTS OF HEAD-CENTRIC REST FRAMES ON EGOCENTRIC DISTANCE PERCEPTION IN VIRTUAL REALITY

by

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# ABSTRACT

It has been shown through several research investigations that users tend to underestimate distances in virtual reality (VR). Virtual objects that appear close to users wearing a Head-mounted display (HMD) might be located at a farther distance in reality. This discrepancy between the actual distance and the distance observed by users in VR was found to hinder users from benefiting from the full in-VR immersive experience, and several efforts have been directed toward finding the causes and developing tools that mitigate this phenomenon. One hypothesis that stands out in the field of spatial perception is the rest frame hypothesis (RFH), which states that visual frames of reference (RFs), defined as fixed reference points of view in a virtual environment (VE), contribute to minimizing sensory mismatch. RFs have been shown to promote better eye-gaze stability and focus, reduce VR sickness, and improve visual search, along with other benefits. However, their effect on distance perception in VEs has not been evaluated. To explore and better understand the potential effects that RFs can have on distance perception in VR, we used a blind walking task to explore the effect of three head-centric RFs (a mesh mask, a nose, and a hat) on egocentric distance estimation. We performed a mixed-design study where we compared the effect of each of our chosen RFs across different environmental conditions and target distances in different 3D environments. We found that at near and mid-field distances, certain RFs can improve the user's distance estimation accuracy and reduce distance underestimation. Additionally, we found that participants judged distance more accurately in cluttered environments compared to uncluttered environments. Our findings show that the characteristics of the 3D environment are important in distance estimation-dependent tasks in VR and that the addition of head-centric RFs, a simple avatar augmentation method, can lead to meaningful improvements in distance judgments, user experience, and task performance in VR.

## ACKNOWLEDGMENTS

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# CHAPTER 1: INTRODUCTION

Virtual Reality (VR) technologies have become more accessible, commonplace, and widely used not only for entertainment but also for education, training, retail, tourism, and real estate [38]. Distance perception in Virtual Reality (VR) refers to the accuracy of users in perceiving distances between objects, between themselves and other objects, and perceiving depth within the virtual environment (VE) [47,55,102]. Poor distance estimation can limit the full benefits that VR affords by negatively affecting navigation, presence, object selection, and other tasks in VR [27, 60, 83]. Several efforts investigating distance perception for the past three decades unveiled that users underestimate distances in VR compared to real life [16,17,31,83]. This underestimation is attributed to several dissimilar factors that impact distance judgments using their own mechanisms (i.e. target scale manipulation, camera placement, field of view (FOV) restrictions, head-mounted display (HMD) weight, eye height manipulation, ergonomic burden, etc.) along with that other systematic differences in distance estimation errors have also been reported under dissimilar visual stimulus conditions, such as environment type (indoor/outdoor), the presence or the absence of various scene components including visual cues, obstacles, gaps, etc. [16,17,40,51,59,67,83]. We expand on these factors in the background and literature review chapter 2.

Various methods were shown to improve distance estimation accuracy and reduce its underestimation in VEs, such as increasing the FOV, reducing HMD weight, adding more depth cues, enabling a full body avatar representation in the VE, and so on [16, 31, 58, 59, 61, 64]. Visual frames of reference, also called rest frames (RFs), are defined as fixed reference points of view in a VE that contribute to the minimization of sensory mismatch and promote better stability and focus of the user's eye gaze [78, 79, 85]. It was found that head-centric RFs effectively help reduce VR sickness, promote better comfort, eye-gaze focus, and improve visual search, along with other benefits [7, 85, 94, 95]. Given the known effects of RFs, an intuitive question that arises is whether head-centric RFs, as self-avatar augmentations, can improve distance estimation when enabled in VEs. Through our exploratory work, we attempt to fill this gap in the literature on applying head-centric RFs to reduce distance underestimation in VEs.

We conducted a mixed-design study using a blind-walking task [23,59,74], where we varied head-centric RFs (a virtual nose, a hat, and a mesh mask), and environmental characteristics (indoor and outdoor, clutter and no clutter) to assess their influence on egocentric distance judgments. The mesh mask RF (Figure 3.3) represents a new RF that we designed inspired by prior work [8], such that its design was centered on considerations of FOV, eye gaze focus, comfort, and information loss reduction. We collected data from 28 participants and our results show that our chosen RFs (*a virtual nose, a hat, and a mesh mask*) have a positive impact on reducing distance underestimation regardless of the environment. The efficiency of RFs was more prominent for targets at distances of 3m and 4.5m, yet was not apparent for targets at 6m. Furthermore, the presence of clutter in the VE improved distance judgment compared to the uncluttered condition. By delving deeper into exploring the potential effects that head-centric RFs can have on egocentric distance perception in VR, we contribute a new simple avatar augmentation method that promotes better spatial judgments in VR. Our research brings new contributions to the literature on RFs, avatar augmentation, spatial perception, and the distance underestimation problem in VEs. We list our main contributions as follows:

- Results showing that enabling certain head-centric RFs in VEs can improve distance perception.
- A new mesh mask RF that improves distance perception for near-field and mid-field distances.
- A discussion on the impact and future research regarding RFs for distance perception.

# CHAPTER 2: BACKGROUND AND RELATED WORK

For the past three decades, the research community has led several investigations aimed at reaching an efficient solution to the distance underestimation problem in VEs. Distance underestimation is caused by factors that include VE and apparatus characteristics. In this section, we evaluate prior work that explores the use of RFs in VR applications and we review prior attempts at dealing with distance underestimation.

## *VE and Apparatus Impact on Distance Perception*

In VEs, several factors influence the perception of distance. Previous investigations found that distance estimates are more accurate when the environment had familiar size cues for distance, and changing the scale of the VE elements, especially the target, affected distance estimates. Nguyen et al. found that scaling the target size always affected participant judgment of distance to it, as opposed to environment and target separation scaling [67]. In addition, based on the work by Loyola et al. distance judgment accuracy and egocentric dimension estimation improved as visual cues became more abundant [51]. Furthermore, an improvement in distance judgment was recorded when the participant was represented with a self-avatar [64, 99]. It was also shown that enabling character animations for self-avatars during VR tasks enhances execution, accuracy, and performance [61].

Prior work has shown that the quality of graphics has a minimal effect on the accuracy of distance estimates [90]. The texture quality and VE graphics influence distance judgments at least in terms of the verbal report, however, when blind-walking was used, participants did not make less accurate distal judgments overall [37, 90]. In addition, camera placement and eye manipulations in VEs influence the distance compression phenomenon, especially when the camera's placement does not match the user's height [16,40]. Bernhard et al. [3] showed that lower camera positions lead to distance overestimation, while higher camera positions lead to distance underestimation. Also, the precision of distance judgments was found to be dependent on terrain design, such that when a target is placed on a continuous homogeneous texture, users more precisely perceive distance. When there was missing information about the terrain, such as the presence of a gap, distance perception was less accurate [86].

Moreover, it was shown that indoor environments tend to have less distance underestimation compared to outdoor environments [1,16,17,59]. Also, the width of the indoor environment influences egocentric distance perception through the provision of an understanding of which object in that indoor setting is important to focus on compared to others [26]. In addition, in the outdoors, the viewer's bisection judgments tend to reflect distance underestimation for far distances, whereas, in indoor lit VEs, there is a distance expansion for far distances [21]. Depth and distance misperception can have a negative impact on the VR experience [16,28,50]. Depth cues help mitigate those, providing better interactions, performance, and visual perception [75,82]. In addition, distance is judged based on both the actual distance and the estimated effort needed to walk that distance [77]. Other investigations found that distance judgment depends on the perception of walkability in VEs [44], where walkability relates to the ability to stand or walk in the environment based on user judgments and external factors. Also, as the effort of walking increases, the distance perceived by the user increases if they intend to walk to the target, but not if they initially want to throw to the target rather than walk to it and vise versa [100]. Regia-Corte et al. showed that the person's position is a critical factor that influences the perception of affordance of standing on a slanted surface in the VE [81].

VR HMDs have numerous limitations, including display size, quality, and weight. Most of these limitations influence egocentric distance perception. Prior work has related distance compression to mediocre and low-quality graphical HMD displays [49]. Moreover, multiple investigations have shown that the weight of the HMD and its inertia can lead to distance underestimation [5, 97]. However, Combe et al. showed that HMD weight does not influence egocentric distance perception for short distances [14], along with that, judged distance was found to be positively related to FOV and resolution quality of HMDs rather than their weight [30, 31, 59, 73]. Vaziri et al. showed that experiential realism is not solely determined by visual realism, such that they found that a decrease in visual realism alone does not have a significant effect on distance judgment accuracy [92]. Additionally, it was found that larger FOVs promote more accurate distance judgments [30, 41, 59], compared to restricted or reduced FOVs [5, 16, 18]. Other efforts have found that sparse peripheral FOV displays have been efficient in conveying peripheral information and promoting better situational awareness [101]. A different method of introducing implicit change in scale affecting the perception of the VE through geometric minification was found to increase distance estimation [42, 43, 104].

For our experiment, we placed the camera at the eye level of the participant. We designed our environments to be as realistic as possible and they were controlled with a simple system that helped the users preserve their spatial orientation across the trials, as was recommended by Lessels et al. [39]. In order to investigate the effect of various environmental features, we included VE clutter as a variable in our study. We chose to have four environments *Two Indoor and Two Outdoor* with the aim of generalizing our findings. Each environment in our study had two clutter levels and four possible RFs. Thus, the participant's visual stimuli varied based on the changes in the RF and clutter levels. For every level of these, the participant was able to focus on the available cues in the VE of their choice as they needed, to assess the distance to the target. Based on the indications in the literature, several investigations have shown a significant effect of the FOV variance on distance perception [5, 18, 29, 30, 41]. Consequently, we used a large FOV as was used by Masnadi et al. [59], as FOV is not a factor in our experiment and it was found that larger FOVs promote better distance perception in VR [16, 41, 59, 73].

The role of spatial-perceptual references was originally introduced by Steele et al. [88] and later investigated by Prothero et al. [78, 79], who presented the construct behind the use of RFs, referred to as *The Rest Frame Hypothesis (RFH)*. The RFH states that a specific RF is selected by the nervous system to be a visual coordinate system that acts as a comparator for spatial interpretations [78,79]. Since sometimes the nervous system is unable to select a single rest frame, manually providing a rest frame may reduce sensory mismatch and VR sickness, which was evaluated and validated later on projection and HMD-based systems [8, 19, 45, 46, 72].

Numerous investigations have explored different types of RFs, Whittinghill et al. and others suggested the use of a virtual nose as a means to increase the comfort of the user and reduce sickness during a VR experience [11,54,94–96]. Cao et al. suggested the use of a black metallic see-through net that moved with the cockpit controlled by the user, which provided additional comfort for them in the VE [8]. Moreover, other RF designs include the combination of several egocentric 2D view frames referred to as VRCockpit [10], which showed the potential to mitigate VR sickness while maintaining the same level of immersion and performance in the VE. Somrak et al. evaluated the use of RF glasses and a hat, and their results showed no negative impact of head-centric RFs usage in VR settings, the glasses being more adequate for their wearers in real-life, and the hat – for users that do not wear glasses [87]. Cao et al. demonstrated that enhancing the FOV along with adding a granularity overlay brought about better user performance in a search task more than restricting the FOV [7].

In addition, simulated RFs, especially body-centric RFs, showed a promising improvement in navigational search in VEs along with an improvement in spatial orientation, while minimizing the effects of motion sickness [68, 91]. Prior work evaluated first-person view games that used a target reticle as a RF placed in the center of the screen, which was effective at reducing VR sickness [13, 65]. Lin et al. suggested the use of a virtual guiding avatar to provide visual indicators about the virtual motion projected to happen in the VE, which provided affordances to reduce motion sickness in the VE [46]. Additionally, viewing a fully articulated and tracked visual representation of the user in the VE improved distance judgments and reduced task completion times, with an inert avatar improving distance judgments less than an animated and tracked one [61,64]. However, some RF designs did not show potential VR sickness reduction and no significant difference was found between the condition where an RF was used and when it was not. Some of the most relevant ones include a cockpit combined with a radial reticle [52] and a virtual table [105], yet some of their findings pave the path for having a smooth incorporation of additional features that can enhance productive analysis scenarios.

Prior work introduced various RFs that represent tools to reduce sensory mismatch and levels of VR sickness. To our knowledge, our study is the first to explore the effect of head-centric RFs on distance judgment through a distance evaluation task. For our investigation, we used three RFs: *a virtual nose, a hat, and a mesh mask* in different VEs and we evaluated their effect on egocentric distance perception through a blind-walking task. We chose intuitive and common head-centric RFs, and avatar augmentations based on the reviewed literature [7,8,11,54,87,94], and used them in our evaluation. The mask RF represents a new RF that we designed based on inspiration from prior work [8], such that its design was centered on considerations of FOV, eye gaze focus, comfort, and information loss reduction.

### *Evaluations of Distance Estimation*

The Distance judgment process is idiosyncratic, meaning that it is hard to uncover the process the person follows to assess the distance perceived. For this reason, researchers identified a variety of approaches to indirectly measure how the distance was perceived by the user [83]. Renner et al.

categorized egocentric distance perception evaluation and measurement methodologies into three categories: verbal estimation, perceptual matching, and visually directed actions [16, 83]. Moreover, other techniques used for this type of measurement include blind-walking, timed imagined walking, triangulation-by-pointing, and blind-throwing [20, 33, 83]. Here we expand and describe each of the evaluation techniques:

- ***Verbal estimation*** consists of the participant estimating distance by using a measurement unit of some sort [49]. However, it was shown that verbal estimation is mainly accurate for small distances and that the error rate through verbal estimation increases as the distance between the target and the user grows, leading to higher distance underestimation [37, 50, 83].

- ***Blind throwing*** consists of the users seeing the target in the VE, then being blindfolded and given an object that they throw to where they perceived the target to be located in the VE [33, 80, 83, 84]. However, it was found that blind throwing showed substantial underestimation levels for far distances [37, 50, 55, 83].

- ***Timed imagined walking*** consists of showing the target to the user in the VE, then after they have perceived the distance to it and they are ready, they are blindfolded and prompted to imagine walking that distance toward the target and whenever they reach the target through the imagined walking, they notify the researcher [24, 76]

- ***Blind walking*** is similar to timed imagined walking, except the user walks to the target physically instead of imagining the walking process. While walking physically to the target, the user will have their eyes closed until they stop and inform the researcher that they have reached the target [23, 58, 59, 63, 98].

- ***Triangulation-by-pointing*** also referred to as continuous pointing consists of the user viewing the target in front of them and memorizing the location of the target, then the user points to the target with their finger, then walks forward with eyes closed while continuously pointing to the direction of where the target was located [4, 6, 12, 20, 22, 48]. The pointing angle is recorded by the researcher using an instrument both at the start of the trial and when the user stops walking and thinks they reached the target.

Since the most commonly used evaluation methods consist of visually directed action methods [1, 16, 74, 83], we have decided to opt for the *blind-walking* task as our evaluative method for egocentric distance perception.

# CHAPTER 3: METHODOLOGY

We performed an experiment to explore the potential impact that head-centric RFs can have on egocentric distance perception in VR, and we varied the environmental characteristics to uncover any potential interaction effects between head-centric RFs and other environmental properties. The design of the test environments was driven by the literature review, and the aim to generalize our findings to a variety of VEs.

## *Study Design and Evaluation Metrics*

To assess the effect of head-centric RFs across a variety of VE conditions, we decided to vary the RFs and three additional commonly-tested environmental conditions. Our experiment consisted of a $4 \times 3 \times 2 \times 4$ mixed-design study. The environment-based characteristics were the between-subject factors, which consisted of *Two Outdoor* and *Two Indoor* environments representing 4 levels total; the within-subject factors included *target position* (3 levels), *clutter-level* (2 levels), and *head-centric RFs* (4 levels). See Sections "Between-Subjects Variables" and "Within-Subjects Variables" in Chapter 3 for a thorough discussion of these study factors.

Through prior work, visually directed action methods represent the most common evaluation methods of distance estimation [16, 74, 83], we chose the *blind-walking* [23, 59, 63, 74, 90, 98] task as our method to evaluate egocentric distance perception. The blind-walking task starts by allowing the user to view the VE through the HMD and make a judgment about the distance from them to the target. Once the user is ready, they walk to the target with their eyes closed, and their position in relation to the target is logged once they have stopped walking and they think they reached the target. Once the walking phase is completed, the trial ends with them informing the investigator that they reached the target and opening their eyes. When the user reached the target and they open their eyes nothing was displayed in the VE such that no feedback of where they were located in the VE was given. Furthermore, the user is not provided with any feedback about their performance at the end of the trial to avoid any training or correction effects. At the end of the experiment, we conducted an informal interview with participants (see Section "User Study Procedure" in Chapter 3).

### *Study Variables*

#### *Rest Frames Design*

The rest frames used in our experiment were chosen and implemented inspired from prior work [7, 8, 11, 54, 87, 94] and we developed the RFs in our study using the 3D modeling tool Blender [1] and consisted of *a virtual nose, a hat, and a mesh mask* (see Figures 3.1, 3.2, and 3.3). The representation of the RFs can vary from one HMD to another, depending on the FOV. An open-source copy [2] of each RF GameObject that can be directly attached to any VR camera object was made available for quick and easy reproducibility. We designed the RFs to be as user-friendly as possible in terms of design, scale, and position. We considered different areas of the peripheral vision in order to allow for a realistic display and placement of the RFs so that they are not visually invasive and so that they don't cover the majority of the FOV. Thus, the chances of information loss occurring were minimized. We tested our RFs in a pilot study to ensure an intuitive experience in the VE and to reduce the chance of them acting as distractors. The RFs remained static, visible at all times, and followed the head of the user. We list additional specifications of the RFs as follows:

- **Baseball Hat:** We designed a blue baseball hat RF similar to one in real life, such that

[1] `https://www.blender.org`

[2] `https://github.com/YHmaiti/Distance-Perception-in-VR-Study`

the design was natural and was set so users would not feel any discomfort nor disorientation when wearing it. The hat was placed in the upper peripheral view of the user (see Figure 3.1).

Figure 3.1: The hat rest frame used in the study.

- **Virtual Nose:** We designed a virtual nose RF following design recommendations available in the literature [11, 54, 94–96] that were adjusted based on our pilot studies. The nose was placed in the bottom middle central view of the user as it would be in real life. The nose had a neutral color such that we picked a color not specific to any particular skin tone to avoid adding more variables to the study design (see Figure 3.2).

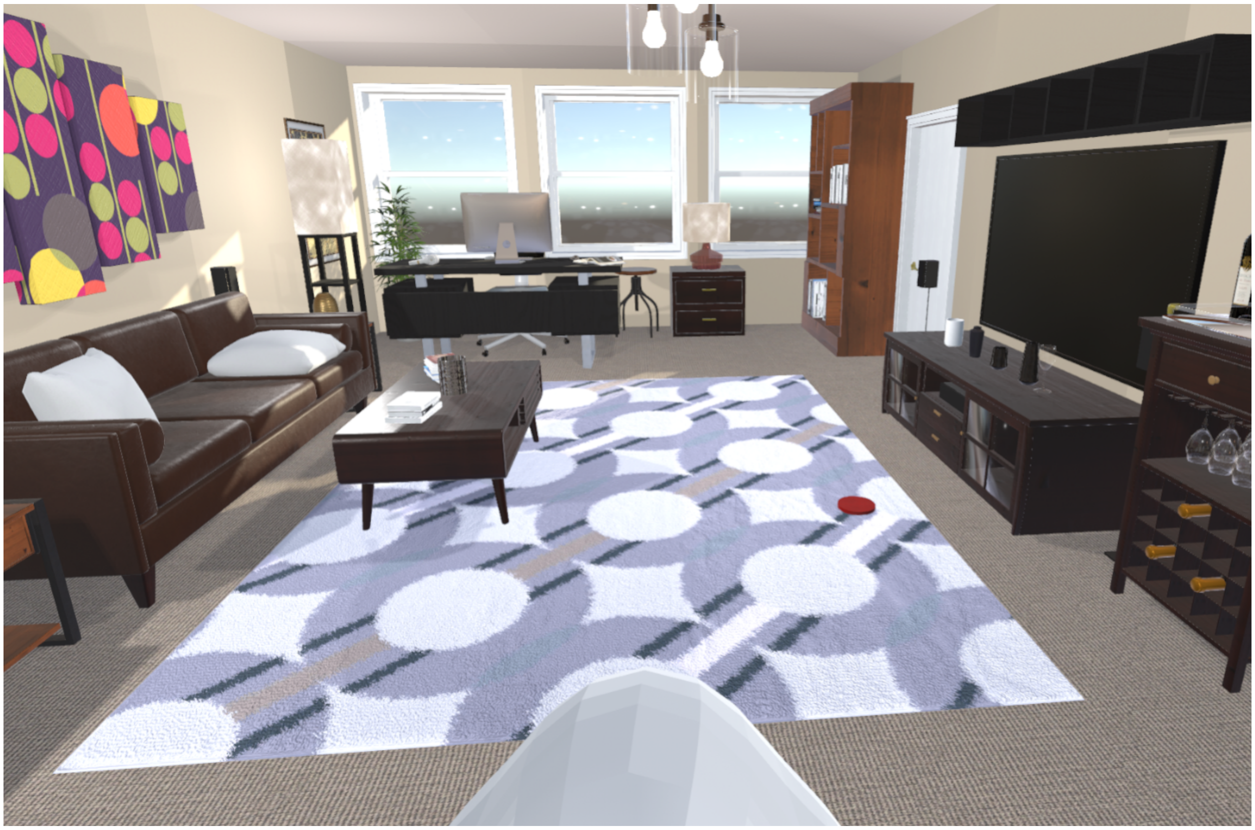


Figure 3.2: The nose rest frame used in the study.

- **Mesh Mask:** We designed our material for the mask RF inspired by the cockpit design of Cao et al. [8]. We obtained the cockpit proportions from the authors and adapted them to fit our mesh mask design that we adjusted based on several pilot studies. We made the see-through pores larger to reduce visual information loss since the mask mesh was placed close to the user's eyes. The mask material was applied to a spherical 3D object placed on the user's head (see Figure 3.3).

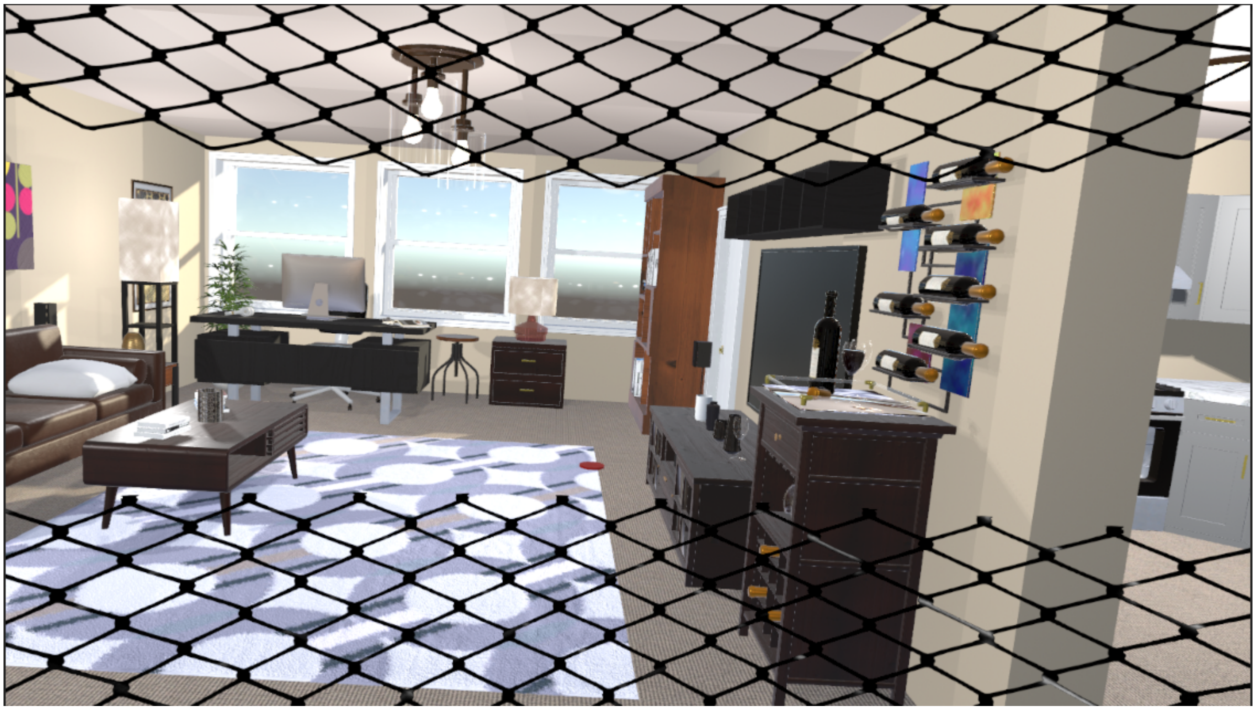


Figure 3.3: The mesh mask rest frame used in the study.

For each trial, either one head-centric RF was assigned or none such that no more than one RF was enabled per trial. The RFs presented were the same across all environments, and we consider the condition with no head-centric RF as the baseline control condition.

*Between-Subjects Variables*

We used four environments in our experiment, two indoor, and two outdoor settings (see Figures 3.4, 3.5, 3.6, and 3.7). These environments were chosen based on prior studies on distance perception and clutter evaluation [58, 59]. The chosen VEs vary in several dissimilar aspects including the setting (indoor/outdoor), light source (sunlight, indoor lamps, etc.), object type (plants, furniture, buildings, etc.), and object position. Since the environment was the between-subject variable, every user was evaluated in only one of those four environments, so that no user saw more than one environment. The environments were assigned using a round-robin order such that the recruited participants were distributed evenly across all the environments, and the VEs used in our experiment were acquired from Unity3D's [3] [4] [5] [6] online asset store. We modified the chosen VEs through the Unity3D editor to fulfill our investigation requirements and to be as realistic as possible. We present the characteristics of each environment as follows:

- ***Indoor Environment 1:*** We chose an indoor library environment 7m wide and 10m long with a ceiling at 4m height. The environment contained tables, chairs, sofas, books, bookshelves, screens, and carpets along with some decorations near the walls. The library was enclosed without windows and the main sources of light were inside (see Figure 3.4-(a)). When uncluttered, the furniture and decorations in the environment were removed as shown in Figure 3.4-(b).

- ***Indoor Environment 2:*** We chose a common indoor space for the participants consisting of a living room in a house. The room was 5m wide and 10m long with a ceiling 3m high. This environment contained windows and furniture and was shown to users during day time such that the main source of light was the sun coming through the windows (see Figure 3.5-(a)). When uncluttered, we removed all the furniture as shown in Figure 3.5-(b).

[3] `https://assetstore.unity.com/packages/3d/props/apartment-kit-124055`

[4] `https://assetstore.unity.com/packages/3d/environments/urban/suburb-neighborhood-house-pack-modular-72712`

[5] `https://assetstore.unity.com/packages/3d/environments/pirates-island-14706`

[6] `https://assetstore.unity.com/packages/3d/environments/urban/library-interior-archviz-160154`

(a) Indoor environment 1 cluttered.

(b) Indoor environment 1 uncluttered.

Figure 3.4: The two levels of clutter for the user study indoor environment 1.

(a) Indoor environment 2 cluttered.

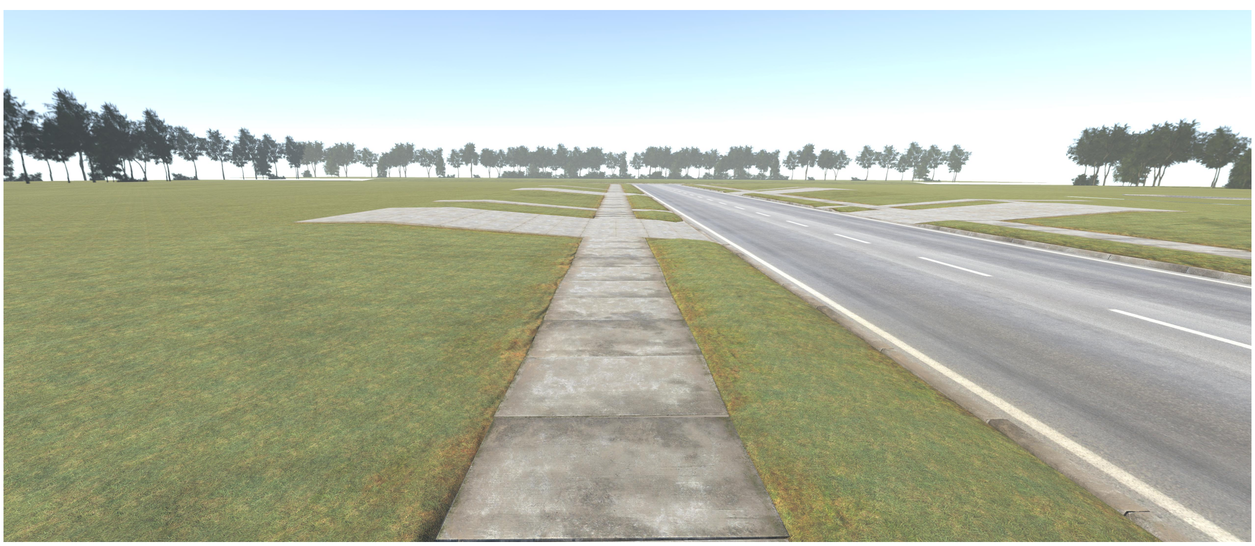
(b) Indoor environment 2 uncluttered.

Figure 3.5: The two levels of clutter for the user study indoor environment 2.

- ***Outdoor Environment 1:*** We chose a street in a suburban area, such that the walking path was on the sidewalk. The environment was presented to users during day time, and the light source was the sun. The sidewalk was surrounded by cars, plants, light poles, fences, and a couple of houses (see Figure 3.6-(a)). When uncluttered, the plants, cars, light poles, fences, and houses were removed as shown in Figure 3.6-(b).

- ***Outdoor Environment 2:*** We chose an area on an island, such that the area was shown to users during the day and the source of light was the sun. The environment had trees, rock mountains, houses, barrels, boxes, and fences (see Figure 3.7-(a)). The uncluttered form of the environment is shown in Figure 3.7-(b).

(a) Outdoor environment 1 cluttered.



(b) Outdoor environment 1 uncluttered.

Figure 3.6: The two levels of clutter for the user study outdoor environment 1.


(a) Outdoor environment 2 cluttered.

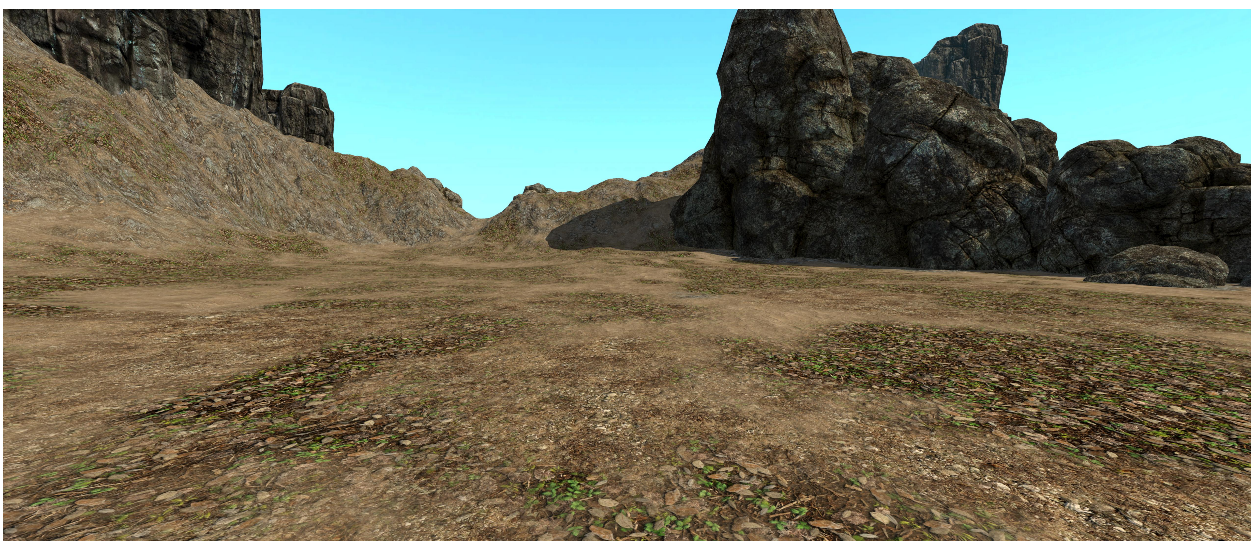

(b) Outdoor environment 2 uncluttered.

Figure 3.7: The two levels of clutter for the user study outdoor environment 2.

*Within-Subjects Variables*

In our investigation, we chose 4 levels of RFs (*1:no rest frame, 2:a virtual nose, 3:a hat, and 4:a mesh mask*). The nose and hat RFs were evaluated in prior studies, and the mask RF represents a new RF we created. These RFs were placed on the participant's head as they would be intuitively in real-life. The RF specifications and characteristics were discussed in the "Rest Frames Design" section in Chapter 3.

Across the literature, there are multiple definitions of clutter due to it being investigated across several evaluations and domains [62]. Nevertheless, the most common definition of clutter relates to the abundance and excess of elements in a scene, which also relates to the number of objects on a display [25, 36, 53, 93]. In our study, we define clutter to be the number of perceivable objects in the VE by the user. We had 2 levels of clutter in the experiment (*1:uncluttered, and 2:cluttered*). The number of objects for each clutter level was the same across all VEs. In addition, the target consisted of a red disk-shaped object placed on the floor at a distance that varied from one trial to another. The target disk cast and received shadows to induce more realism and homogeneity with the environment, while preserving its depth cue efficiency. The disk was placed at one of the following distances from the participant's starting point at each trial for each environment: *3m*, *4.5m*, or *6m* (see Figure 3.8). In addition, we designed the disk to have a 5cm height and a 10cm diameter following prior design choices in work by Masnadi et al. [59]. Furthermore, the target positions were determined by referencing previous investigations that relied on the blind-walking task [31, 58, 59, 73, 84]. Some of these investigations had four target distances (3m, 4m, 5m, and 6m), however, we decided to keep 3 of them 3m, 4.5m, and 6m (see Figure 3.8) with the aim of minimizing any possible learning effect and reducing the chance of the users being physically tired. We placed the user and the target in VR in a *safe walking zone*, the position of which was randomized between trials to ensure that the target placement and path participants see during each

Figure 3.8: Target distances (3m, 4.5m, 6m) used in the study.

trial are not the same (even if the physical starting point is the same). This zone did not have any real-world or virtual objects in the user's walking path. The camera and target positions within the safe zone were also randomized for each trial. This way, we attempt to reduce the chance of the user memorizing the path and number of steps to the target and to ensure that position within the environment would not be a confounding variable.

By considering the within-subject factors discussed, we had three target distances, two levels of clutter, and four levels of RFs. For each trial, only one level from each factor was displayed to the user. These factors make up 24 total conditions. Each condition was displayed thrice for every user resulting in 72 blind-walking-based trials for every user. The order of the conditions was randomized such that for all users, there were no two consecutive trials with the same condition, which reduced the learning and memorization effects during the study. For every trial, we recorded the distance walked by the user. To record the error distance, we subtracted the target distance from the user's walked distance. If the user walked beyond the target, in that case, the error recorded was positive, whereas if the user stopped walking before reaching the target's position, in that case, the error was negative.

In the end, we average the error distances of all trials per condition. By averaging distance errors, we maintain the distance error direction by combining both positive and negative errors, which permits a comprehensive assessment of participant overall performance in each condition. Through averaging, we are able to record the average error distance directional deviation from the target. This preserves the equal importance of both opposite error directions in the participant's distance judgment assessment for every trial per condition. If we use the absolute distance, then negative and positive errors will be treated equally, since the sign of the recorded distance will not be preserved, which obscures the true nature of the participant's performance. In contrast, averaging the distance errors ensures a more nuanced understanding of overall distance error bias (overestimation or underestimation) for every trial per condition.

### *Apparatus*

We performed the study using the Pimax 5k Plus VR headset. The resolution of the chosen HMD is $2560 \times 1440$ pixels per eye along with a large FOV of $170° \times 110°$, which was kept constant in our experiment, as it is not a factor in our study. The headset weighed 500g with the head strap and had a 144hz refresh rate. Since the users were required to walk to targets with different distances in multiple trials, we decided to use a portable battery-based HP Z VR backpack. The backpack was equipped with a CPU Intel 7820HQ, a GPU NVIDIA Quadro P5200, and 32GB RAM. We equipped the backpack with headphones that the user wore to listen to verbal instructions. These headphones were comfortable and did not disturb the user during their execution of the study-related walking task. The described apparatus, which includes backpack, headset, and headphones had an end weight of 4.37kg.

The study location was our laboratory room (see Figure 3.9), which has an empty area where participants were able to walk safely. The lab room dimensions were $6m(w) \times 9m(l) \times 3.3m(h)$ and the area used for the investigation was $4m(w) \times 9m(l)$. The outermost target was located 6m away from the user, and for user safety, we ensured that this target was 3m away from any nearby object that was not involved in the study. Moreover, the apparatus used SteamVR[7], which offers the option to have a visual safeguard show up whenever the participant was close to the study area limits. We set the safeguard wall activation distance to 0.5m and since participants never came close to the wall of the room, no participant reported seeing the wall. Additionally, we developed our experiment to perform with a constant 80 frames per second (FPS), which was possible through the Pimax 5k+ HMD.

[7]https://partner.steamgames.com/doc/features/steamvr/info

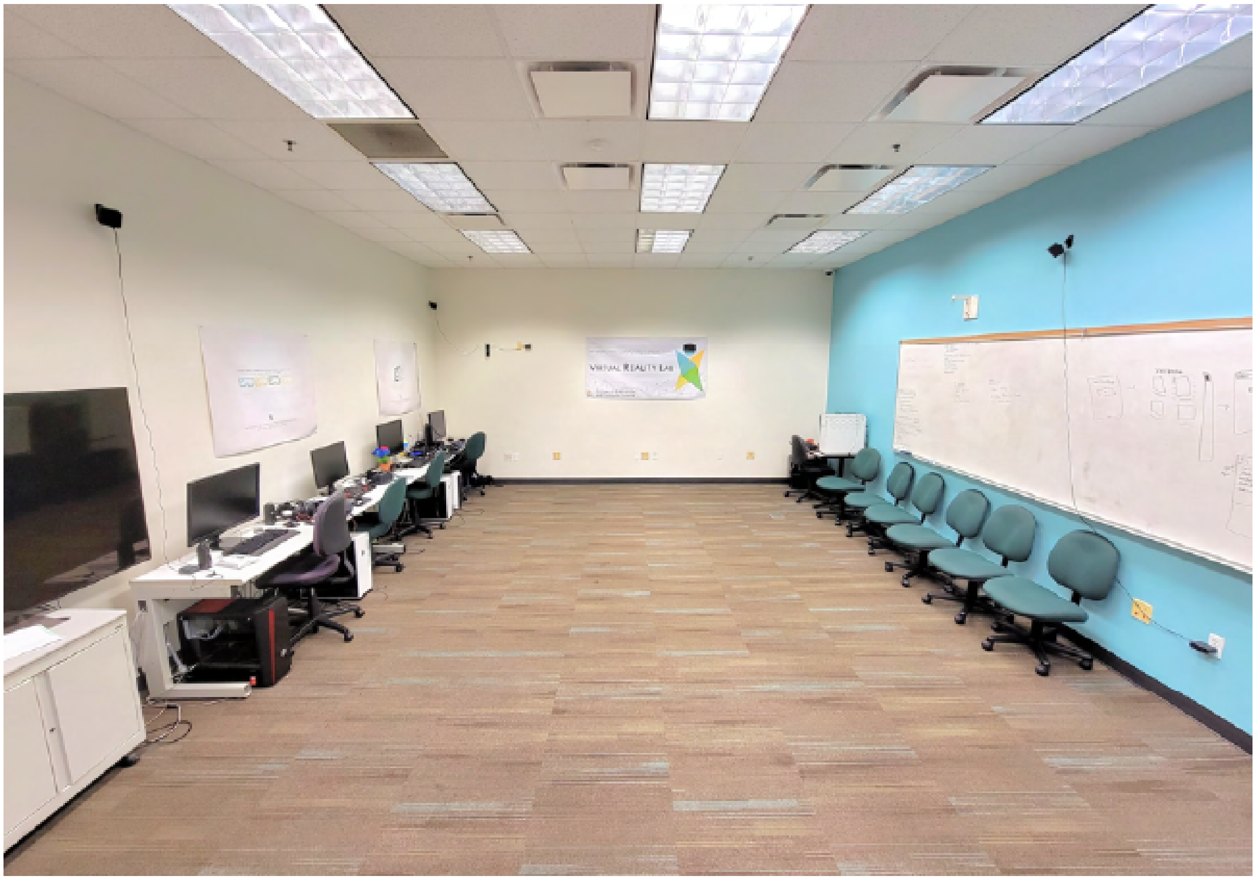


Figure 3.9: The laboratory room used to conduct our investigation.

In addition, to avoid interrupting the participant's view of the VE and reduce any influence from outside the VE, we created a tool similar to the one used by Masnadi et al. [59]. The tool allowed us to monitor the user's view and their behavior in real-time from a different computer. This tool used a WebSocket connecting the backpack and the investigator's remote computer. It permitted a high-quality video stream to be sent to the remote device that the investigator used without any negative effects on the user VR experience or study trials. We improved the tool by running several pilot studies, to ensure the consistency and quality of the stream, while also providing the investigator with text and visual information regarding the environment, user view, and trial characteristics accurately on the remote computer in real-time.

*Participants*

Once the study was approved by the Institutional Review Board (IRB), we recruited 30 participants from a local university. All participants were over the age of 18 and had diverse heights, and varying experience levels using VR technologies. We only accepted participants with normal or corrected-to-normal vision, who were able to speak, understand English, and walk without assistance. No participants expressed any visual, neuropathic, or physical disability, and all participants passed the visual acuity test. Additionally, we asked the participants if they perceived the graphics quality as low at any stage of the study, as in that case their data would be disregarded considering that perception of distances is dependent on the display quality [37]. Nevertheless, no participants were excluded based on this criterion. However, we excluded 2 participants because it was evident from their performance that their commitment to the experimental task diminished, leading to incorrect execution of the prescribed trials (more on this exclusion in the results section). We recorded the participant's self-reported frequency of interactions with VR systems on a scale from 1 to 5, with 1 being “never" and 5 being “always" (M=2.4, SD=0.78). Our final participant pool was 28 participants (10 females, 18 males) of ages ranging from 18 to 34 (M=22.34, SD=3.04).

*User Study Procedure*

Upon the participant's arrival, we first greeted them and thanked them for participating. We then gave them a consent form that listed all study information, and after they read it, we prompted them for their consent to run the study. Upon receiving their consent, we administered a Snellen chart visual test [89] to ensure that they had normal or corrected-to-normal vision (20/20 vision score) with both eyes. If the participant passed the vision evaluation test, we asked them to fill out a demographics survey to gather their age, gender, and prior experience using VR.

After the survey, we explained in detail the study task and emphasized its main components. Afterward, we invited the participant to ask any questions for clarification. If there were no questions, we proceeded to demonstrate and explain the study apparatus. Then, the participant wore and adjusted the gear (see Figure 3.10), and we asked if they felt comfortable, assisting with adjustments until they were at ease. When the user was equipped, we walked them to the starting position and asked them to align themselves towards the walking area at their front. Then, we turned off the lights in the room to reduce light leakage through the HMD gaps. Afterward, the in-VR task started by first logging the user's start position, since they needed to go back to it at the end of every trial. We note that no practice trials were conducted.

Nothing was shown through the HMD until the user stated that they were ready to begin the evaluation. After informing the investigator that they were ready by saying "ok", the investigator enabled the display of the scene. We allowed the participant to view the VE for five to six seconds to spot the target in the VE and assess the distance from them to the target. After five seconds passed and the participant was ready to walk, they informed the investigator by saying "ok". Upon hearing the confirmation, the investigator disabled the view of the VE (to ensure that no VE-based visual cues were given in case the participant opened their eyes while walking) by clicking a button on a remote controller. The same button triggered a vocal message played through the headphones that said "go", and then the user began walking eyes closed to the target.

When the participant thought they reached the target and fully walked the distance they viewed before starting the walking process, the participant informed the investigator by saying "ok". The participant's position was logged by a button click on the remote controller by the investigator. The participant then opened their eyes after a vocal message through the headphones said "done". Then, the participant followed a red arrow on the floor to navigate back to the starting position. The red arrow remained linked to the participant's feet and pointed to the logged starting position at all times. At the end of each trial, the participant followed this red arrow until a green one appeared, then they stopped and aligned with the green arrow. The green arrow represented an alignment tool to help the user locate their starting position and orient themselves towards the walkable area in the room. We proceeded to the next trial only when both arrows, the red directional arrow, and the green alignment arrow were overlapping fully, and only the alignment arrow remained. We note that while walking back to the starting position between trials, nothing except the red arrow and current trial RF was enabled.

When the user was well-aligned and comfortable to begin the next trial, they informed the investigator by saying “ok". Afterward, the investigator launched the next trial by pressing a button on the remote controller. We present an illustration of the steps for each trial of the blind walking task and their description (see Figure 3.11, we adapted the user representation from Nilsson et al. [69]). At the end of the experiment, we asked the participant in an informal interview setting about their impression and opinion on the design of the RFs, graphics quality across trials, and if they felt any discomfort during the experiment. During pilot studies, some participants mentioned not paying attention to the presence of the nose RF, thus we included a question about it in the interview. The informal interview questions were as follows:

- Was the graphics quality in all trials high and consistent?
- Did any rest frame disturb your comfort or interfere with your view of the VE?
- Did you notice a nose added to your view in any of the trials?

We followed this user study procedure to minimize any direct interaction with the user during the in-VR task. This allowed us to reduce the chance that the investigator provided any type of cues to the participant that they could use for target distance judgment or locating themselves inside the room. After completing the study, the participant was awarded $10 and the study took around 50 min to complete.

Figure 3.10: A participant wearing the study apparatus.

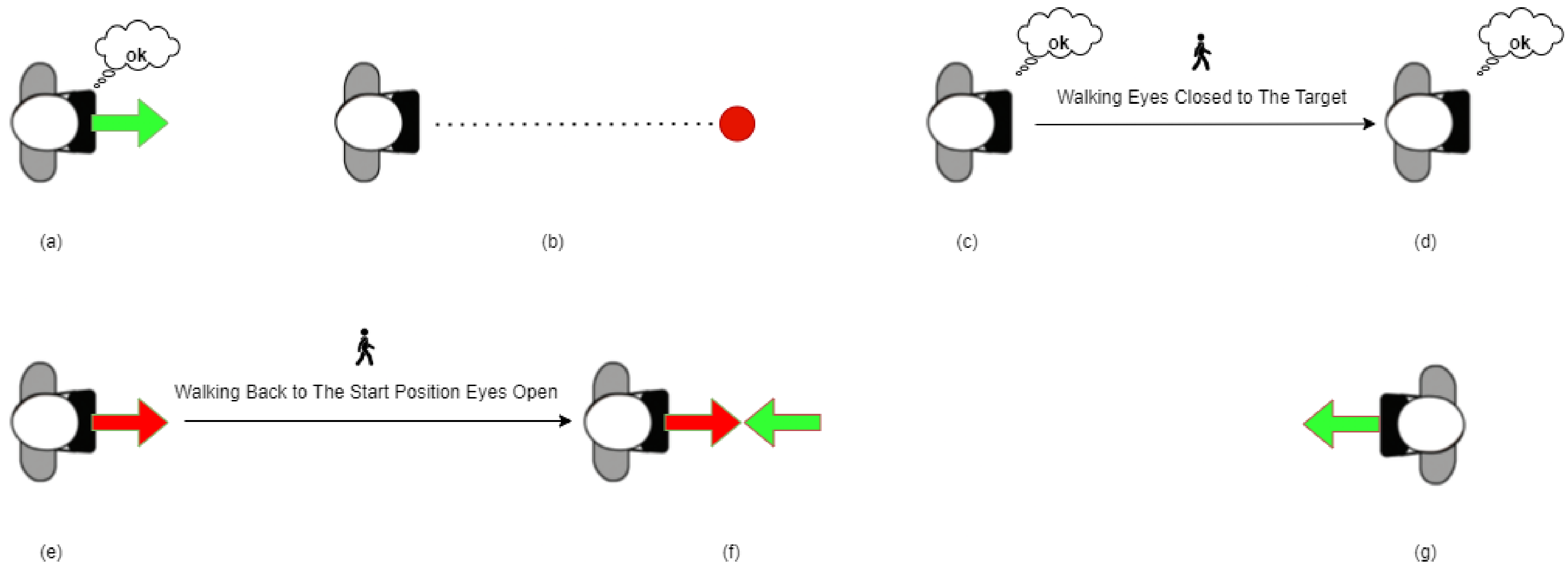



Figure 3.11: Representation of the steps for each trial of the blind walking task: (a) The user aligns with the alignment arrow (Green) on the floor that marks the start position and orientation, then when ready they say "ok". (b) The alignment arrow (Green) disappears and the environment is enabled for the user to view the target. (c) The user says "ok" when ready to walk, the environment is disabled, the screen is black and the user starts walking with eyes closed to the target. (d) The user says "ok" when they think they reached the target and they open their eyes. (e) The user turns around and a directional arrow (Red) is attached to their feet. (f) The user follows the directional arrow (Red) that points to the start position until the alignment arrow (Green) appears marking the mentioned start position. (g) The user aligns with the alignment arrow (Green) until the directional arrow (Red) disappears for a full correct alignment, then the next trial starts with step (a) again.

# CHAPTER 4: RESULTS

Before analyzing the error distances recorded per each condition and environment for each user, we initially averaged the error distances recorded for each trial of each condition for each user, since each condition was repeated three times. Two participants did not follow the investigator's instructions, due to being discouraged from having to walk for an extended period of time. Specifically, no matter what the target distance was, for approximately half of the trials, these participants only took a single step forward and reported their arrival at the target. Thus, all their data was discarded. Since the blind-walking task we used had a large number of trials, we suspected that in some trials, participants would not execute the tasks as instructed, and such data would bias the results. Thus, we determined a threshold to exclude outliers to be above or below three standard deviations from the mean ($< \mu + 3\sigma$ or $> \mu + 3\sigma$) per condition. However, no outliers were detected and all data of the remaining 28 users was kept.

Afterward, we tested the normality of our data through a Shapiro-Wilks test and found that data was normally distributed ($W = 0.943, p = 0.129$). The environment type (*Indoor or Outdoor*) was a between-subjects factor, whereas the within-subjects factors consisted of (*Target Distance, RF Level, and Clutter Level*). For the between-subject factor, we grouped in our analysis the indoor environments together, and the outdoor environments together after checking that each of the VEs with a similar environment type had distributions that were nearly identical. Figures 4.1, 4.2, and 4.6 show the average distance error by RF compared to the control condition, and we present the mean error distance and standard deviation for each distance traveled to the target per RF condition (see Table 4.2). We performed an RM-ANOVA to test the main and interaction effects (see Table 4.1), applying Greenhouse-Geisser correction whenever the sphericity assumption was violated based on Mauchly's sphericity test, which explains the degrees of freedom obtained. Pairwise and independent t-tests comparisons were performed with the Bonferroni post-hoc corrections method. Moreover, for the error bars to be informative in the case of within-subject comparisons, we applied Cousineau's and Morey's approach to remove the between-subject variability [15, 66].

Table 4.1: RM-ANOVA statistical effects for each factor and factor interactions. The strongest effects sizes are highlighted in bold. *RF*: Rest frames, *C*: Clutter, *T*: Target Distances, *E*: Environment Type. (* = $p < .05$; ** = $p < .01$; *** = $p < .001$)

| Factor | $F$ | $df_{\text{effect}}$ | $df_{\text{error}}$ | $p$ | $\eta_p^2$ | Sig |
|---|---|---|---|---|---|---|
| $RF$ | 14.453 | 2.405 | 62.524 | <.001 | **.357** | *** |
| $C$ | 9.603 | 1 | 26 | .005 | **.270** | ** |
| $E$ | 0.091 | 1 | 26 | .765 | .003 | no |
| $T$ | 3.613 | 1.56 | 40.548 | .046 | **.122** | * |
| $RF \times C$ | 4.311 | 3 | 78 | .007 | **.142** | ** |
| $RF \times T$ | 17.749 | 3.829 | 99.555 | <.001 | **.406** | *** |
| $RF \times E$ | 0.301 | 3 | 78 | .824 | .011 | no |
| $C \times T$ | 7.099 | 2 | 52 | .002 | **.214** | ** |
| $C \times E$ | 0.077 | 1 | 26 | .784 | .003 | no |
| $T \times E$ | 0.25 | 2 | 25 | .779 | .010 | no |
| $RF \times C \times E$ | 0.42 | 3 | 78 | .739 | .016 | no |
| $RF \times C \times T$ | 1.672 | 6 | 156 | .131 | .060 | no |
| $RF \times T \times E$ | 0.089 | 6 | 156 | .997 | .003 | no |
| $C \times T \times E$ | 3.023 | 2 | 52 | .057 | .104 | no |
| $RF \times C \times T \times E$ | 1.051 | 6 | 156 | .395 | .039 | no |

*Main Effects Results*

*Main Effect of Rest Frames*

A highly significant main effect of RFs ($F_{2.405,62.524} = 14.453$, $p < 0.001$, $\eta_p^2 = 0.357$) on distance estimation was found. We conducted post-hoc comparisons using pairwise t-tests with Bonferroni corrections, where we compared the effect of each RF to the control condition (M=$-49.14$, SD=55.47). We found no significance on distance judgment for the hat RF compared to the no RF condition ($t_{27} = -2.422$, $p = 0.143$) (M=$-57.63$, SD=58.96), we found a significant difference for the nose RF compared to the no RF condition ($t_{27} = 3.324$, $p < 0.019$) (M=$-41.48$, SD=60.72), also a significant difference was recorded for the mask RF ($t_{27} = 3.535$, $p < 0.011$)(M=$-37.86$, SD=63.82). This shows that overall participants had more accurate distance perception when the mask and nose RFs were enabled in the VE, whereas this effect was not observed with the hat RF (see Figures 4.1, 4.2, and 4.6). Moreover, we found no significant difference between the nose and the mask RFs ($t_{27} = -1.404$, $p = 0.987$). However, we found a significant difference between the hat and the mask RFs ($t_{27} = 5.458$, $p < 0.001$) and also between the hat and the nose RFs ($t_{27} = -4.221$, $p = 0.002$). Thus, we conclude that in our experiment the nose and the mask had a similar effect on distance judgment, whereas overall the hat under-performed compared to them.

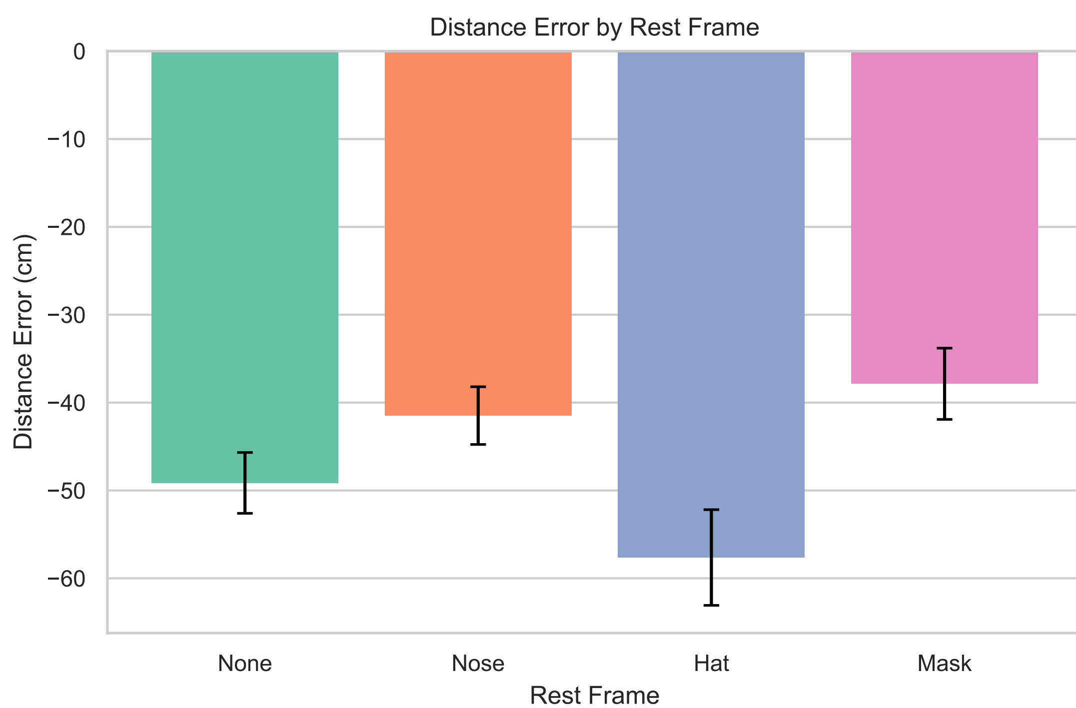



Figure 4.1: Distance error mean (cm) by each individual RF level (95% CI).

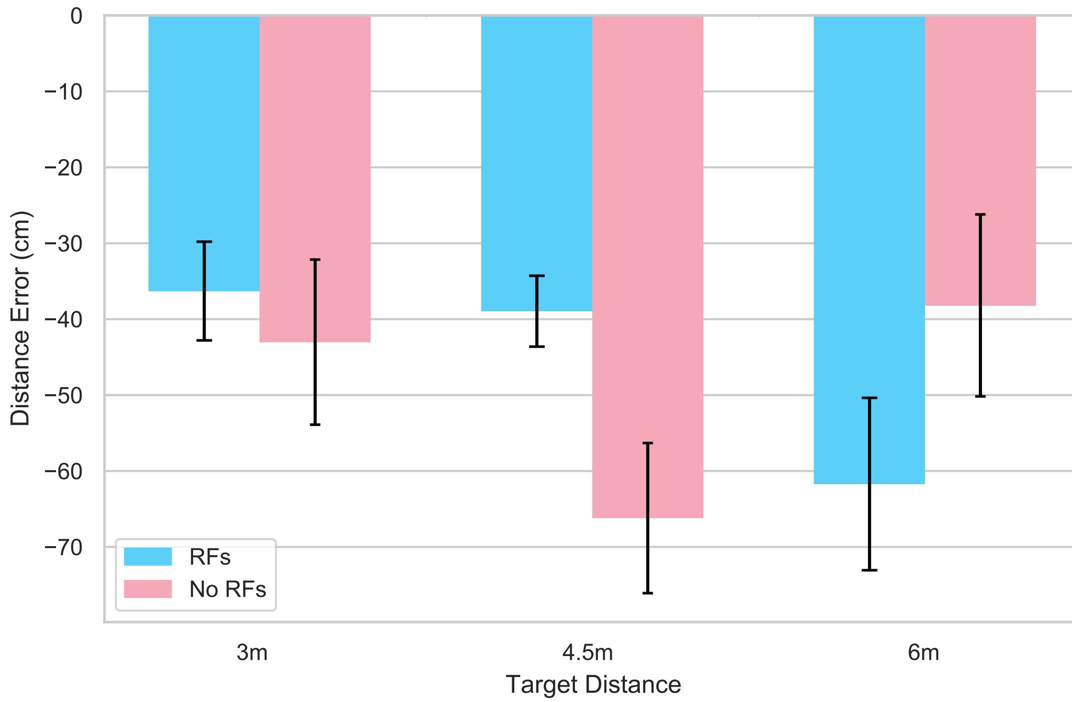



Figure 4.2: Distance error mean (cm) for each individual RFs across all target distance levels (95% CI).

*Main Effect of Clutter*

A significant main effect of clutter ($F_{1,26} = 9.603$, $p < 0.01$, $\eta_p^2 = 0.27$) on distance estimation was found. A higher degree of underestimation was recorded in the uncluttered conditions (M=−52.26, SD=60.22), whereas less underestimation was recorded in the cluttered conditions (M=−40.79, SD=59.14). We noticed an improvement in distance estimation by 21% between the two clutter conditions (see Figure 4.3).

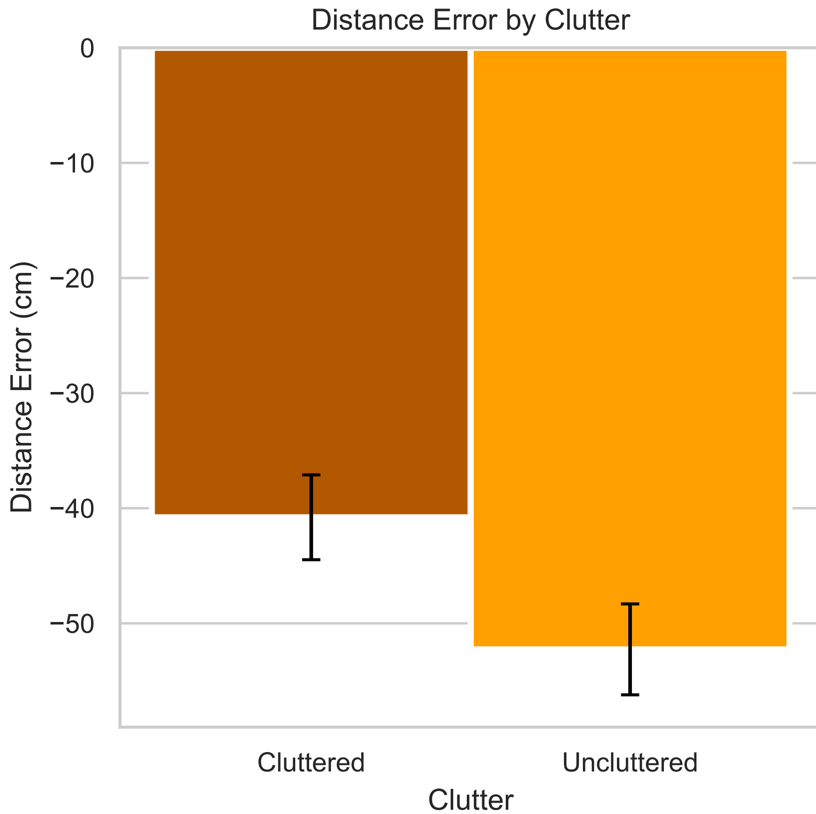



Figure 4.3: Distance error mean (cm) in cluttered vs uncluttered conditions overall (95% CI).

*Main Effect of Target Distance*

A significant main effect of target distance on distance judgment was found ($F_{1.56,40.548} = 3.613$, $p = 0.046$, $\eta_p^2 = 0.122$). More distance underestimation was recorded for the far-field target of 6m (M=$-55.83$, SD=66.74) compared to the 3m (M=$-37.98$, SD=49.27), and 4.5m (M=$-45.77$, SD=68.81) targets as is shown in Figure 4.4. We did not find a significant difference through post-hoc analysis between all target distances: 3m vs 4.5m ($t_{27} = 1.525$, $p = 0.418$), 4.5m vs 6m ($t_{27} = 1.580$, $p = 0.379$), and 3m vs 6m ($t_{27} = 2.191$, $p = 0.113$).

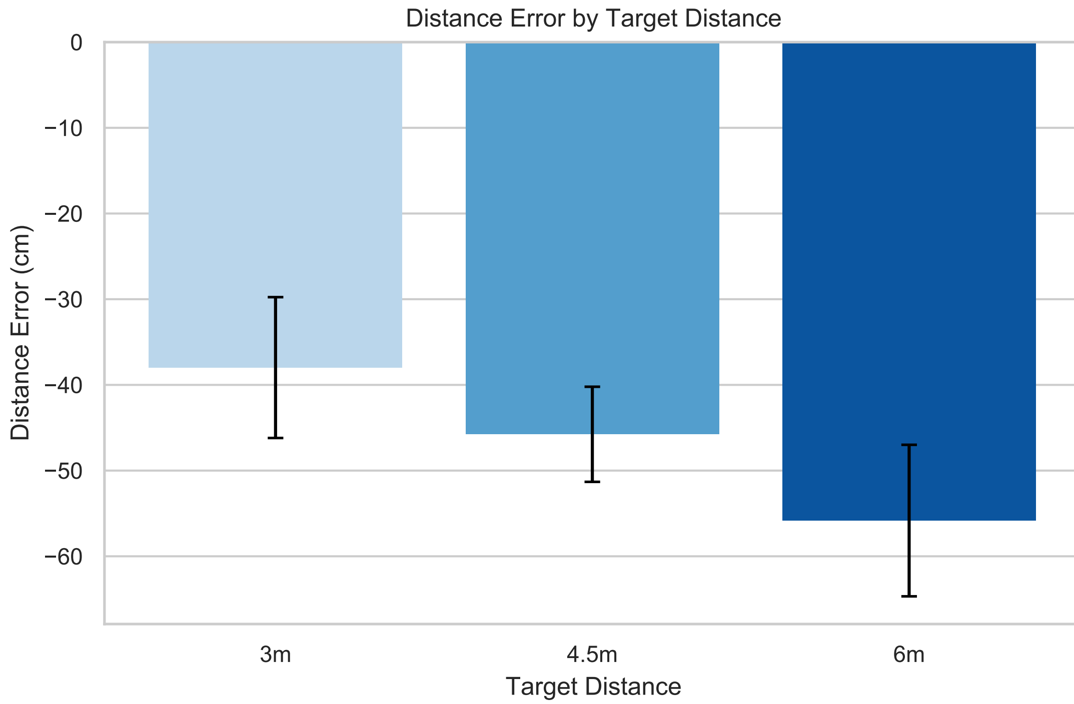



Figure 4.4: Distance error mean (cm) across all three target distance levels (95% CI).

*Interaction Effects Results*

In this subsection, we only report the interaction effects relevant to our study and the rest can be found in Table 4.1.

*RFs x Clutter*

A significant interaction effect was found between the RFs and clutter ($F_{3,78} = 4.311$, $p = 0.007$, $\eta_p^2 = 0.142$). A post-hoc comparison through pairwise t-tests using Bonferroni correction uncovered a significant difference between the cluttered and uncluttered conditions for the nose RF ($t_{27} = 5.065$, $p < 0.001$) and for the mask RF ($t_{27} = 2.669$, $p = 0.013$) for distance perception.

Whereas, no significant difference between the cluttered and uncluttered conditions were found for the hat ($t_{27} = 1.073$, $p = 0.293$) (see Figure 4.5).

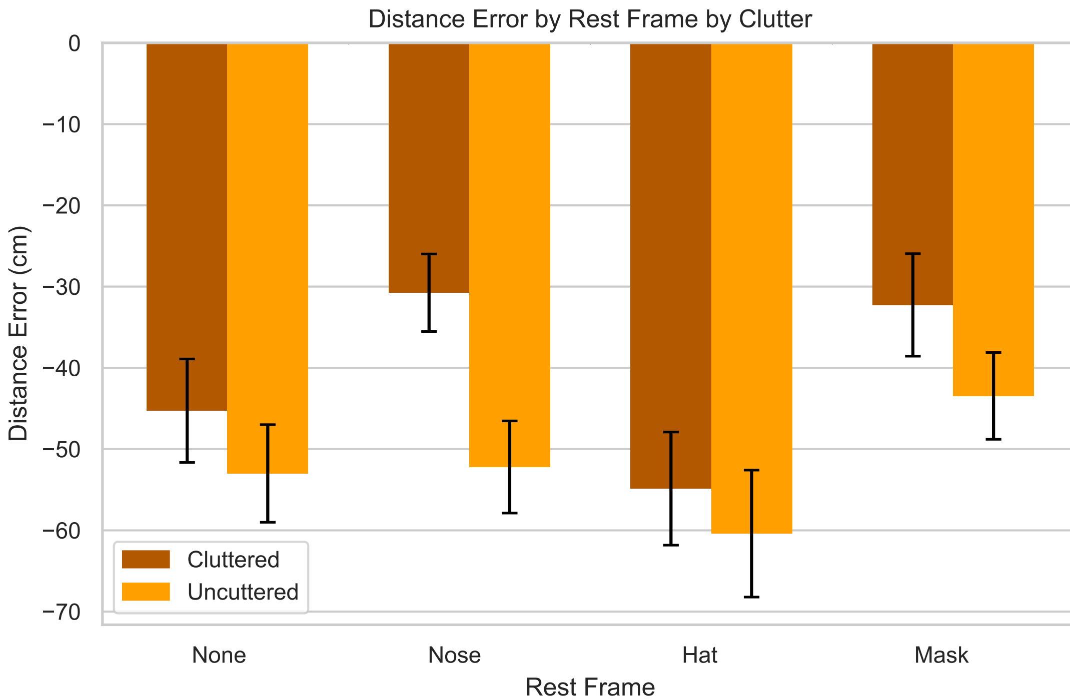



Figure 4.5: Distance error mean (cm) for each individual RF level across clutter levels (95% CI).

*RFs x Target Distance*

A significant interaction effect between RFs and distance was found ($F_{3.829,99.555} = 17.749$, $p < 0.001$, $\eta_p^2 = 0.406$). We conducted post-hoc pairwise comparisons using Bonferroni corrections, where we compared all RF conditions averaged together against the control condition, across the three target distance levels (see Figure 4.2). We found that at the near-field distance (3m), there was no significant difference between user performance with RFs and with the non-RF condition ($t_{27} = 1.899$, $p = 0.068$). At the mid-field (4.5m) and the far-field distances (6m), there were significant

Table 4.2: Mean error and standard deviation by target distance by rest frame (RF).

| Target (meters) | RF Condition | Error (centimeters) |
|---|---|---|
| 3m | Mesh Mask | M = -25.19, SD = 51.46 |
| | Virtual Nose | M = -42.50, SD = 48.26 |
| | Baseball Hat | M = -41.20, SD = 56.48 |
| | No Rest Frame | M = -43.02, SD = 47.20 |
| 4.5m | Mesh Mask | M = -38.23, SD = 69.18 |
| | Virtual Nose | M = -35.90, SD = 72.18 |
| | Baseball Hat | M = -42.74, SD = 70.67 |
| | No Rest Frame | M = -66.20, SD = 70.58 |
| 6m | Mesh Mask | M = -50.15, SD = 79.80 |
| | Virtual Nose | M = -46.05, SD = 74.58 |
| | Baseball Hat | M = -88.95, SD = 61.55 |
| | No Rest Frame | M = -38.19, SD = 64.75 |

differences between the RF and non-RF conditions, with the RF condition outperforming the non-RF condition at the mid-field ($t_{27} = 5.831$, $p < 0.001$), but under-performing at the far-field ($t_{27} = -5.661$, $p < 0.001$) (see Figure 4.2).

To better assess the impact of each RF at each target distance level on distance judgment, we conducted additional post-hoc comparisons with Bonferroni corrections, where we compared each individual RF level to the non-RF level. At 3m, we found that only the mask RF was significantly different from the control condition ($t_{27} = -3.708$, $p = 0.006$). At 4.5m, all the RFs performed significantly differently from the non-RF condition: nose RF ($t_{27} = -6.06$, $p < 0.001$), mask RF ($t_{27} = -4.746$, $p < 0.001$), hat RF ($t_{27} = -4.352$, $p < 0.001$). As for the 6m distance, only hat RF performed significantly different from the non-RF condition, however instead of improving user distance judgment, it worsened it ($t_{27} = 7.362$, $p < 0.001$), as seen in Figure 4.6 and Table 4.2.

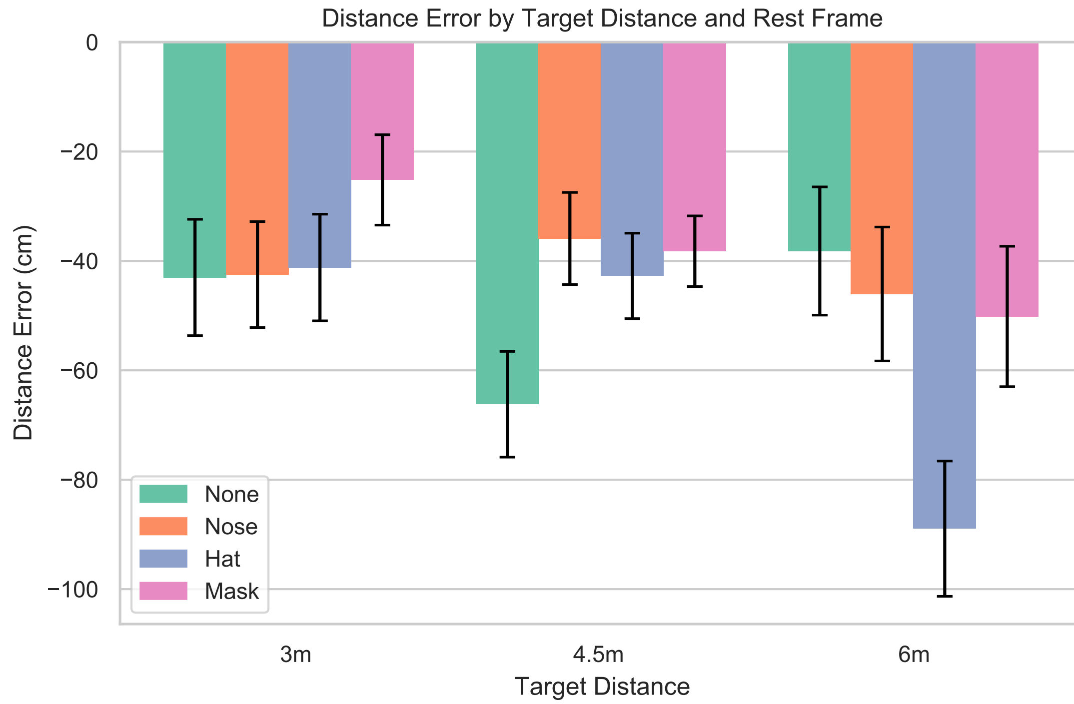



Figure 4.6: Distance error mean (cm) for all RF conditions (nose, hat, and mask) together vs no RF condition across three target distance levels (95% CI).

*Clutter x Target Distance*

A significant interaction effect between clutter and target distance was found ($F_{2,52} = 7.099$, $p = 0.002$, $\eta_p^2 = 0.214$). For all target distances, on average users estimated distance more accurately when clutter was present (see Figures 4.3, and 4.7), however after conducting post-hoc comparisons using Bonferroni corrections, we found that the improvement was significant only at the mid-field (4.5m) target distance ($t_{27} = 4.87$, $p < 0.001$).

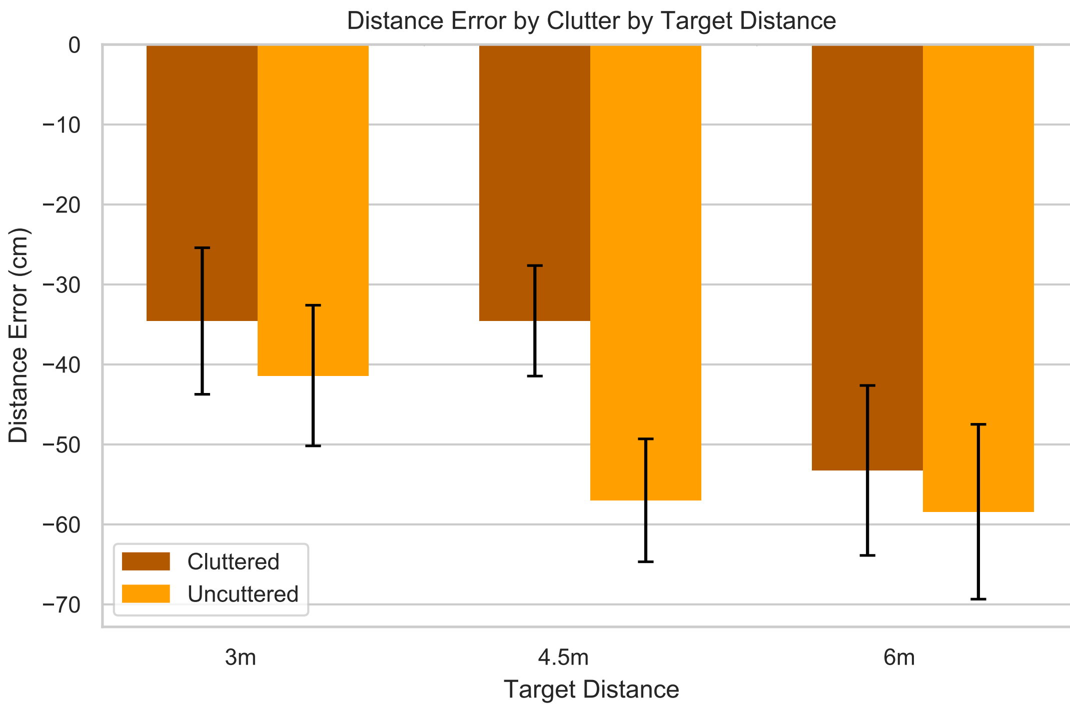



Figure 4.7: Distance error mean (cm) for the cluttered vs uncluttered conditions across target distance levels (95% CI).

# CHAPTER 5: DISCUSSION AND RESULTS IMPLICATION

The goal of our investigation was to evaluate the effect head-centric RFs (*a virtual nose, a mesh mask, and a hat*) can have on egocentric distance perception. The user study results show that most RFs we tested promote better distance judgments in the near-field and mid-field distances compared to the control condition (see Figures 4.2, and 4.6). In addition, through our experiment, we assessed the impact of other environmental variables on distance perception, and here we discuss their implications.

### *Head-centric RFs Affect Distance Estimation*

Our results show that overall the mask and nose RFs contribute to reducing distance underestimation compared to the baseline condition (***mesh mask RF by 23%, and nose RF by 16%***). The hat RF overall under-performed compared to the no RF condition. This finding was enough to assess that not all RFs contribute to improving distance judgments in VEs overall. To our knowledge, our work is the first to evaluate and uncover the efficiency of such head-centric RFs in a distance judgment task, consequently, some findings are difficult to contrast with work in the literature and the underlying mechanisms by which RFs impact spatial judgments are not clearly established in the literature. Our results show that for the near-field distance (3m) there was a significant difference between the impact of the mask RF compared to the control condition on distance judgments, whereas no significant difference was recorded for the other RFs at this distance (see Table 4.2 and Figures 4.2, and 4.6). We found that at this near-field distance, the mask RF significantly improved the distance estimation (**by 41%**) (see Figure 4.6).

We found that at the mid-field distance (4.5m), a significant difference between the impact of RFs on distance estimation compared to the control condition was recorded, with RFs providing more accurate distance estimation (see Table 4.2 and Figures 4.2, and 4.6). At 6m, a significant difference between RFs performance compared to the baseline condition was recorded, and more underestimation of distance was recorded when RFs were enabled (see Figures 4.2, and 4.6). However, at 6m the significant difference was only recorded for the hat RF, whereas for the other RFs, no significant difference was recorded compared to no RF condition. Also, based on pairwise comparisons (see Section "Main Effect of Rest Frames" in Chapter 4), we found that the mask RF and the nose RF are overall better at reducing distance underestimation than the hat RF (see Figures 4.1, and 4.6).

We suspect that these performance results are due to the mask and nose being located closer to the central view of the user, and that the mask with its unique design helps users ignore irrelevant visual information in the VE with the metallic see-through pores surrounding the view area not covered with a mesh. The mask design can be considered similar to adding granularity to the view of the user, which was already found to improve visual search compared to FOV restrictors [7]. Moreover, we think that the efficient nose RF performance is due to it promoting better stability of the user's eye gaze during the in-VR task as was shown before in the literature [11, 54, 94–96]. Additionally, the hat under-performed excessively at 6m distance compared to the remaining RFs and control condition. This could be due to its location in the upper peripheral view of the user and its effect of shadow and reflection casting not improving distance perception. In real life, a hat can help improve contrast and minimize glare, which can help assess visual input better, however, that seems not to apply in VR. Additionally, even though the hat was designed with the consideration of not restricting much of the user's FOV, this RF covered a portion of the user's upper view, which one may argue is similar to FOV restriction. This could contribute to reducing environmental and depth contexts, which was already found to cause distance underestimation compared to having a large FOV [5, 16, 41, 59]. Furthermore, the placement of the hat in the upper FOV also relates to vertical FOV and its impact on distance perception, which was already found to contribute minimally to improving distance judgments compared to the horizontal FOV [29, 57, 59].

The RFs placement relative to the VR camera was set to resemble a real life setting. However, we suspect that changing the positioning of RFs might alter their effect on distance judgments since that would cause a change in the perception of the VE and a change in the FOV. Additionally, our results show that the RFs effect on distance judgment is potentially independent of environment type, however, a future study with a larger participant pool is needed to confirm this finding. Moreover, the nose and mask RFs effect on distance judgment was significantly different between the cluttered and uncluttered conditions. These two RFs worked better with the presence of clutter in the VEs, however, this effect was not observed for the hat RF (see Figure 4.5). A follow-up investigation to better explain these observations is needed to uncover more concrete conclusions.

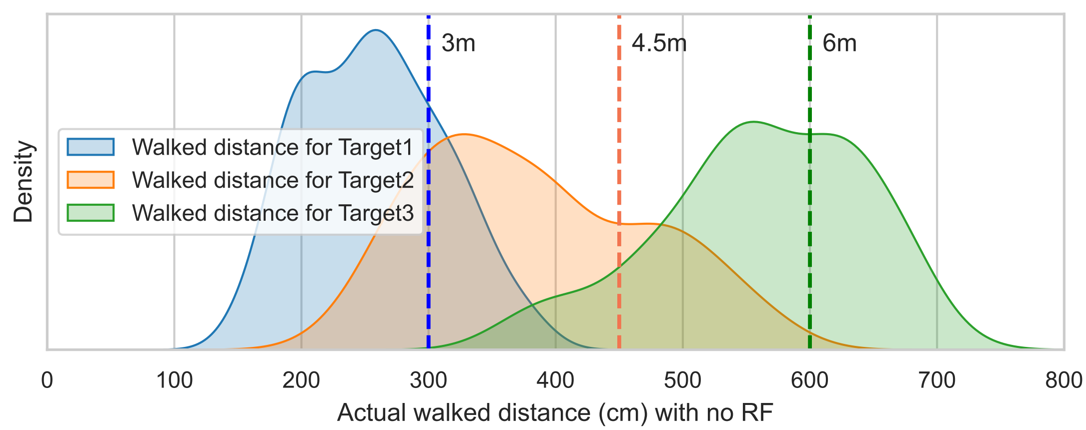



Figure 5.1: Distance estimation distributions (no RF) around respective actual targets (vertical dashed lines).

We discussed our reasoning regarding why the hat caused more underestimation at the 6m distance, however, even if the other RFs did not have a significant difference from the control condition at 6m, they also evolved in an interesting way as the target distance increased (see Figure 4.6). The mask RF distance error almost doubles from 3m to 6m, which we expected considering that the number of depth cues reduces with increased distance. The nose RF had an error distance that was approximately the same across all targets, which we mainly attribute to the perceptual filling-in phenomenon (see Section "Informal Interview Implications" in Chapter 5). Another phenomenon we observed is the no RF condition having the largest error at 4.5m, compared to the 3m and 6m distances. Figure 5.1 shows the distribution of distance estimations in the no RF condition. The distribution for the 4.5m looks slightly bimodal, which may suggest that participants mistook it for the 3m target. One possible reason for this phenomenon could be justified by recent findings from the visual perception field, indicating that visual stimuli seen a moment ago influence what we perceive in the present [71], and when perceiving distances to similar objects, participants rely on the mean of previously observed locations [32]. Furthermore, to better assess any potential ordering or learning effects on the obtained results, we decided to visualize the error distance raw data collected per participant per trial, and overall the participant performance got better with time. This was not expected considering that no explicit feedback was provided to participants at the end of the trial, which is rather surprising for a distance estimation task. However, similar learning effect patterns were observed in prior findings (i.e. [61, 74]) with the distance error improving over the first few trials after which the distance error starts to only depend on the conditions, and we think that the learning effect recorded might be due to participants walking more naturally and gaining more confidence and velocity with time as was pointed out by Philbeck et al. [74].

### *Effect of Clutter and Environment Type*

We did not find a significant difference between distance estimation indoors and outdoors, which is unexpected as prior work suggests that egocentric distance underestimation is less apparent indoors compared to outdoors [16, 17, 59]. This could be simply due to the environment type being a between-subject factor, requiring a larger sample size to uncover a significant difference between conditions, however, we also suspect that the blind-walking task isn't responsive enough to capture the effect of the environment type. Specifically, when viewing displayed content, participants mostly focused on the target, sometimes without even looking around to view their surroundings. Additional work is needed to better understand how spatial information indoors and outdoors is perceived by humans for egocentric distance estimation.

We found a significant difference between the cluttered and uncluttered conditions, with the distance underestimation being reduced by 21% in cluttered environments (see Figure 4.3), confirming prior findings [58,59,70]. We relate this effect to the presence of more depth cues in the VE, as it was found that distance judgments improve with the presence of more depth cues [75,82]. In the uncluttered condition, participants had a wider horizon to view and fewer visual cues and reference points to effectively judge distance. In our experiment the VE clutter was more prominent in the surroundings of the walking path of the user and beyond the target. No objects were placed on the walking line from the user to the target disk on the floor, as such clutter could hide the target or be perceived as obstacles. It is unknown how this could affect user behavior, and future work should assess the impact that clutter can have on egocentric distance perception when different densities of objects are placed directly on the walking path of the user. Another interesting finding is the effect of clutter being most apparent at 4.5m, and additional work that varies clutter across different distances is needed to help explain this finding.

### *Informal Interview Implications*

Based on the results of the informal interviews, all users found the graphics quality consistent across the experiment and were comfortable whenever the head-centric RFs were enabled in the VE. This finding suggests that our RFs were not an obstacle to intuitive user behavior in the VE, and did not cause discomfort. In addition, **78.57%** of participants reported not seeing the nose RF enabled in the VE, whereas **21.43%** affirmed seeing the nose RF added during the experiment.

Additionally, the participants that did not notice the nose also did not inquire about having a gray object located in their bottom view, thus, this indicates that users not viewing a nose can directly be attributed to them not noticing it. This finding is interesting as it could mean that the same effect of perceptual filling-in [34] that makes people not notice their nose on a regular basis in real life also filters out the nose in VR. Nevertheless, additional work is needed to explain this finding along with the potential effects of perceptual filling-in in VR.

This finding along with the significant impact of the nose RF and mask RF on distance perception suggests that in the absence of a full avatar, which was found to improve distance estimation in VR [46, 61, 64], head-centric RFs, especially the nose and the mask, can help promote more accurate distance judgments overall. At the same time, the nose is barely noticeable by users, is simple to implement, and reduces distance underestimation overall. Thus, in the case where the FOV can only be modified minimally, the nose would be a good RF choice. For a game setting, the mask RF is a better fit as in addition to being very efficient at improving distance judgment overall, it has a more gamified appearance. Some participants also pointed out that the black lines of the mask can be made thicker and darker. However, additional work should be done to see if the mask RF will have a similar or different impact on egocentric distance judgments when its design characteristics are changed.

# CHAPTER 6: LIMITATIONS AND FUTURE WORK

Future investigations should conduct similar studies with different HMDs and FOV settings, considering that the appearance of our RFs can change when vertical or horizontal FOVs are modified. In addition, we used a VR backpack system, and future investigations could execute the same task with commercial headsets that have smaller FOVs than the Pimax 5k+, and that do not require a battery-equipped backpack. Additionally, we managed to get enough participants to obtain statistical significance and support our statistical power and analysis, however, it was difficult to recruit participants willing to engage in a substantial number of trials requiring physical effort. While our study is an initial exploration, future work can consider exploring the effect of head-centric RFs on egocentric distance perception with a broader representation of age, gender, and VR experience level in different settings from the mixed reality spectrum.

Additionally, our study is an exploratory study aimed at generating new insights about the use of head-centric RFs in a distance judgment task. Thus, we focused on the within-subject variables and opted for a number of participants that was enough to get statistical significance and pave the path for large-scale future investigations that rely on the use of RFs. Additionally, making the environment type a within-subject factor would have resulted in over 250 trials of walking. Consequently, we kept the environment as a between-subject factor for applicability purposes. In our future work, we plan to carefully design a study where the environment would be within-subject. Moreover, as we applied several adequate corrections during our analysis (i.e. Bonferroni, Cousineau, and Morey) we ensured that the significance and effects we found are not due to chance or noise in the data.

Head-centric RFs are quick to implement and do not cause major changes to the VE appearance. Future work can evaluate user preferences to determine whether RFs should be enabled by default or remain optional settings. Moreover, we used three static head-centric RFs, and an interesting idea to investigate is the effect of additional head-centric and non-head-centric RFs (i.e. virtual avatars, guidance arrows/lines, virtual hands) on egocentric distance perception and contrast it to our findings. Comparing the effects of both RFs and full avatar will inform the design of VR systems, as developers could spend less time designing applications while still receiving the benefits of improved distance judgments through head-centric RFs. Moreover, we used a neutral color for the nose RF, and future work can set the nose color based on the skin tone of the user to assess if further improvements in egocentric distance judgment can be reached. In the future, we plan to create several nose models with different colors to better represent the participant pool.

Comfort, embodiment, and ownership in the VE when RFs are used should also be investigated further. Moreover, we defined clutter in our experiment as object density, yet its definition can differ based on the context, which allows further possible interpretations in future studies. Some of the clutter definitions that can be evaluated consist of auditory clutter, which refers to an abundant amount of noise and sound that can impact the user and their in-VR task performance, and cognitive clutter, which relates to the mental processing of information needed by the user to perform the in-VR task or different actions in the VE, other physical and visual clutter types can also be evaluated such as varying the amount of light, shadows, granularity in the VE and so forth and so on. Furthermore, we plan to investigate the effect head-centric RFs have in other use cases where accurate spatial perception and eye-gaze focus matter, such as in selection tasks in dense and occluded VEs [9, 35, 56, 103], or on height perception [2], to better generalize their efficiency on overall spatial perception in VR.

# CHAPTER 7: CONCLUSION

In this investigation, we explored the effects of head-centric RFs on egocentric distance perception through a blind-walking task in a mixed-design study. The head-centric RFs used in our investigation included *a virtual nose, a mesh mask, and a hat*. Literature relevant to this topic suggests that RFs are efficient sickness mitigation techniques in VR, however, prior work did not investigate the effect of their application on egocentric distance perception. We found that using some head-centric RFs reduced distance underestimation for the near-field and mid-field distances (3m, 4.5m), whereas for far distances (6m) RFs either performed similarly, or under-performed compared to the no RF condition. We also found that the presence of clutter improves distance judgment. We conclude that RFs offer cost-savvy means to improving distance estimation in VR applications and our research findings contribute to leveraging the use of head-centric RFs in VR applications, systems, and immersive user experiences.

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