Display Size does not Affect Egocentric Distance Perception of Naturalistic Stimuli

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CR Categories: H.1.2 [Models and Principles]: User/Machine Systems—Human factors, Human information processing H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities J.4 [Social and Behavioral Sciences]: Psychology

Keywords: distance perception, virtual reality, misperception, HMD, display size, indirect walking

Abstract

Although people are quite accurate in visually perceiving absolute egocentric distances in real environments up to 20m, they usually underestimate distances in virtual environments presented through head-mounted displays (HMDs). Several previous studies examined different potential factors, but none of these factors could convincingly explain the observed distance compressionin HMDs. In this study, we investigated the potential influence of naturalistic stimulus presentation and display size – a factor largely overlooked in previous studies. To this end, we used an indirect blindfolded walking task to previously-seen targets. Participants viewed photos of targets located at various distances on the ground through different-sized displays (HMD, 24" monitor, and 50" screen) and walked without vision to where they thought the location of the target was. Real-world photographs were used to avoid potential artifacts of computer-graphics stimuli. Displays were positioned to provide identical fields of view ($32^o \times 24^o$). Distance judgments were unexpectedly highly accurate and showed no signs of distance compression for any of the displays. Moreover, display size did not affect distance perception, and performance was virtually identical to a real world baseline, where real-world targets were viewed through $32^o \times 24^o$ field of view restrictors. A careful analysis of potential underlying factors suggests that the typically-observed distance compression for HMDs might be overcome by using naturalistic real-world stimuli. This might also explain why display size did not affect distance judgments.

1 Introduction

Due to the possibility of running tightly controlled and reproducible experiments with naturalistic multi-modal stimuli, virtual reality (VR) is used increasingly as a versatile tool for human perceptual and behavioral experiments. Possibly because of the high quality of modern computer graphics, it is often simply *assumed* that humans perceive and behave similarly in real and virtual environments – which is essential for the usefulness and effectiveness of these techniques. There is, however, accumulating evidence of considerable systematic misperception in VR, in particular in terms of egocentric distance perception: When users are asked to judge distance in virtual environments presented via a head-mounted display (HMD), they typically underestimate distances by as much as a factor of two (see [Loomis and Knapp 2003] for an excellent review). This is in striking contrast to real-world distance perception, which seems to be almost perfect for distances up to about 20m. What do these perceptual differences in real versus virtual environments stem from? The current study was designed to investigate some of the potential underlying factors, in particular the importance of naturalistic stimulus presentation in VR and the effect of display type.

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While there is consistent evidence for underestimation of egocentric distances when presented via HMDs, the source of underestimation is still not clear, and there seems to be converging evidence that there is not one single factor responsible for the observed distance compression. [Loomis and Knapp 2003; Witmer and Sadowski 1998]. For example, Thompson et al. examined the effect of low-quality computer graphics on distance perception in virtual immersive environments through blindfolded walking tasks and found that even a photorealistic image of real environment viewed on HMDs does not reduce the distance underestimation in virtual environments [Thompson et al. 2004]. Despite extensive research efforts using HMDs, surprisingly little effort has been spent on understanding the effect of the physical size of a display on egocentric distance perception. Plumert et al. showed that distance perception in virtual environment with large immersive display is similar to distance perception in a real environment [Plumert et al. 2005]. They used a very large screen (305×244 cm) in the virtual environment experiment and used people's time-to-walk estimates (converted into distances) instead of using tasks that are more common in distance perception experiments (verbal report, direct walking, or indirect walking). The discrepancy of this result with previous studies in distance perception in virtual environment may suggest that the distance compression observed for HMDs might be a result of the small FOV and/or the small size of LCD panels in HMDs. The time-to-walk measure they used might also have contributed, although experiment 3 showed that time-to-walk and blindfolded walking measures yield similar responses, at least for real world stimuli. Even though Tan et al. demonstrated that increasing screen size while keeping the physical FOV constant can increase performance a variety of spatial tasks [Tan et al. 2006], so far nobody has directly compared the effect of display size on ego-centric distance perception. The current study was designed to close this gap. To this end, we conducted an experiment in which observers judged the distances of targets presented on different-sized displays (HMD, regular 24" LCD Monitor, and a 50" inch large screen) using an indirect blindfolded walking paradigm and a constant physical FOV.

2 Method

Our study was designed to investigate whether presenting a natural environment to the users through different-sized displays can influence their egocentric distance perception. To ensure that we are indeed testing the effect of display size without any confounds of computer graphics rendering quality, we used actual photographs of a real scene instead of computer graphics renderings. This allowed us to also assess if the typically observed distance compression in VR might be ameliorated by using photorealistic real-world stimuli. A real-world condition was included as a baseline.

Participants Twelve graduate students aged 22-32 (6 females, 6 males) voluntarily participated in the experiment. None of them had ever seen the experiment room before. All participants had normal or corrected-to-normal vision.

Stimuli and Apparatus Egocentric target distances were presented using non-stereoscopic real-world photographs of a circular red foam disk 27 cm in diameter which was placed on the ground at the distances of 4, 5.5, and 7 meters, as illustrated in Figure 1 (top). Three different-sized screens were used: For the HMD condition, an eMagin Z800 3DVisor with $32^o \times 24^o$ FOV and a resolution of 800× 600 pixels in each eye was used. The mid-sized display was a regular 24" LCD monitor (Dell/2408WFP, image size 42 cm × 32 cm) and the large-sized display was a 50" LCD screen (Nec/50XM2A, image size 80 cm × 60 cm). In order to provide a constant FOV for all three displays, the LCD monitor and the large screen were positioned such that they were seen under the same physical FOV of $32^o \times 24^o$ as the HMD. Furthermore, to simulate the restricted field-of-view of the HMD for the other two displays and for the real-world condition, a field-of-view restrictor with the same $32^o \times 24^o$ FOV as the HMD was built and used in all but the HMD conditions (Fig. 1 (bottom)). The simulated (image) FOV of $32^o \times 24^o$ matched the physical FOV under which the displays were viewed. Instead of taking photos for different eye-heights to reflect different people's actual eye-height [Thompson et al. 2004], participants were seated during the stimulus presentation and asked to rest their chin on a box located in front of their chair where the field-of-view restrictor and HMD was set up. This ensured that participants' physical eye-height was always kept at 110cm from the ground and thus matched the camera height of 110 cm used for the stimuli. The other purpose of this setup was to prevent users from moving their heads, thus allowing for the same FOV for each display, and to avoid the possible effect of motion parallax. Note that the HMD was mounted to the apparatus and not head-mounted, to provide the same constant viewing conditions as the LCD monitor and large screen. In the real-world baseline condition which occurred after the display conditions, participants were seated behind the same FOV restrictors and observed the actual lab with the same red disk positioned as in Figure 1, instead of a photograph. Each part of the experiment (except the real-world condition) was conducted in a darkened room and the area around the displays and starting position was covered by thick curtain to avoid any possible visual cue from the environment (see Fig. 1). Another curtain was covering the floor of this area to conceal the floor tiles.

Procedure After receiving written and verbal instructions, participants practiced blind-folded walking in a different room for about 5 minutes. They were then blindfolded and guided to the experiment room. For each trial, participants were seated and positioned their head on the chin rest, in front of the HMD or FOV restrictors. Once participants confirmed that a good image of scene has been observed, they were asked to close their eyes, put on the blind-fold, stand up, step to the side (see Fig. 1, (a)), and walk with the guidance of the experimenter through the now-opened curtain until being stopped by the experimenter (see Fig. 1, (b)). This indirect walking procedure was necessary to ensure that participants can pass the set-up displays safely and also ensured that participants could not pre-plan their path or motor action [Willemsen et al. 2004]. Participants were then asked to turn to face the target, walk to the previously-seen target location, and stop (c). After measuring the participant's end position, the experimenter led participants (who were still blindfolded) back to the starting location for the next trial. Participants in the HMD condition performed the same task as for the other two display conditions, except that they looked through the HMD instead of the FOV restrictor. We avoided mounting the HMD on participant's head to reduce the time between seeing the target and starting to walk. Once participants completed the

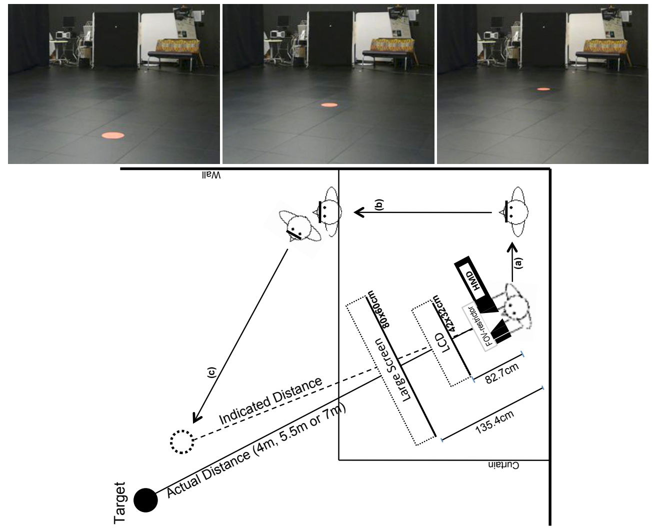

Figure 1: ***Top:*** *Three different pictures used in the distance perception experiment, displaying targets (red circular foam pads on the floor) at a distance of 4m, 5.5m, and 7m. Pictures are gamma-corrected for printing purposes.* ***Bottom:*** *Top-down schematic view of the experimental setup and indirect walking procedure.*

tasks for all three displays and distances, they were asked to perform a similar indirect walking task in a fully lit, real-world condition. We conducted the real-world trials after completing display trials since previous research had shown that distance perception in VR can be considerably affected if people experience the real world condition first [Plumert et al. 2005]. In the real-world condition, participants viewed the real environment through the same FOV restrictor as before and performed the same indirect walking task (cf. Fig. 1). The overall procedure (including breaks between display conditions) took about 45 minutes.

Experiment design Participants completed two sessions: In the **display session**, participants performed 9 trials, consisting of a factorial combination of 3 displays (HMD, LCD monitor, large screen; blocked) × 3 target distances (4m, 5.5m, 7m; randomized order). The order of the display condition blocks was balanced across participants to avoid systematic order effects. In the subsequent **real-world session**, participants performed 3 additional trials, one for each of the three distances (4m, 5.5m, 7m) in randomized order. Perceived distance was estimated as the distance between the initial viewing position and the endpoint of the participant's walking trajectory, and will henceforth be referred to as "indicated distance" (cf. Fig. 1).

3 Results and Discussion

As shown in Figure 2 (left), the distances people walked without vision were very similar regardless of the display presenting the distances, and closely resembled the data from the real world condition. Figure 3 confirms this and highlights the overall high accuracy and lack of any consistent over- or underestimation of distances for any of the conditions tested: The ratio between indicated distance (which is an estimate of perceived distance) and actual distance is on average very close to 100%, indicating only minimal over- or undershooting of distances. Mean values for the different visualization conditions were 99.45% for the HMD, 98.98% for the LCD monitor, 98.64% for the large display and 95.98% for the real world condition. To test for any significant effects or interactions,

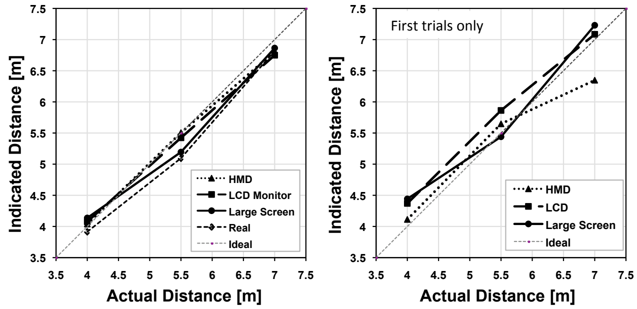

Figure 2: ***Left:*** *Mean indicated distances for the different displays and the real world condition. Note the overall high accuracy and lack of any systematic distance compression for all display conditions.* ***Right:*** *Mean indicated distances for the* first viewed display condition *only, where each line contains the mean data of the four participants that were tested with a given display first, thus eliminating transfer and learning effects for the later display conditions.*

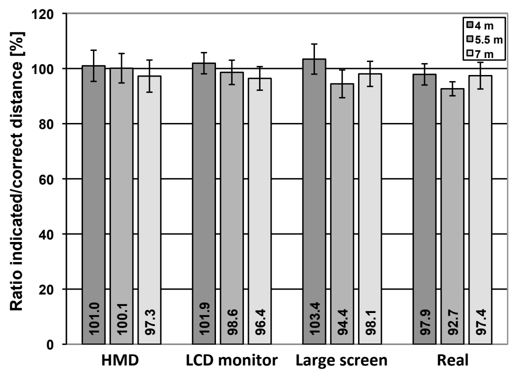

Figure 3: *Mean percentage of indicated vs. correct distance. 100% indicates perfect performance (no under/overshoot). Error bars depict ± 1 SEM. Note the high overall accuracy and lack of any clear differences between the display conditions or distances used.*

a 4 (viewing condition: HMD, monitor, large screen, real world; blocked) × 3 (distance: 4m, 5.5m, 7m; randomized) repeated measure ANOVA with environment and distance as within-subject variables was performed on the ratio between participant's indicated and the correct distance data (i.e., the data presented in Fig. 3). As suggested by the data plots, there was no significant effect of viewing condition or distance and no significant interaction (see Table 1). In summary, our data suggests that perceived egocentric distances are (for the current stimuli and procedures) independent of the physical size of the display through which the environment is viewed, at least when they are viewed at the same physical FOV. Moreover, there was no noteworthy tendency to underestimate distances presented via HMD, and performance equaled real-world performance. These results are surprising given the fact that previous studies indicated that people usually underestimate distances in virtual environment using HMDs. In the following, we will discuss several factors that might have contributed to this apparent contradiction with previous work.

Eye height and perceived angular declination below horizon The observer's eye height is one of the main differences between the current study and previous distance perception studies that reported distance underestimation for HMDs. While previous studies typically used standing observers and matched the simulated/depicted eye height accordingly, we used seated observers and a constant

	Ratio indicated/correct distance		
		p	η_p^2
Viewing condition	$F(3,33) = 0.340$	.797	.030
Distance	$F(2,22) = 2.246$	.129	.170
Viewing cond. × distance	$F(6,66) = 0.667$	.677	.057

Table 1: *ANOVA results showing the lack of any significant effects or interactions. The effect strengths partial eta squared (η_p^2) indicates the percentage of variance explained by a given factor, and suggests here that neither viewing condition nor target distance can explain a noteworthy portion of the observed variance.*

(physical and simulated/depicted) eye height of 1.1m[1]. We are not aware of any study that directly compared different eye heights for distance perception in HMDs, and it is thus possible that the reduced eye height in the current study might have affected distance estimates. In an influential study, Ooi et al. demonstrated that distance perception depends partly on the perceived angular declination below the horizon [Ooi et al. 2001], thus corroborating earlier results by [Philbeck and Loomis 1997]. Furthermore, Ooi et al. argued that perceived eye height is used by our visual system as a reference value for computing angular declination below the horizon. While it is feasible that the current procedure could have resulted in a misperceived angular declination and/or eye height, possibly due to a misperceived horizon, it seems plausible that such misperception should have occurred similarly in all viewing conditions (due to using the same chin rest, fixed viewing position and eye height, and FOV restriction). Hence, this hypothesis cannot easily account for the finding that distances in the current study were reported accurately for both the real-world and all of the display conditions.

3-segment indirect walking procedure Our procedure required participants to walk on a 3-segment path around the displays and FOV restrictor, whereas much of the previous literature used direct or 2-segment paths. It seems rather unlikely, though, that our walking procedure could have caused much systematic distortion of results, given that previous research found that blind walking distance estimates are quite robust against changes in procedure and path layout [Philbeck et al. 1997; Loomis and Knapp 2003].

Familiarity with the real environment Previous exposure to the real environment has been shown to affect distance judgements in a virtual replica of the environment [Ziemer et al. 2009; Interrante et al. 2008]. In the current study, however, such familiarity effects can be excluded, as none of the participants had previously seen the experimental room, and that they never saw the actual experimental room other than through the pictures presented on the displays or through the FOV restrictors in the subsequent real-world condition.

Learning effect and limited number of stimuli A potential limitation of this study is that we used the same stimuli (one image for each of the three target distances) for the different display conditions. While none of the participants reported using this strategy, it is still possible that they somehow realized the image similarity and memorized the distances which they walked for each image and somehow tried to reproduce it for the different displays. If true, this might account for the similarity in the data between the three displays. It cannot, however, explain the overall high accuracy and lack of any distance compression in the display conditions. To further investigate this potential confound, we plotted participants' indicated distances just for displays which were presented first, i.e.,

[1]Due to combination of using a small FOV and different displays including two stationary monitors, we could not allow for head motions to explore the depicted scene. As we needed the floor to be visible at distances beyond about 3m, we decided to lower the simulated/depicted eye height accordingly, which resulted in a comfortable sitting eye height of 1.1m.

the conditions where participants saw each of the three images first (Fig. 2, right) and compared it with the full data set (Fig. 2, left). The overall similarity in results, and the fact that there were no repetitions of conditions, make it seem unlikely that the learning effect due to the uniformity of images per distance was fully responsible for the similar results between the different displays.

Combination of restricted head motion and limited FOV Participants in our study did not rotate their heads and thus could not explore different views of the environment, which might have affected distance perception. In fact, Creem-Regehr et al. showed in a real-world distance perception study that the combination of a restricted FOV and prohibiting participants from rotating their head yielded an underestimation of real-world distances, although neither FOV restriction nor limited head-motions themselves resulted in any such underestimation [Creem-Regehr et al. 2005]. This predicts that participants in the current experiment should also have underperceived distances in all conditions, as the FOV was always restricted and head-motions were discouraged. Interestingly, though, we did not observe any noteworthy distance compression for any of the viewing conditions. This suggests that other factors might have compensated for the effect of restricted head motion and FOV and allowed for accurate distance perception.

High-fidelity replica of real environment instead of computer graphics rendering Unlike previous studies which used computer graphics generated scenes, we presented participants with static high-quality photographs of the real environment. As Loomis and [Loomis and Knapp 2003] suggested, viewing a replica of real world with natural textures and illumination which people are more familiar with might provide a better sense of presence and lead to better distance perception. However, Thompson et al. reported that distance underestimation did not improve significantly when using photorealistic panoramic images of a real environment as compared to low quality computer graphics or a simple wireframe rendering of the same scene [Thompson et al. 2004]. It remains puzzling that our study with restricted viewing conditions reported no distance compression for photorealistic cues, whereas [Thompson et al. 2004] reported a compression by more than 50%, despite allowing head movements. Another study that used real-world stimuli examined the accuracy of distance estimation in two real-world conditions (restricted FOV and unrestricted viewing) and an HMD condition using a visually directed walking task [Messing and Durgin 2005]. In the HMD condition, people were viewing a video of the real environment captured by a video camera attached to the left side of the HMD. Consistent with previous studies, people accurately walked to the target in the real-world condition, irrespective of FOV restriction. However, they walked only about 77% of the actual distance when the HMD presented live video images of the real environment. Although as [Thompson et al. 2004] they argued that presenting a high-fidelity replica of the real world cannot considerably improve the distance underestimation in immersive virtual environment using HMD, there are some potential confounds in their experiment which might have affected the results. These include the limited resolution of their HMD (640$\times$480) and the considerable video delay of >433ms and the horizontal offset of $\geq$10cm between the video camera and participant's eyes. Furthermore, the attached video camera added more weight and inertia to the HMD, and these factors are known to contribute to distance underestimation [Willemsen et al. 2004]. Comparing our study with the results from [Thompson et al. 2004] and [Messing and Durgin 2005] which both used real-world stimuli but allowed for head motions might suggest that the delays and and other imperfections in motion tracking of HMDs could potentially contribute to distance misperception in VR. Further carefully designed studies are needed, though, to test this and other related hypotheses. In fact, it is likely that there is no single factor that can sufficiently explain the well-established phenomenon of distance underestimation in HMDs. Instead, we propose that only an interaction between several (seemingly unrelated) factors might be able to fully account for perceptual phenomena like distance perception.

Conclusion In this study, we hypothesized that presenting a virtual environment through larger screens (while using the same FOV) might improve egocentric distance perception compared to viewing the environment through HMDs. Using an indirect blind walking measure to assess participant's perceived distance, we unexpectedly found no such effects. In fact, participants showed on average quite accurate performance and no signs of distance compression, irrespective of whether they saw a real-world scene or a photograph thereof displayed using an HMD, a computer monitor, or a large screen. While further experimentation is needed to extend and corroborate these findings, the current results suggest that presenting a photorealistic replication of real environment might, under certain conditions, be sufficient to eliminate the considerable distance compression that is commonly found for HMDs. Thus, we might not need more elaborate and expensive VR equipment to allow for veridical spatial perception in VR, but rather more veridical and perceptually effective virtual environments.

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