Stereoscopic Egocentric Distance Perception: The Impact of Eye Height and Display Devices

José G. P. Corujeira *
M-ITI, Portugal

Ian Oakley †
UNIST, Ulsan, Republic of Korea

Abstract

Stereoscopic displays can simulate the perception of depth information, potentially increasing human distance perception in remote viewing scenarios such as those involved in robotic tele-operation. However, distance perception is a complex perceptual task that is not yet fully understood. Two current research issues are how different stereoscopic displays and viewing heights affect egocentric distance perception. This paper describes an experiment conducted to investigate these issues. It compared distance perception in a real environment with that in identical visual scenes observed through an HMD and 3D Stereo Display. Other parameters, notably field of view, were tightly controlled. Motivated by fact that many tele-operation scenarios involve near ground viewing positions (due to the fact that many robots are small), the study also explored the impact of viewing height (at 20 cm and 110 cm) on distance perception. Results indicated substantial under-estimation of distance across all conditions. Interesting, low eye-height led to a significant reduction in the level of underestimation in the HMD and 3D Stereo Display, a variation that may be due to changes in the perceived height of the horizon in the real world 20 cm viewing height condition, compared to the fixed height of the perceived horizon in the videos shown on the HMD and 3D Stereo Display.

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Keywords: Distance perception, egocentric distance perception, distance estimation, head-mounted displays, HMD, 3D stereo displays, eye height

1 Introduction

Stereoscopic displays, systems in which a users eyes are presented with images from slightly offset perspectives in order to mimic real world depth perception, present a range of alluring prospects and application areas. Indeed, 3D displays are already established as a mainstream technology in cinemas, TVs and computer gaming[Kulshreshth et al. 2012]. Fundamentally driving the rapid roll-out of this technology is the idea that 3D displays evoke greater levels of immersion in audience members or game players[Yang et al. 2011] - they more accurately mimic the real world, better drawing in their viewers to the content they show. This notion is valuable, but insufficiently detailed for more demanding application scenarios. For instance, in applications such as remote robotic control[Marques et al. 2006] stereoscopic displays have the potential to enhance depth perception[Livatino et al. 2009], allowing more accurate estimation of range of key targets or objects and other related aspects.

In such scenarios, the goal is to display stereoscopic video feeds to operators so that they are able to apply their highly accurate real world depth perception skills [Creem-Regehr et al. 2005] to the remote robotically mediated environment. However, the set of technical and perceptual requirements that must be met to precisely achieve this are demanding and not yet fully understood. For example, fundamental technical challenges include the display of stereoscopic images in such a way that eyestrain due to disparities between accommodation of the lens and convergence of the eyes are avoided [Loomis et al. 1999; Creem-Regehr et al. 2005] Such problems are partly due to hardware issues such as the fixed effective viewing distance to the displays, the distortion of the binocular disparity by the optics (or image misalignment) and the inhibition of motion parallax [Creem-Regehr et al. 2005]. In work exemplifying the complexity of these issues, Piryankova et al. [Piryankova et al. 2013] observed that implementing either stereoscopic projection or motion parallax leads to a deterioration in the accuracy of distance estimates when head movements are allowed. Other research highlights gaps in our knowledge of the human perceptual system. For example, Livatino et al. [Livatino et al. 2009] showed that egocentric distance estimation improves with stereoscopic visualization and that on a 3D desktop monitor the percentage of improvement was higher than when using a Head-Mounted Display (HMD). A full explanation for these differences was beyond the scope of the study and, indeed, work to provide accounts for such variations continues today (e.g. [Piryankova et al. 2013]). This paper aims to contribute to this on-going effort. Specifically, it seeks to compare stereoscopic display devices under highly controlled conditions in order to shed light on precisely what qualities of these display devices influence perceptual performance.

This paper also notes that important aspects of the tele-operation application scenario of remotely controlling a robot have not received attention in prior work on stereoscopic displays. One of the most prominent of these relates to the height of the observation point. Quite simply, many land-based remotely operated robots are small [Marques et al. 2006] [Doroodgar et al. 2010], featuring cameras and other sensors mounted at ten to twenty centimeters from the ground, a substantial departure from normal human eye-height, a viewpoint that has been the focus of much of the existing literature on distance perception performance. Reasons for constructing robots with such diminutive statures include practical concerns such as reduced weight and complexity, improved stability and balance, as well as application level constraints[Messina and Jacoff 2007]. For example, in Search and Rescue (SAR) tasks [Linder et al. 2010; Casper and Murphy 2003], robots may be required to enter into areas that would be too small for humans; a diminutive size is clearly beneficial. This paper argues that in critical tasks such as robotic tele-operation, the impact of such variations on an operators performance matter. Indeed, this assertion is supported by prior research suggesting that the variations to the viewer's eye height can influence distance judgements [Leyrer et al. 2011]. The work in this paper seeks to elaborate and better quantify this data.

*e-mail: corujeirat@gmail.com
†e-mail: ian.r.oakley@gmail.com

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In summary, this paper seeks to extend the literature on depth perception in stereoscopic displays in two ways. Firstly, it seeks to extend and clarify prior findings through a rigorously controlled study that can cast light on the specific factors that influence perception through different stereoscopic display devices. Secondly, it seeks to extend this work by investigating how changes in eye height (and therefore visual perspective) impact egocentric distance perception. Before describing the study investigating these issues, the following section provides an overview of prior work on this topic.

2 Related Work

A substantial body of work has explored how Egocentric Distance Perception (EDP) is influenced by display modality (e.g. [Grechkin et al. 2010; Messing and Durgin 2005; Piryankova et al. 2013; Plumert et al. 2005; Riecke et al. 2009; Steinicke et al. 2009; Dixon et al. 2000]). Real world perception is typically reported to be highly accurate for distances up to 15 meters [Plumert et al. 2005], whereas performance with scenes rendered on Large Screen Immersive Displays (LSID) or HMDs results in substantial underestimation at distances between two meters and seven meters [Grechkin et al. 2010], a distortion typically characterised as linear [Messing and Durgin 2005]. In contrast, for distances closer than two meters, overestimation of distances is reported [Philbeck et al. 1997]. A number of candidate explanations for these findings have been advanced. For example, many display systems offer a Field of View (FOV) considerable lower than that of the human visual system (approximately 200° horizontal by 135° to 150° vertical [Creem-Regehr et al. 2005; Wandell 1995]. Typical figures for an HMD are between 20° and 80° diagonally (e.g. [Riecke et al. 2009; Messing and Durgin 2005] and research has indicated that this reduced FOV affects participants' ability to perceive egocentric distances when head motions are not permitted [Creem-Regehr et al. 2005]. This effect is attributed to a reduction in perspective cues in peripheral vision [Kline and Witmer 1996].

An alternative explanation, proposed by Warren et al. and supported by Willemsen et al. [Warren et al. 1990; Willemsen et al. 2004] suggests that the encumbrance of wearing an HMD may cause the EDP underestimation, due to the shift its weight causes in the centre of mass and inertia of the participant's head during walking. This notion was validated in [Grechkin et al. 2010] experiment which compared two distance estimation measurement protocols (blind walking and time imagined walking) and showed greater distance underestimation during the blind walking protocol, where participants have to physically pace out distances, against timed imagined walking, which is a purely mental exercise of envisaging how long it would take to reach an observed distance by walking to it.

However, results from studies of LSIDs, such as immersive CAVE environments, furthermore complicate this picture. They typically provide a FOV that approximates that of natural vision and may involve relatively lightweight head mounted equipment. Nevertheless participants still exhibit similar underestimation biases during distance estimation tasks [Grechkin et al. 2010; Piryankova et al. 2013] suggesting that neither display FOV or equipment weight may not be cause (or at least the sole cause) of this effect. For instance, in a recent investigation of this issue, Piryankova et al.[Piryankova et al. 2013] looked at how EDP varied across three different LSID setups (semi-spherical, MPI cabin and stereoscopic flat). They found underestimation in all three LSIDs, and reported that estimation accuracy is influenced by distance to target in both real and virtual environments. In contrast, in a comprehensive and similarly motivated study attempting to cast light on the disparate EDP findings across different display devices, Riecke et al. [Riecke et al. 2009] compared three display devices (a 50" screen, a 24" monitor and a HMD while simulating a constant FOV of 32° horizontal by 24° vertical). They found very little variation in EDP and that performance with the displays was close to that in real world perception. One possible explanation for this discrepancy with prior work is that Riecke's study used a relatively complex experimental environment a typical office space featuring furniture, a regular floor tile pattern and other highly recognizable features that participants could have been previously exposed to. This stands in contrast to prior work that has taken place in highly controlled visual environments and serves to highlight that the perceptual processes underlying distance perception are complex and not yet fully understood.

One cue that has attracted considerable attention for its role in distance estimation is the presence of, and perspective provided by, the ground plane between an observer and a visual target. A range of work on this topic exists. For instance, in an examination of real world perception, Creem-Regehr et al. [Creem-Regehr et al. 2005] investigated the impact of obscuring sections of the ground proximal to the observer (via participants wearing a collar that obscured the area around their feet) and found no effect on EDP. They concluded that the visible area of the ground plane does not contribute to distance estimation performance. Willemsen et al. [Willemsen et al. 2004] backs up this finding with a broadly similar account.

However, the ground plane may also be used to support accurate acquisition of eye height, a factor thought to contribute to estimations of object size and distance [Dixon et al. 2000; Creem-Regehr et al. 2005]. One possible explanation for this relationship is that the heights of objects can be estimated by establishing how much of the horizon they occlude [Dixon et al. 2000]. Supporting such speculations, changes to eye height have been shown to lead to variations in distance estimations. For instance, Leyrer et al. [Leyrer et al. 2011] performed a study that presented participants with objects in a rich virtual environment and from three different eye heights (normal eye height and 50 cm above and below this level). Their results showed an underestimation of distance with higher, but not lower, viewpoints, an asymmetry the authors suggest may be due to the fact that people are more accustomed to lower perspectives (e.g. while seated) than higher ones and may have developed effective strategies to cope with this commonplace situation. Yet, in contrast to this conclusion, in one of the experiments by Sinai et al. [Sinai et al. 1998] they reported an overestimation of distance judgment when the participants were situated on a 2 m high platform. This effect was attributed to participants exaggerating their eye height in respect to the artificially lowered ground. While these studies do not represent a thorough characterisation of the impact of eye-height on distance perception, they do serve to show its importance in mediating the accuracy of EDP judgements.

Within this area, another focus has been on the angle of declination, the angle between a target and an observer's eye. In a study by Ooi et al. [Ooi et al. 2001] the angle of declination was artificially increased with optical prisms. This led to underestimation of distance, and compared strikingly with subsequent overestimation in normal viewing scenarios. In some of the only work on this topic using digital displays, Messing replicated this effect in a rich virtual environment [Messing and Durgin 2005]; this study used HMDs and showed that lowering the horizon by 1.5° leads to significant underestimation of distance judgements.

In summary, the literature relating to distance perception using technologies such as HMDs is complex. It is clear that aspects of human performance vary in such viewing scenarios, but current evidence and explanations for these effects conflict as often as they agree. For instance, while Leyrer et al. [Leyrer et al. 2011] reports no influence of lower eye height on performance, earlier work by both Ooi et al. [Ooi et al. 2001] and Messing et al. [Messing

Table 1: *The four order conditions used in the study.*

	First	Second	Third	Fourth	Fifth	Sixth
Order 1	HMD / 20	HMD / 110	3DM / 20	3DM / 110	RRW / 20	RRW / 110
Order 2	3DM / 20	3DM / 110	HMD / 20	HMD / 110	RRW / 20	RRW / 110
Order 3	HMD / 110	HMD / 20	3DM / 110	3DM / 20	RRW / 110	RRW / 20
Order 4	3DM / 110	3DM / 20	HMD / 110	HMD / 20	RRW / 110	RRW / 20

and Durgin 2005] on, respectively, angle of inclination and the position of the horizon suggest that manipulations related to the perceived ground plane alter distance estimates. Similarly, although most work suggests that reduced FOVs in virtual display systems leads to underestimation of object distance (e.g. [Kline and Witmer 1996; Loomis and Knapp 2003]), the comprehensive study by Riecke's [Riecke et al. 2009] suggests there is no effect. These variations in findings are made particularly hard to reconcile due to the diversity of experimental conditions and setups between the different studies. This paper aims to address this problem by describing a tightly controlled empirical study that holds some variables constant (e.g. FOV) while systemically adjusting others (e.g. display device and observer perspective). By doing so it hopes to shed light on the data reported in the existing literature and move towards a clearer and more accurate understanding of distance estimation performance with stereoscopic display devices such as HMDs.

3 Method

This study examined two aspects of depth perception in stereoscopic displays. The first was the variability in depth perception across a range of display scenarios and devices that all featured the same, tightly regulated FOV. The goal of this manipulation was to contrast the study data against prior work on this topic that has used a range of both devices and FOVs (e.g. [Riecke et al. 2009; Grechkin et al. 2010]). By maintaining an identical FOV across different displays, we hope to shed light on impact of this parameter in distance perception tasks. The second was the role of viewing height in depth perception. This issue is interesting as, in many remote viewing or control scenarios, camera viewpoints are situated relatively close to the ground (e.g. mounted on relatively short robots [Marques et al. 2006]), while prior perception studies have tended to focus on higher, and more human realistic, viewpoints of approximately 1.6 m (e.g. [Messing and Durgin 2005; Grechkin et al. 2010]). Reflecting the on-going debate regarding the most appropriate metrics to assess distance perception tasks, the study followed a blind walking protocol [Plumert et al. 2005; Grechkin et al. 2010]. Full details of the experimental setup are described in the following sections.

3.1 Participants

Twenty-four people participated in the experiment. They were not compensated. Participants were aged between 23-37 (14 males, 10 females) and 11 had normal vision, 12 had corrected to normal vision and one had corrected to 50% vision. Ten of the participants with corrected vision had myopia, one had astigmatism and the remaining two had both conditions. No participants reported vestibular disorders, but one male participant had muscle dystrophy in both legs. Participants all reported prior experience of stereoscopic displays, primarily from visits to the cinema. No participant had previously visited the experimental space, or seen any of the experimental media, prior to the study.

Three additional participants completed the task, but were excluded from the analysis. One was excluded due to equipment problems: the HMD battery became depleted mid-study, disabling the stereoscopic functionality. The remaining two experienced difficulties with the blind walking task. One participant walked with a large degree of curvature (basically in a circle), disrupting the distance measurement protocol. The other participant consistently walked longer than anticipated distances. Specifically, in five consecutive trials in one condition, the participant walked directly into the wall at the far end of the room (11 meters from the start point). This prevented accurate measurement of the data.

3.2 Design

The study involved three independent variables: display type (three levels: Head Mounted Display (HMD), 3D Monitor (3DM) and Restricted Real World (RRW)), eye height (two levels: 20 cm and 110 cm) and target distance (three levels: 3 meters, 5 meters and 7 meters). These were simply arranged into six blocks of trials covering all display types and eye height and presented using a fully repeated measures design - every participant completed all six blocks. Within each block, all target distances were presented twice, in a random order.

To mitigate practice effects, the experimental design followed past work [Plumert et al. 2005] by always placing RRW blocks last, after the HMD and 3DM blocks had been completed. This was done to prevent knowledge gained during real world perception from influencing performance achieved with the stereoscopic display systems. The order of the HMD and 3DM blocks was balanced among participants. Within these constraints, viewing posture was also fully balanced: half of the participants always experienced 110 cm conditions before 20 cm conditions while the other half experienced the inverse arrangement. This led to a total of four order conditions, as shown in Table 1.

3.3 Apparatus

3.3.1 Stereoscopic Media and Real World Scenes

In order to capture the stereoscopic scenes used in the experiment, a bespoke camera rig was constructed. Two C905 Logitech webcams (1600 by 1200 resolution, focal length of 50mm to infinite, FOV 65° diagonally) were placed within specially designed 3D printed stands (printed with a precision of 0.25 mm). Each stand firmly supported and held the camera and also fully enclosed the lens. Fourteen mm in front ofthe lens was a 8.029 mm by 5.952 mm aperture that enforced a 32° x 24° Field of View (FOV). The two stands

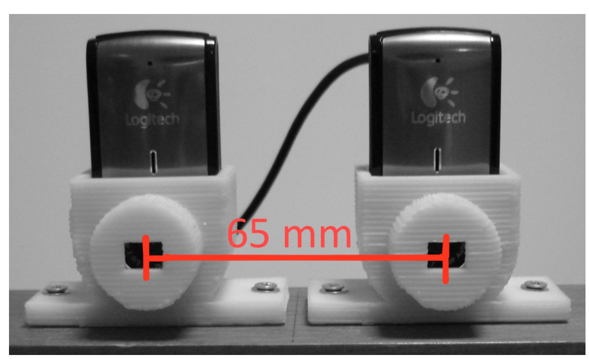

Figure 1: *Front view of the stereoscopic camera rig, with interaxial distance of 65 mm.*

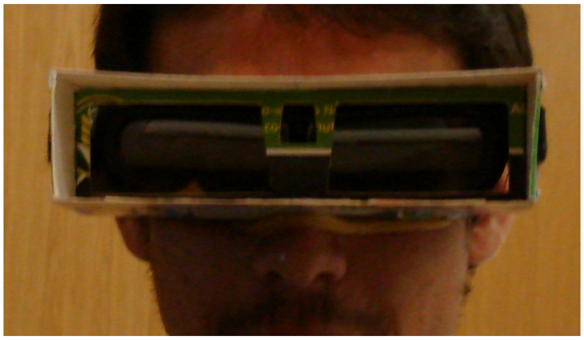

Figure 2: *Box that encloses the 3D shutter glasses to restrict vision to the stereoscopic screen.*

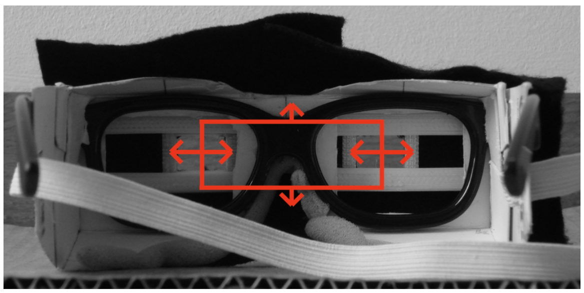

Figure 3: *Adjustable interocular mechanism in the glasses frame.*

were mounted on a wooden base such that they had an inter-axial separation of 65 mm and converged to infinity (see Figure 1).

This setup was used to record two sets of stereoscopic videos in the 12 meter by 9 meter room where the experiment later took place. The first was recorded from a height of 110 cm with an angle of declination to the intersection between the floor and the back wall of approximately 82°, while the second was recorded from a height of 20 cm with an angle of declination to the intersection between the floor and the back wall of 88°. The angle of declination was set in regard to the intersection between the floor and the back wall as this served as a makeshift horizon. It also differed for the two heights in order to enable viewing of the targets situated at all three of the distances used in the study. It was also estimated to resemble the angle of declination to the back wall that participants in the real world condition would need to adopt. To record the first set of clips, the base was mounted on a Sony VCT-PG10RM tripod. Each set of clips showed a red ball (diameter 11.24 cm) at 3 meters, 5 meters and 7 meters along the ground plane from the camera position. This media was used in the HMD and 3DM experimental conditions.

The experimental room was carefully prepared in order to exactly mimic this media in RRW trials. This was achieved by using the same ball and point of view. Subtle chalk marks on the carpet to indicate the precise locations at which the ball should be placed. We were careful to ensure no distance information was provided by these lines - the carpet was light blue and the chalk marks light yellow; they were invisible except from very close range and from directly above.

3.3.2 Display Systems

Three display setups were used in this work: HMD, 3D Monitor and Restricted Real World. They are described below. The HMD conditions were presented through an eMagin Z800 3DVisor. This stereoscopic device has a resolution of 800 x 600, a refresh rate of 60 Hz and a FOV of 32° x 24°. To ensure that participants were only able to attend to the content presented on the HMD, it was enclosed in a box constructed from lightweight cardboard. The videos shown on this device had a resolution of 1440 x 1080 and were shown at 25 fps. The video player and HMD video driver automatically performed down sampling and anti-aliasing in order to present this content at the lower HMD resolution.

The 3DM conditions were shown on a Sony Vaio VPCL22Z1E 3D capable all-in-one PC. This device features a screen with a diagonal size of 61 cm, a resolution of 1920 x 1080 and a refresh rate of 120 Hz. To view 3D content participants needed to wear Sony TDG-BR250 3D shutter glasses. To present a restricted FOV on this device, the shutter glasses were enclosed in a cardboard frame so the participants were only able to see content presented on the computer monitor (Figure 2). The videos shown the 3DM conditions had a 1280 x 720 resolution and were shown at 25 fps.

In order to create the RRW FOV condition a plastic glasses frame was extensively modified. The lenses were removed and a cardboard enclosure was mounted around the glasses to block peripheral vision. A 3D printed mechanism was attached in place of the lenses. This device featured two 17.2 mm by 12.8 mm slots (one in front of each eye) through which light could enter, but was otherwise opaque. The mechanism was designed to sit 3 cm in front of the eye, where a slot of these dimensions corresponds to a FOV of 32° x 24°. This device is shown in Figure 3. The slots could be adjusted in both x (independently) and y dimensions to ensure they were situated in the centre of a participants FOV. To achieve this calibration, participants faced a test pattern in the form of a 229 mm by 170 mm printed sheet showing a cross at the centre and a red border at the edge. Participants stood in front of this sheet at a distance of 40 cm and manually adjusted the slot position on each eye of the glasses until the sheet was centred and they were able to see all four of its extremities at the edge of their FOV with each eye.

3.3.3 Physical Environment and Props

The experiment took place in a large (12 meters by 9 meters) and relatively featureless office room with a plain floor and wall decorations. This space was selected to minimise extraneous environmental depth cues such as texture; a barren space was selected to ensure the only cues were the distance to the ball and the observer height. Trials in 110 cm height conditions were conducted with participants seated at a table and with their chins resting comfortably on a stand at a height of 1 m from the ground. On the other hand, trials in the 20 cm height condition were presented with participants lying facedown on an exercise mat on the floor. Again, they were looking forward, with their chins resting on a stand of 10 cm in height. These values ensured that participants' eye height was approximately 110 cm and 20 cm above ground, matching the media shown in the study. These postures are shown in Figure 4.

3.4 Procedure

Participants met the experimenter and were escorted to an empty hallway directly outside the experimental room. Participants then received the experimental instructions and completed calibration and setup processes. This typically took five to fifteen minutes. Lighting in the hallway was very similar to the experimental room, so this process allowed participants' eyes to appropriately adjust to the level of illumination. The first thing the participants did was review written experimental instructions and fill in basic demographics (age, gender, visual and vestibular condition). The experimental procedures were also discussed orally and participants encouraged to ask questions.

Figure 4: *Participants and views during the 110cm eye-height (seated, left) and 20 cm (lying, right) conditions used during the study.*

Participants then calibrated the equipment. Specifically, they donned and adjusted the viewing apertures on the glasses used in the RRW condition (see section 3.3.2 for a full description of this process). They also wore the HMD for a similar calibration process that involved viewing a short stereo 3D video (Knight's Quest 3D - Oric and Bodkin in Divided Ye Fall by Red Star Studio) while adjusting the display position and head straps for comfort and clear stereo perception. They then practiced the physical postures of sitting and lying using the chin rests and, finally, spent five minutes practicing the blind walking task used as an experimental measure.

Participants were able to rest in the corridor between each of the six blocks of experimental trials. For each block, participants were blindfolded and led into the experimental room. Each trial in the study followed broadly the same procedure. Whilst keeping their eyes shut, participants removed the blindfold and donned the relevant equipment (HMD, stereo glasses or FOV restrictor) and adopted the relevant posture (sitting or lying) with their chin resting comfortably on a precisely positioned stand. They then viewed the trial and, if necessary, closed their eyes, removed the equipment and put the blindfold on once again. They then stood and were then led to the starting line for the walking distance measure. Although standing from the 20cm condition (where participants were lying down) was a more laborious process than in the 110 cm condition (where they were seated), no participants reported difficulty with this process. This indirect walking procedure was used to ensure that participants were unable to pre-plan their path or motor action [Warren et al. 1990]. After completing the blind walking task, they were guided back to start another trial or, if the block was complete, out to the corridor. The spatial arrangement of the different display setups, the walking distance measurement space and the paths taken between these sites are shown in Figure 5.

The three display devices required there be minor variations to the procedure. Specifically, the HMD was tethered, so participants needed swap it for a blindfold prior to completing the blind walking task. This was a three-step process: the enclosure was removed from the HMD, the HMD was taken off and, finally, the blindfold was donned moved up from its default position around the neck to cover the eyes. Although this introduced a short additional time between the viewing task and making the distance estimate it also ensured that the HMDs weight did not influence the blind walking measure. To ensure the HMD was always worn correctly, a 2D image with no depth cues was briefly displayed every time the participants donned the device. For the other display devices, a blind was incorporated into the glasses and simply swung into place as required. This meant that no calibration procedures were necessary between trials. Furthermore, although the apparatus used in the HMD and 3DM conditions was constructed to block vision outside of the 32° x 24° FOV, the experimental room was kept dark during these conditions to further minimise the chance that useful information would be present in peripheral vision. By contrast, the lights were turned on during the RRW conditions. Similarly, although adjusting the trial presented to the participants in the HMD and 3DM conditions was done purely digitally, in the RRW condition, the physical ball was moved to appropriate locations in the room between trials. In total, including break time, the study took an average of 86 minutes to complete.

3.5 Measures

The primary measure used in this study was blind walked distance. In each trial, after experiencing the presented media, participants were blindfolded, led to the same location (marked by tape on the floor) and asked to walk forward until they felt they had reached the location the ball had been shown in. When they stopped walking, the distance was measured from the start point using a Bosch PLR 25 digital laser range finder and then manually noted down. The PLR 25 is capable of measuring distances between 0.05 m and 25 m with an accuracy of 2 mm. Prior to measurement it was always placed on the floor and directly on the start line to ensure accurate and consistent measurements.

4 Results

Mean blind walked distance for each display and eye height are shown in Figures 6 and 7. It is immediately clear that distances were underestimated in all conditions. This data was analysed using a three-way repeated measure ANOVA with factors of Display (three levels), Eye Height (two levels) and Distance (three levels) as within-subject variables. In cases when sphericity was violated, Greenhouse-Geisser corrections were used.

No significant effect between Display conditions ($F(1.448, 27.516) = 1.702, p < 0.205$) was observed. On

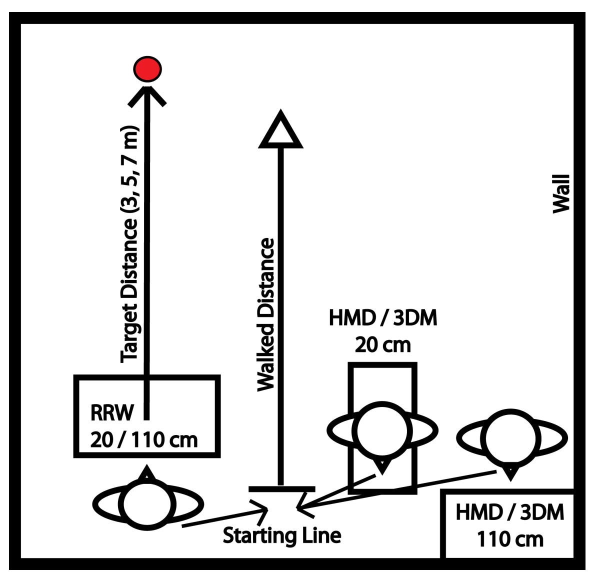

Figure 5: *Schematic of participants' positions and movements.*

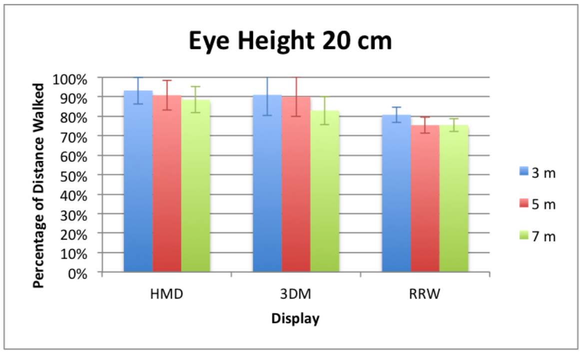

Figure 6: *Comparison of mean distance walked for each target distance between view conditions at the eye height of 20 cm.*

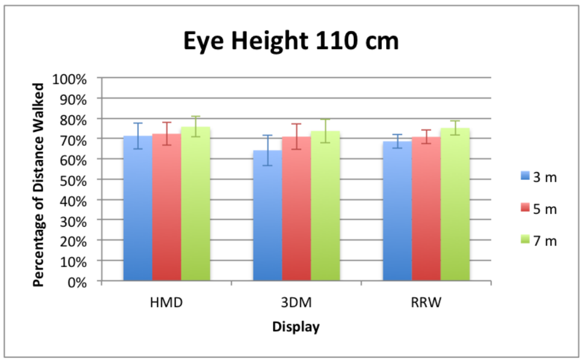

Figure 7: *Comparison of mean distance walked for each target distance between view conditions at the eye height of 110 cm.*

the other hand, both Eye Height ($F(1, 19) = 22.608, p < 0.001$) and Distance ($F(1.104, 20.983) = 231.592, p < 0.001$) led to significant variations in estimated distance. Post-hoc pairwise t-tests incorporating Bonferroni confidence interval adjustments clearly indicated that all three levels of Distance differed from one another (all at $p < 0.001$ or better). In terms of interactions, only that between Display and Eye Height attained significance ($F(1.481, 28.145) = 7.567, p < 0.005$) - these data are illustrated in Figure 8. Statistics for the other interactions are as follows: Display by Distance ($F(4, 76) = 1.217, p < 0.311$); Eye Height by Distance ($F(2, 38) = 1.485, p < 0.239$); and the three-way interaction of all variables ($F(4, 76) = 1.289, p < 0.282$).

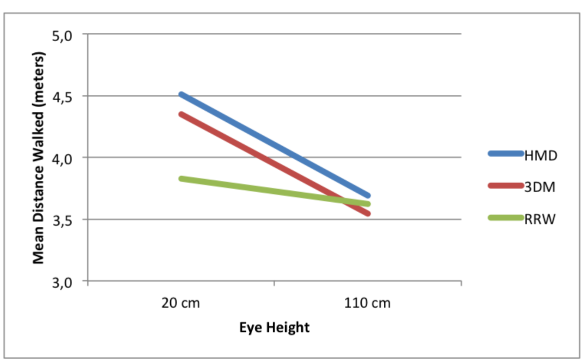

Figure 8: *Interaction between Display and Eye Height.*

5 Discussion

The current study sought to investigate performance in an egocentric distance perception task when media are displayed in three different stereoscopic display scenarios: a HMD, a computer screen and the real world. Conditions were tightly controlled, including participant FOV across the three display scenarios (at 32° x 24°). It also varied eye height between two heights (20 cm and 110 cm). The scenario of robotic teleoperation, in which low camera viewpoints are relatively common, motivated this choice of postures we wished to determine how extreme proximity to the ground plane might influence distance estimations.

In line with prior work (e.g. [Creem-Regehr et al. 2005; Kline and Witmer 1996; Loomis and Knapp 2003]), the study reported substantial underestimations of distance (between 15 and 29 percent). However, there was no main effect of display. This corroborates the findings of both Grechkin [Grechkin et al. 2010] and Riecke [Riecke et al. 2009] and suggests that presentation method (reality, HMD or monitor) has little influence on the underestimation of distances when viewing conditions are homogenous (e.g. with the same restricted FOV and without head movement). In this way, the current results suggest that the mechanical aspects related to optical arrangement of the displays (e.g. distortions of perceived space and conflicts with cues relating to binocular disparity) cannot account for the distance underestimation, an assertion that conflicts with that of Creem-Regehr et al. [Creem-Regehr et al. 2005]. Although not all of these conflicting accounts show EDP underestimation (e.g. Riecke [Riecke et al. 2009]), the findings in this study suggest that other factors, such as object and textural cues [Lappin et al. 2006] may account for the high levels of performance observed in these studies.

Eye Height, on the other hand, led to significant variations in distance estimation performance. Interestingly, the lower eye-height led to a reduction in EDP underestimation the near-ground viewpoint led to more accurate EDP. A possible explanation for this effect is that lower eye heights impact the perceived angle of declination and horizon inducing a (relative) increase in distance judgements. Evidence supporting this claim comes from similar effects observed in angle of declination studies in both virtual reality scenarios (Messing [Messing and Durgin 2005]) and in real world viewing (with the manipulation achieved by optical prisms, Ooi [Ooi et al. 2001]). However, to the best of our knowledge, no prior work has explored such extreme low eye heights, so the current study both corroborates prior work and also serves to extend it. Specifically this study suggests that, in contrast to the relatively small variations in eye height investigated by Leyrer et al. [Leyrer et al. 2011], in which no performance variations were observed as eye height was reduced, substantial reductions lead to substantial changes in performance.

However, the most interesting finding from the study is the interaction between eye height and displays this effect dominates the main effects. Essentially, whilst real world EDP judgments remained broadly the same between the two eye heights, judgments in the two computer display conditions varied significantly the level of underestimation recorded decreased. This finding is in stark contrast to previous studies that have isolated effects of angle of declination on EDP that are independent from presentation method [Messing and Durgin 2005; Ooi et al. 2001]. One explanation for this phenomenon is the fixed position of the perceived horizon in the videos was lower than the perceived horizon in the 20 cm RRW condition. This may have occurred as the participants tended to adjust their head for each of the three target distances to maintain the target in the centre of their FOV, thus changing the angle to both the target and perceived horizon. As Messing et al [Messing and Durgin 2005] suggested, lowering the position of the horizon (by as little as

1.5°) can lead to higher estimations of distance. Although this explanation is reasonable, future studies will be required to verify this notion and fully explain the effects observed in the current paper.

6 Conclusion

In conclusion this paper has presented a study on distance perception, a complex, important and poorly understood issue [Creem-Regehr et al. 2005; Grechkin et al. 2010]. It sought to contribute to the emerging body of literature examining different display and viewing parameters in order to characterize human performance and isolate the relevant perceptual cues used to make distance judgments. The two key foci were the judgment of distances using otherwise tightly controlled stimuli on different display devices and the influence of very low eye heights. The first issue was selected in order to contribute to the currently conflicting literature relating to distance perception performance on stereoscopic display systems. This second parameter, of low viewing height, is an interesting issue to study as such viewing positions are typical of many remotely operated robots (e.g. [Casper and Murphy 2003; Doroodgar et al. 2010; Linder et al. 2010; Marques et al. 2006]). In such scenarios, a robot must be controlled primarily from visual camera cues and steering and navigation errors are frequent, particularly in complex and/or tight spaces [Casper and Murphy 2003]. The work in this paper hopes to better understand the perceptual biases that may impact performance in these scenarios.

The results showed no difference in EDP between immersive displays and real world performance, a finding likely attributable to the tight control of factors such as FOV and head movements, and which supports prior work that has made this same argument [Riecke et al. 2009; Grechkin et al. 2010]. However, possibly due to the plain environments used in the studies [Montello 1997], substantial underestimations of EDP were observed throughout the study. Interestingly, this was less extreme in the low (20 cm) viewing posture when computer displays were used. Establishing the exact cause of this effect goes beyond the scope of the current paper, although angle of declination [Leyrer et al. 2011] is likely a major factor.

Future work need investigate these phenomena further. Although vertical displacements of viewing position have been shown to effect real world EDP [Leyrer et al. 2011; Sinai et al. 1998], there is relatively little work on this issue that considers performance with stereoscopic displays. As systems, such as remotely operated robots, that yield such data become more commonplace, and are used in more diverse application scenarios, it will become more important to fully characterize how low viewing heights impact human perceptual performance. This current paper contributes to this goal.

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