Minification affects verbal and action-based distance judgments differently in head-mounted displays

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Numerous studies report that people underestimate egocentric distances in head-mounted display (HMD) virtual environments compared to real environments as measured by direct blind walking. Geometric minification, or rendering graphics with a larger field of view than the display's field of view, has been shown to eliminate this underestimation in a virtual hallway environment [Kuhl et al. 2006; Kuhl et al. 2009]. This study demonstrates that minification affects blind walking in a sparse classroom and does not influence verbal reports of distance. Since verbal reports of distance have been reported to be compressed in real environments, we speculate that minification in an HMD replicates peoples' real-world blind walking and verbal report distance judgments. We also demonstrate a new method for quantifying any unintentional miscalibration in our experiments. This process involves using the HMD in an augmented reality configuration and having each participant indicate where the targets and horizon appeared after each experiment. More work is necessary to understand how and why minification changes verbal and walking-based egocentric distance judgments differently.

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General Terms: Human Factors

Additional Key Words and Phrases: virtual environments, distance judgments, perception, head-mounted display, minification

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1. INTRODUCTION

Head-mounted display (HMD) systems are a useful platform for training, prototyping, education, rehabilitation, entertainment and research. For many of these applications, it is beneficial or a requirement that the users judge virtual world distances similarly to real world distances. Direct blind walking is a commonly used method to measure distance judgments and involves having a person view a target, close their eyes and walk the distance to the target. In real environments, people can accurately make these judgments for distance ranging from 2 to 25 meters [Rieser et al. 1990; Rieser et al. 1995; Witmer and Sadowski Jr. 1998; Loomis et al. 1992; Thompson et al. 2004; Andre and Rogers 2006; Grechkin et al. 2010]. However, researchers have repeatedly found underestimation to similar distances in HMDs [Sahm et al. 2005; Mohler et al. 2006; Kuhl et al. 2009; Williams et al. 2009; Kunz et al. 2009]. In addition, other response measures

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can be used to investigate absolute distance perception including verbal reports [Kunz et al. 2009; Mohler et al. 2006; Messing and Durgin 2005; Knapp 1999], bean-bag throwing [Sahm et al. 2005], speech volume when communicating with avatars [Obaid et al. 2011] and imagined walking [Grechkin et al. 2010]. Similar errors occur in relative distance judgments in HMDs compared to real environments [Bodenheimer et al. 2007]. Finally, distance compression has also been reproduced in screen-based virtual environments [Klein et al. 2009; Alexandrova et al. 2010; Grechkin et al. 2010].

Imperfect simulation of the virtual world, ergonomics of HMD use, or some other perceptual mechanism may be the cause of this discrepancy between the real and virtual worlds. Although many of these factors have been studied, none of them conclusively explain the entirety of the distance underestimation. For example, the quality of graphics does not influence blind-walking measures [Thompson et al. 2004; Grechkin et al. 2010] but does influence verbal reports [Kunz et al. 2009]. The limited field of view and ergonomics of the HMD have been shown to explain some of the underestimation [Wu et al. 2004; Knapp and Loomis 2004; Willemsen et al. 2009]. Other work suggests that increasing a user's sense of presence in the virtual world by exposing them to a similar real world environment can improve distance judgments [Interrante et al. 2008]. Other studies show virtual avatars can improve distance judgments [Mohler et al. 2008; Ries et al. 2008; Ries et al. 2009; Mohler et al. 2010].

Previous work [Kuhl et al. 2006; 2009] shows that minification can reduce or eliminate distance compression without avatars. This work, however, is limited to direct blind walking distance judgments in a hallway environment. Therefore, the robustness of minification across environments and response measures is the primary focus of the current study. If minification causes distance judgments in an HMD to be similar to that of an equivalent real environment, then it may be a useful tool to eliminate distance compression in a variety of applications. For example, minification can improve distance judgments without the need for an animated avatar [Mohler et al. 2010] or a training phase where people improve their spatial judgments with experience or feedback [Mohler et al. 2006; Richardson and Waller 2007]. Another benefit of minification is that people prefer minified graphics when they are instructed to adjust the amount of minification/magnification in the HMD until it matched a previously seen real environment [Steinicke et al. 2011]. This preference, however, may be because minification made perceived distances in the virtual correspond more closely with the previously seen real world. Therefore, if people adapt in response to a feedback phase, they may prefer calibrated imagery over minified.

It is prudent to examine the effects of minification across response measures and environments because different response measures are not always consistent. For example, many real-world studies involving egocentric distances ranging from 1 to 34 meters indicate that verbal reports indicate approximately 65–75% of the actual distance in hallway, field, and gymnasium spaces [Loomis et al. 1998; Witmer and Kline 1998; Proffitt et al. 2003; Kelly et al. 2004; Andre and Rogers 2006]. Two of these studies reported near accurate walking-based distance judgments in the same environments [Loomis et al. 1998; Andre and Rogers 2006]. One possible explanation for the verbal report compression is that people incorrectly estimate the units used in the measurements. However, Andre et al. [2006] (p. 360) found no correlation between participant's estimation of the length of a foot and verbal reports of egocentric distance.

We speculate that high fidelity virtual environments in HMDs may already create a situation where people will make verbal reports of egocentric distance which are similar to a corresponding real environment. Studies examining verbal reports in HMDs have shown that verbal reports indicate that distances are 50–78% of intended distances ranging from 2–34m in hallway, classroom and field HMD-based virtual environments [Witmer and Kline 1998; Knapp 1999; Messing and Durgin 2005; Kunz et al. 2009]. Many of these studies used simple, low fidelity imagery. Recent work by Kunz et al. [2009] showed graphical fidelity influences verbal reports of distance. They found verbal reports ranged from 62% of actual distance in a low fidelity virtual classroom to 78% in corresponding high fidelity environment. These values approximately correspond to the 65–75% reported in the real world literature. Therefore, the utility of minification might be reduced if it eliminates compression of verbal reports in HMDs.

2. EXPERIMENT 1: BLIND WALKING

Previous results have demonstrated that minification influences direct blind walking distance judgments in a hallway environment. The goal of Experiment 1 was to reproduce these results in a sparse, high-fidelity classroom model.

2.1 System calibration

Experiments were conducted in a virtual environment displayed with an NVIS nVisor ST HMD. This HMD can be configured for use in either an opaque or a transparent (i.e., augmented reality) configuration. The HMD was always in the opaque configuration during Experiments 1 and 2. A WorldViz PPT-H four camera system tracked the 3D position of two LEDs mounted on the HMD. An InertiaCube2 tracked the orientation of the HMD.

Before we began our experiments, we calibrated our HMD by comparing a carefully constructed virtual imagery with the real world by using the HMD in a transparent configuration (similar to Kuhl et al. [2009]). These adjustments allowed us to compensate for the offset between the eyes and the tracked points, the unknown orientation of the orientation sensor relative to the optical axis of the display, differences in orientation of the left and right optical axis and the previously unknown field of view for our HMD. We did not perform pincushion distortion compensation because our HMD has little optical distortion. This procedure resulted in a system which was well calibrated at the position where the user would be standing to look at the target. We measured the field of view of our HMD to be 47.40×39.85 degrees in the horizontal and vertical directions respectively.

Our calibration process has at least two shortcomings. First, we performed the calibration once with several people and agreed on a generally accurate calibration. Individual participants may require different settings to result in a calibrated image. Second, the tracking system may have errors that depend on position and orientation. For example, although the system may be calibrated near the origin, a small amount of rotation around the origin may result in relatively large errors near the edge of the tracked space. More complex distortions are also possible. If a magnetic compass is used for yaw, then similar orientation errors can occur. The two tracked LEDs in our system meant that we did not need to use a magnetic compass. The tracking system software fuses this information with the inertial yaw information from our orientation sensor. These limitations motivated us to develop the mechanism described in Experiment 3 to measure miscalibration for each participant in our study.

2.2 Procedure

A total of 25 participants between the ages of 18 and 35 were assigned to a calibrated or a minified condition. In the minified condition, the imagery was effectively scaled to 0.7 times its original size to correspond with previous work [Kuhl et al. 2009]. We implemented minification by rendering the graphics with a field of view of 54.75×64.18 degrees. Participants were given credit through the psychology participant pool or paid $10 for their participation. After participants provided informed consent, they were screened to ensure that they had at least 20/30 visual acuity and were not stereoblind by identifying a 3D shape on a random-dot stereogram. Participants wore their contacts or glasses if they were needed for corrected-to-normal vision. All of this interaction with the participant occurred in a lobby area outside the laboratory.

The experimenter explained the parameters of the experiment as follows. Participants would be brought into a laboratory and use a head-mounted display, through which they would view a virtual environment with targets on the ground. They were encouraged to look at the virtual world for five seconds or longer and create a “mental image” of it. Next, participants were to close their eyes, say “OK,” walk to the target, and stop when they believed they were standing at the center of the target. They were encouraged to imagine

Fig. 1. View of the virtual world from the participants' perspective in the normal (left) and minified (right) conditions.

their mental image updating as they walked. The experimenter told participants that they must not use strategies involving math or counting. For example, we told participants not to count their steps, count tiles on the floor or count the number of steps they were going to walk. Upon reaching where they believed the target to be located, they were to keep their eyes closed as they were guided back to the same position in the real world. Participants were not allowed to practice the task in the real world before the experiment. However, the experimenter demonstrated the task. Participants were encouraged to rotate their head to view the space due to the limited field of view in the HMD. These instructions were presented in written and verbal form by the experimenter.

After the explanation, the participant wore a blindfold and walked around outside the laboratory for several minutes under the guidance of the experimenter. After this process, the participant was brought into the laboratory with the blindfold on. This blind-walking process was designed to familiarize the participant with blind walking, encourage them to trust the experimenter and to bring the participant into the laboratory without seeing it. The participants closed their eyes, removed the blindfold and the HMD was fitted on their head. Noise canceling headphones with white noise blocked acoustic cues. The participant could hear the experimenter through the headphones via a microphone. The participant saw the virtual lab imagery shown in Figure 1. The virtual laboratory contained tables, a desk, a tall shelving unit and a tall cabinet to the left and right of the main view shown in the figure.

The first three trials consisted of a random ordering of targets at 2.5, 3.5 and 4.5 meters. The next 15 trials consisted of the distances 2, 3, 4 and 5 meters displayed three times each and the distances 2.5, 3.5 and 4.5 meters displayed one time each. We randomized the order of these 15 trials. The half meter trials and the starting location randomization were intended to make it difficult for a user to memorize the four different distances we were studying. The size, color and shape of the targets were randomized. After the participant walked to the target and stopped, they kept their eyes closed and were guided back to the starting position in the real world. When they reached the starting position and were facing the target, they opened their eyes. The participant always started from the same real world location and the entire virtual environment was translated randomly (without translating the target) to make it appear that the virtual starting location had changed. The HMD screens were blank whenever the participants' eyes were supposed to be closed. Participants were not given any feedback on their accuracy during the experiment.

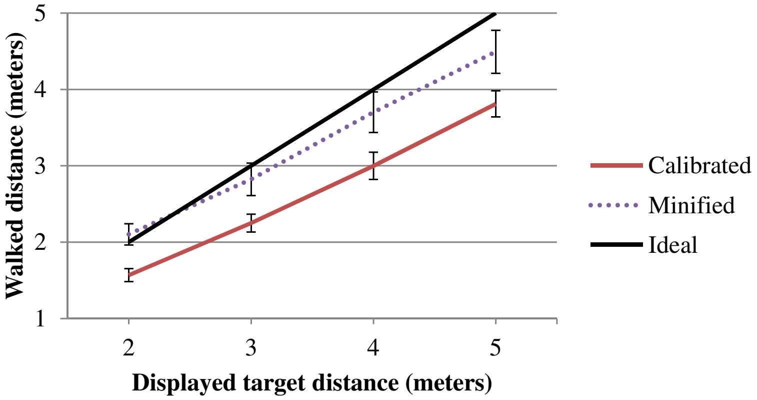

Fig. 2. Direct blind walking distance judgments in a calibrated and minified virtual environment.

2.3 Results

As shown in Figure 2, minification affected the distance which participants walked. On average, participants walked 76 and 95% of the displayed target distance in the calibrated and minified conditions respectively. A 2 (display condition) × 4 (target distance) repeated measures ANOVA showed that both the display condition ($F(1,23) = 6.00, p < 0.05$) and the target distance ($F(3,23) = 277.82, p < 0.001$) significantly affected blind walking distance judgments.

2.4 Discussion

The results of this experiment are consistent with previous minification studies [Kuhl et al. 2006; 2009] in a hallway virtual environment and shows similar results in a classroom-sized virtual environment. In addition, the magnitude of the compression in the calibrated condition is similar to other HMD direct blind walking studies [Sahm et al. 2005; Mohler et al. 2006; Williams et al. 2009; Kunz et al. 2009; Leyrer et al. 2011].

Minification changes numerous visual cues which could increase in perceived distance. Minification reduces binocular disparity because the images seen in the left and right eyes are reduced in the HMD. As a result, all corresponding points in the left and right images become closer together. Minification also reduces the overall optic flow for a given viewpoint movement. A familiar example of this occurs when people use binoculars which magnify an image and cause large amounts of optic flow during small amounts of movement. If a person uses their actual viewpoint velocity information with minification-reduced optic flow, the mathematical equations will indicate that the distance to the points in the flow field have increased. Minification reduces the visual angle of any given object and therefore can cause familiar size cues to indicate that the object is farther away.

Minification changes linear perspective cues and the angle of declination in complex ways. For example, if horizon and a target on the ground plane are simultaneously visible, minification will reduce the visual angle between them. Reducing the angle of declination from the real or virtual horizon to a target on the ground plane can change the perceived distance to the target [Sedgwick 1986; Ooi et al. 2001; Messing and Durgin 2005; Thompson et al. 2007]. Pitching the entire virtual world relative to the real world in an HMD, however, does not affect distance judgments [Williams et al. 2009; Kuhl et al. 2009]. This reduction in the angle of declination is complex because minification does not move anything at the exact center of the HMD screens. Therefore, someone could use a head-pointing approach where they look directly at the horizon and then looks directly at a target. Minification does not change the amount of head rotation between these two views. Since minification changes distance judgments and the angle of declination likely contributes to distance judgments, the results of Experiment 1 suggest that people do not use the second head-pointing

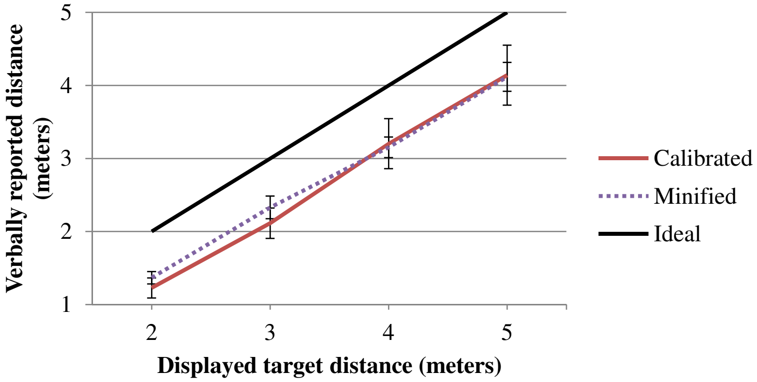

Fig. 3. Verbal reports of distance in a calibrated and minified virtual environment. The error bars represent the standard error of the mean.

approach to measure the angle of declination while making blind walking distance judgments.

Figure 2 shows that minification deviated from the actual displayed distance as the target distance increased. In our calibration verification process (Experiment 3) we provide evidence that this deviation could be explained by the fact that people generally pointed the center of the HMD above the nearest targets and below the furthest targets. When combined with minification (which pushes all virtual points toward the center of the screens), this may explain why the longer distances appeared compressed. Another explanation may be that participants were concerned about colliding with the virtual wall beyond the target at the longer distances. Other studies using a hallway model and different equipment have not found a similar effect [Kuhl et al. 2006; 2009]. Because the minified and calibrated lines in Figure 2 are nearly parallel, a third explanation is that minification affected judged distance by a constant percent in this experiment.

3. EXPERIMENT 2: VERBAL REPORTS

This experiment was designed to determine if minification affects verbal reports of distance.

3.1 Procedure

We used a between-participant design with 13 participants in the calibrated condition and 14 participants in the minified condition. The procedure was the same as Experiment 1 (Section 2.2) except that participants verbally indicated the distance between themselves and the center of the target verbally in their preferred units (yards or meters) with a resolution of at least one tenth of a unit. Participants were allowed to examine a meterstick or a yardstick (with markings indicating individual centimeters or feet) and encouraged to memorize its length prior to the experiment. During the experiment, participants were allowed to watch the target as long as they need and verbally indicated the distance. While the participants called out the distance, they were allowed to keep their eyes open viewing the target. Next, the participants closed their eyes and were guided to walk 2–5 meters forward, then back to the starting position. This walking procedure approximately reproduced the walking which occurred in Experiment 1 and has been used by other researchers [Philbeck and Loomis 1997; Andre and Rogers 2006; Kunz et al. 2009] in experiments comparing verbal reports and blind walking.

3.2 Results

As shown in Figure 3, minification did not significantly affect verbal reports of distance. On average, participants reported targets to be 74% and 77% of the veridical distance in the calibrated and minification conditions respectively. A 2 (display condition) × 4 (target distance) repeated measures ANOVA showed

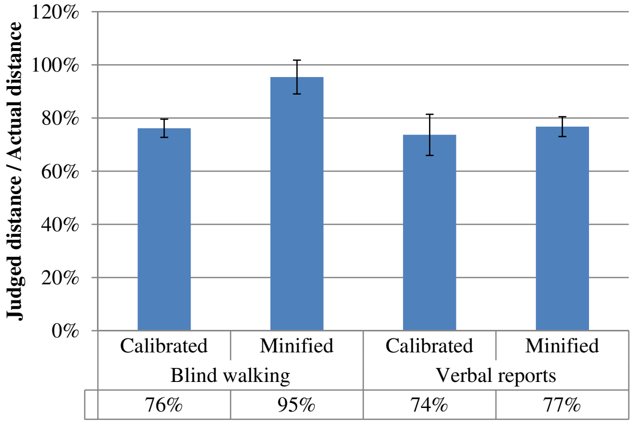

Fig. 4. Results of Experiments 1 and 2. The error bars represent the standard error of the mean.

that target distance ($F(3, 24) = 204.12, p < 0.001$) affected distance judgments but the display condition did not ($F(1, 24) = 0.057, p = 0.81$). One of the 14 participants in the minified condition was excluded from the analysis because Grubb's outlier test strongly ($p < 0.01$) flagged them. The flagged individual reported distances 1.6 times greater than the other participants in the condition. If the outlier is included in the analysis, the average distance indicated in the minification condition was 82% and there was still no statistically significant difference between the calibrated and minified conditions ($F(1, 25) = 0.55, p = 0.46$).

3.2.1 *Between-experiment analysis.* We performed a 2 (response measure) × 2 (display condition) × 4 (target distance) repeated measures ANOVA to compare the results between Experiments 1 and 2. The target distance significantly affected responses ($F(3, 141) = 448.19, p < 0.001$). In addition, there was a significant interaction between the response measure and the target distance ($F(3, 141) = 4.31, p < 0.01$) indicating different slopes of the responses shown in Figures 2 and 3. There was no statistically significant difference in response measure ($F(1, 47) = 1.97, p = 0.17$) or display condition ($F(1, 47) = 3.03, p = 0.09$). There was no significant interaction between display condition and response measure ($F(1, 47) = 1.98, p = 0.17$) because our results lacked a strong crossover interaction and three of the four conditions had remarkably similar results (see Figure 4).

Post-hoc analysis showed that the significant interaction between response measure and target distance existed only between the two calibrated conditions ($F(3, 69) = 3.37, p < 0.05$). Additional post-hoc analysis showed that response measure did not significantly change distance judgments across the two calibrated conditions ($F(1, 23) = 0.002, p = 0.96$). However, the judged distance was significantly affected by response measure across the two minified conditions ($F(1, 24) = 4.53, p < 0.05$).

3.3 Discussion

Experiment 2 provides evidence that minification does not change verbal reports of distance in the same way that it changes blind walking responses in a high-fidelity virtual environment. One interpretation of the results of Experiments 1 and 2 is that minification can be used to make blind walking in virtual environments more consistent with real environments while maintaining the compressed verbal reports which have been found in real environments (see Table I). Although the result is promising, additional research is needed to provide additional evidence to support this hypothesis.

It is remarkable that minification does not change verbal reports of distance judgments when minification leaves few absolute distance cues unchanged. For example, minification reduces the visual angle that any object subtends on the retina and should make familiar objects appear more distant. One of the motivations

Table I. Summary of studies measuring egocentric absolute distance to targets on the ground with verbal reports. Percentages are the indicated distance divided by veridical distance. Percentages were estimated when they were not explicitly provided in the paper (∼).

Study	**Environment**	**Verbal**	**Walking**	**Range**
[Loomis et al. 1998]	Real: Field	∼75%	∼95%	4–16m
[Witmer and Kline 1998]	Real: Hallway	72%		3–34m
[Proffitt et al. 2003, Exp. 1, no backpack]	Real: Field	∼75%		3–34m
[Kelly et al. 2004]	Real: Field	68%		3–25m
[Andre and Rogers 2006, Exp. 2]	Real: Gym	∼78%	∼95%	1.5–18m
[Andre and Rogers 2006, Exp. 2]	Real: Field	∼72%	∼95%	1.5–18m
[Witmer and Kline 1998]	Virtual: Hallway (LoFi)	47%		3–34m
[Knapp 1999]	Virtual: Hallway (LoFi)	∼55%		2–18m
[Messing and Durgin 2005]	Virtual: Field (LoFi)	70%	73%	3–7m
[Kunz et al. 2009]	Virtual: Classroom (LoFi)	62%	78%	3–6m
[Kunz et al. 2009]	Virtual: Classroom (HiFi)	78%	83%	3–6m
Current paper	Virtual: Classroom (HiFi)	74%	76%	2–5m
Current paper	Virtual: Classroom (HiFi-minified)	77%	95%	2–5m

to evaluate if the quality of graphics influences distance judgments [Thompson et al. 2004; Kunz et al. 2009] involves the idea that higher quality graphics provides additional opportunities for the visual system to use familiar size cues. One hypothesis is that the quality of graphics affects verbal reports because verbal reports relies more heavily on familiar size cues [Kunz et al. 2009, p. 1291]. The results of this experiment could be interpreted to support the opposing claim that familiar size cues more strongly affect blind walking than verbal reports. Additional speculation about the impact of the angle of declination on this experiment can be found in Section 4.3. Analysis which only involves a single visual cue, however, overlooks the numerous and complex ways minification changes visual cues.

Kunz et al. [2009] provides a framework of three different hypotheses which could be used to explain a dissociation between verbal and action-based response measures. First, the two visual system hypothesis suggests that there are separate visual systems which process visual information differently [Goodale 1995]. Verbal reports and walking-based judgments may rely on a perceptual awareness pathway and walking-based judgments may rely on an action-oriented pathway. Second, a task-specificity hypothesis argues that the different responses rely on different types of perceptual information. Third, a single-representation hypothesis argues that different judgments rely on the same perceptual representation but are modulated differently depending on the response. This work provides additional evidence of differences between response measures, but does not provide compelling evidence to support one hypothesis over another. More research will be needed to identify the cause of the verbal and action-based dissociation.

4. EXPERIMENT 3: CALIBRATION VERIFICATION

Although we attempted to calibrate our HMD system (Section 2.1), miscalibrations could have occurred based on how the participant wore the HMD, the participant's height or other factors. To quantify these miscalibrations, participants completed a new post-experiment calibration verification process after completing Experiment 1 or 2. We developed this procedure with the goal of quantifying the distance or angle between important virtual landmarks (i.e., the targets and the horizon) to the corresponding real-world landmarks. This procedure also allowed us to measure how minification moved the virtual target and horizon relative to the real world. An additional goal was to estimate the distance indicated by the angle of declination in both the control and minified conditions.

Table II. Experiment 3: The average distance from the participant to the projection of the virtual targets into the real world. The angular offset between the real and virtual locations are also reported (positive angles indicate the virtual imagery appeared above the corresponding real world imagery). Standard deviations are shown in parentheses.

	Condition	**2m**	**3m**	**4m**	**5m**
Distance between participant and the virt. target projected into the real world	Calibrated	1.98m (0.06)	2.98m (0.10)	3.93m (0.16)	4.88m (0.20)
	Minified	2.21m (0.13)	3.12m (0.28)	3.89m (0.38)	4.74m (0.43)
Degrees between displayed target and corresponding real world distance	Calibrated	-0.24°(0.84)	-0.16°(0.75)	-0.37°(0.81)	-0.26°(0.45)
	Minified	2.43°(1.58)	0.70°(1.85)	-0.50°(1.58)	-0.70°(1.13)
Degrees between real & virtual horizons	Calibrated	-0.86°(0.51)			
	Minified	-1.33°(0.89)			

4.1 Procedure

At the end of each experiment, the experimenter converted the HMD to a transparent configuration without removing it from the participant's head. A target was displayed in an empty virtual world. Because the HMD was in a transparent configuration, the participant saw the real laboratory with an overlaid virtual target. Participants indicated verbally or with a laser pointer the point in the real world which corresponded with the center of the virtual target. For the verbal indication procedure, the experimenter put a piece of tape on the floor and the participant repeatedly told the experimenter if it needed to be moved further, closer, left or right. In the laser pointer procedure, the participant pointed the laser at the center of the virtual target and the experimenter placed a piece of tape at the location of the laser pointer. We switched from the verbal procedure to the laster pointer procedure in the middle of the experiment to save time. The process was repeated two times for each of the 2, 3, 4 and 5 meter target distances. The experimenter measured the distance between the participant and the virtual target location. Next, participants were instructed to look straight ahead at a whiteboard on a wall across the laboratory from the participant. The experimenter measured the participant's eyeheight with the tracking system and drew a large virtual rectangle which aligned with the wall and extended from the floor to the measured eyeheight. The top of the rectangle corresponded with the horizon in the same way that an infinitely large virtual ground plane would. Next, the participants indicated where the top of the rectangle was on the real wall. Since the rectangle was displayed across the room from the participant, any eyeheight measurement errors by the tracking system would have a relatively minimal impact compared to the error caused by a miscalibrated orientation. The participant performed this procedure once and then rotated their head left, right, up and down before repeating it a second time. This movement sometimes introduced a small difference in the way the virtual imagery aligned with the real environment due to imperfect orientation tracking.

Participants in the minified condition effectively saw miscalibrated imagery during the experiment. As a result, they would see the virtual and real worlds float relative to each other depending on the direction they were looking. We encouraged participants to simply look at the target and indicate the location of the target and update their estimate if the target moved. Since people rarely rotated their head while they were indicating the corresponding real world point, participants were able to complete this task without difficulty. Participants in the minification conditions repeated this entire process for calibrated imagery to allow us to verify that the system was functioning properly.

4.2 Results

The results of our calibration verification process are shown in Table II. When participants were instructed to look straight ahead, the virtual horizon was displayed significantly lower than the corresponding real horizon by 0.81 degrees in the calibrated condition ($t(24) = -6.47, p < 0.05$) and 1.33 degrees in the minified condition ($t(25) = -8.22, p < 0.05$) condition. For reference, the width of one's little finger at arm's length covers approximately one degree of visual angle. On average, our calibrated imagery caused the targets to appear an average of 98.6% of the corresponding distance in the real world. In the minified conditions, the virtual targets at 2 and 3 meters were displayed further from (or above) the corresponding distances in the real world. The targets at 4 and 5 meters were displayed closer than (or below) the corresponding real world distances. This suggests that participants pointed the center of the HMD's screens to be above the 2 and 3 meter targets and below the 4 and 5 meter targets when they were instructed to look at them and the minification of the imagery pulled the targets toward the center of the screen.

4.3 Discussion

The angle of declination is thought to influence absolute egocentric distance judgments even when the horizon is not directly visible [Sedgwick 1986; Ooi et al. 2001; Messing and Durgin 2005; Thompson et al. 2007]. Since Experiment 3 provides information about how the virtual horizon and targets map to corresponding locations in the real world, we can use the participant eyeheights and analyze the distance indicated by the angle of declination. For example, the angle of declination from the virtual horizon in the calibrated condition should have indicated that the virtual targets appeared 107, 107, 106 and 105% of the distance we intended to display them at for the 2, 3, 4 and 5 meter distances respectively. This result occurred because the virtual horizon was lowered by a larger angle than the targets. In general, the results indicate that the calibrated condition imagery was pitched down slightly relative to the real world. However, there is evidence that pitched virtual environments in HMDs does not influence direct blind walking distance measures [Kuhl et al. 2009; Williams et al. 2009]. Although our calibrated condition was not perfect, we do not believe that our system was less calibrated than the majority of HMD studies.

Minification changes angles in complex ways. If the HMD user keeps their head in a fixed position, the visual angles between every pair of objects is decreased. If the user rotates their head, minification reduces the optic flow in a way that does not change the amount of head rotation to point the center pixel of the HMD at one object and then another (i.e., a 90 degree physical turn will produce a 90 degree turn in the virtual world even when minification is used with an HMD). A combination of both approaches could also be employed to measure angles. Therefore, minification will have a variable affect on the angle of declination depending on how the angle is measured. In future work, we hope to continuously record the participant's head orientation, similar to Leyrer et al. [2011], so we can determine the range of angles participants point their heads while viewing a target in the virtual world.

Despite these complexities, we can also analyze the results of the minification condition in terms of the angle of declination. This analysis, however, assumes that the perceptual system is using the angle between the two real-world points indicated during our calibration verification process. We found that the angle of declination may have indicated that targets appeared at 124, 117, 109, and 106% of their intended distance. These results could be interpreted to indicate that the two meter target would appear 18% further in the minified condition than the calibrated condition. In Experiment 1 (blind walking), we found that minification for all distances increased the judged distance to the objects by 19%. Furthermore, our angle of declination analysis indicates that minification would cause the five meter judgments to remain unchanged across the minification and calibrated conditions. The results of Experiment 1 did not, however, show this result. The experiment did show that minification had a reduced effect on blind walking at the 4 and 5 meter distances.

The calculations above assume that the participant's real world eyeheight is used in the equations which calculate absolute egocentric distance using the angle of declination. However, people could also use their visually-indicated eyeheight for such calculations—and minification could change the perceived eyeheight. Research by Leyrer et al. [2011] provides evidence that people rely on body-based metrics instead of visually-indicated eyeheight during distance judgments.

Finally, since the participants in the minified conditions also repeated the calibration verification process with calibrated imagery, we were able to use the data to look for outliers which may be caused by unintentional changes in the tracking system, graphics software or HMD over the course of the study. We also found no correlation between the participant's eyeheight and the judged distance to the target.

5. CONCLUSIONS AND FUTURE WORK

This work has several practical implications for egocentric distance perception in HMD-based virtual environments. First, this work extended previous work and showed that minification can affect blind walking judgments of distance in a sparse classroom environment. Second, this work showed that minification does not influence all distance response measures uniformly. Specifically, we found that verbal reports were unaffected by minification. Previous work showed that verbal reports are compressed in real environments and therefore minification might be one tool which can make distance judgments in HMD-based virtual environments match judgments in similar real environments. Additional research is needed to understand why minification affects blind walking judgments and why different response measures are not affected similarly.

We also outlined a new procedure for quantifying miscalibrations which can be used with any HMD with transparent and opaque capabilities. The procedure is straightforward, quick and can be easily modified to collect additional information. This process allowed us to double check our calibration across numerous participants and gave us an additional method to detect any unintentional mistakes. It also allowed us to explore the correlation between the angle of declination found in the calibration verification results to the participants' distance judgments.

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