The Effects of Head-Mounted Display Mechanical Properties and Field-of-View on Distance Judgments in Virtual Environments

PETER WILLEMSEN, MARK B. COLTON, SARAH H. CREEM-REGEHR, and WILLIAM B. THOMPSON, University of Utah

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Research has shown that people are able to judge distances accurately in full-cue, real-world environments using visually directed actions. However, in virtual environments viewed with head-mounted display (HMD) systems, there is evidence that people act as though the virtual space is smaller than intended. This is a surprising result given how well people act in real environments. The behavior in the virtual setting may be linked to distortions in the available visual cues or to a person's ability to locomote without vision. Either could result from issues related to added mass, moments of inertia, and restricted field of view in HMDs. This paper describes an experiment in which distance judgments based on normal real-world and HMD viewing are compared with judgments based on real-world viewing while wearing two specialized devices. One is a mock HMD which replicated the mass, moments of inertia, and field of view of the HMD and the other an inertial headband designed to replicate the mass and moments of inertia of the HMD, but constructed to not restrict the field of view of the observer or otherwise feel like wearing a helmet. Distance judgments using the mock HMD showed a statistically significant underestimation relative to the no restriction condition, but not of a magnitude sufficient to account for all the distance compression seen in the HMD. Indicated distances with the inertial headband were not significantly smaller than those made with no restrictions.

Categories and Subject Descriptors: I.3.7 [**Computer Graphics**]: Three-Dimensional Graphics and Realism—*Virtual reality*

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1. INTRODUCTION

Head-mounted display (HMD) systems facilitate fully immersive viewing conditions for interaction with virtual environments, but do so with the added constraints of

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Author's addresses: Peter Willemsen, Department of Computer Science, University of Minnesota Duluth, 331 HH, 1114 Kirby Drive, Duluth, MN 55812; email: willemsn@d.umn.edu; Mark Colton, Department of Mechanical Engineering, Brigham Young University, 435 CTB, Provo, Utah 84602; email: colton@byu.edu Sarah H. Creem-Regehr, Department of Psychology, University of Utah 380 South 1530 East, Room 502, Salt Lake City, Utah 84112-0251; email: sarah.creem@psych.utah.edu; William B. Thompson, School of Computing, University of Utah, 50 So. Central Campus Dr., Room MEB-3190, Salt Lake City, UT 84112-9205; email: thompson@cs.utah.edu.

wearing helmets with substantial mass, reduced field of view, and other inherent limitations. Even with these constraints, HMDs still can provide a fairly robust and meaningful way to interact with virtual spaces. HMDs and other virtual display technologies have the potential for large impacts on psychology research, training, science, and education, but will first require that the influences that these devices have on perception and action in virtual environments are well understood.

Recent research on the perception of absolute, egocentric distances in HMD-based virtual environments has found striking underestimation to targets presented on the ground at a range from 2 to 15 meters [Witmer and Kline 1998; Witmer and Sadowski Jr. 1998; Loomis and Knapp 2003; Thompson et al. 2004; Sahm et al. 2005; Richardson and Waller 2007]. This is both surprising and interesting because these same types of distance judgments in real world, full-cue settings are accurate [Loomis et al. 1992]. (Distance perception in screen-based visually immersive display systems has received far less study, and results to date are contradictory [Plumert et al. 2005; Ryu et al. 2005; Klein et al. 2006]). The sources contributing to the underestimation of distance judgments in virtual environments remain an open question. There are several ways in which HMD system mechanics, such as mass and moments of inertia might affect the judgment of absolute, egocentric distances in virtual environments. One possible account for the mechanism underlying the perception of distance to targets on the floor has focused on the role of angle of declination coupled with eye height [Sedgwick 1986; Ooi et al. 2001]. The weight of an HMD and the torques it places on a user's head might well bias the determination of this angle. The most common experimental mechanism for probing distance perception in virtual environments over ranges greater than 2m has been *blind walking*. In this task, subjects view a target, close their eyes, and then attempt to walk to or toward the location of the target. Wearing an HMD could bias this distance or direction of walking, even if the spatial location of the target is correctly perceived.

We explored these issues by comparing distance judgments made in a virtual world presented with a conventional HMD to distance judgments made in the real world while wearing one of two devices designed to match the mass and moments of inertia of the real HMD: 1) a mock HMD created to match a real HMD's mass and moments of inertia, which restricted field of view as in the conventional HMD and 2) an inertial headband which approximated the same forces and torques that would act on a user's head while wearing the real HMD, but did not restrict field of view or otherwise seem to users as if their head were inside a helmet. Our results show that the inertial headband had little influence on the accuracy of distance judgments in real world. The mock HMD condition did lead to underestimation of distances, though not enough to account for the full effect seen when performing the same tasks using a real HMD.

2. BACKGROUND

Perceptual psychologists have investigated the relationships between perception, representation, and action in terms of spatial updating and locomotion in a physical environment. Specifically, internal representations of space are influenced and updated by both visual and motoric input [Thomson 1983; Rieser et al. 1990].

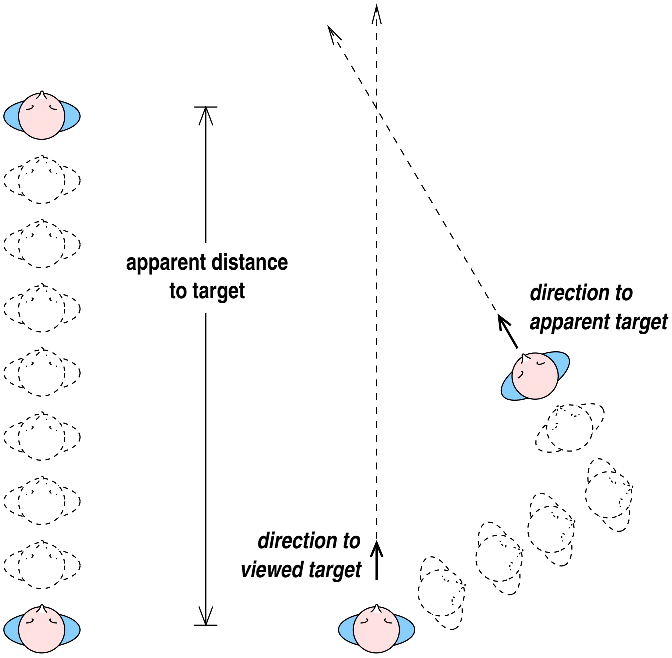

Fig. 1. Visually directed actions involving direct and triangulated walking to targets. Subjects initially view a target without moving, after which they are blindfolded. For direct walking tasks they are then asked to walk to the apparent location of the previously viewed target. For triangulated walking, they are asked to walk for a few steps in a direction oblique to the target direction, stop, turn towards the where they judge the previously viewed target to be, and finally take two steps in the direction of the apparent target.

In particular, this research has shown that visually directed actions such as blind walking to previously viewed targets are good response measures for how physical space maps to perceived visual space. In these studies, participants first construct a visually-based representation of an environment, and then walk without vision, either in a direct path to or an indirect path toward the perceived location of some object in the environment. As participants walk without vision, they are told to focus on how their internal, mental representation of the space updates based on their movement. Figure 1 illustrates the visually directed actions of direct and triangulated walking. Results from these studies, conducted in real world indoor and outdoor spaces under full cue conditions, show that people are accurate at judging distances to targets resting on the ground out to about 25 meters [Rieser et al. 1990; Loomis et al. 1992; Philbeck et al. 1997; Fukusima et al. 1997].

Other research efforts have investigated the effectiveness of different cues necessary for absolute distance perception. Accommodation and convergence are absolute egocentric cues, but individually, do not have much direct effect beyond personal space (i.e., out to about 2m) [Cutting and Vishton 1995]. Similarly, absolute motion parallax has been found to be a weak cue for absolute distance beyond personal space [Beall et al. 1995]. However, at distances up to 2m, accommodation and convergence have been shown to be important cues that influence space perception in virtual environments [Ellis and Menges 1997; Surdick et al. 1997]. This paper focuses specifically on distance judgments in action space, in which visual cues such as accommodation, vergence, and motion parallax have little impact on absolute distance judgments. Action space is described as space beyond personal space out to about 30 meters, signifying an area in which we can quickly move and interact with our surroundings[Cutting and Vishton 1995].

When visually directed actions are used as response measures for distance perception in HMD-based virtual environments, judged distances are underestimated relative to the modeled geometry. Thus, people act upon the spaces as though the spaces were smaller than intended. One common explanation for the underestimation is the relatively small field of view (FOV) in most HMDs. Several studies have shown, however, that restricting real-world FOV to what is supported by the majority of current generation high-quality HMDs does not significantly affect the accuracy of blind walking to targets if participants are able to move their head and look around the environment [Knapp and Loomis 2004; Creem-Regehr et al. 2005]. On the other hand, restricting vertical FOV more narrowly does have an effect on distance judgments in some circumstances [Wu et al. 2004]. Distance compression in an HMD is the same with either stereo or monocular viewing, suggesting that defects in the stereo display of images in an HMD such as accommodation-vergence mismatch are not the cause of the compression [Willemsen et al. 2008]. Another possible explanation for the compression of space is the lack of graphics realism used in many studies. However, graphics quality does not appear to be a major factor of the compression since results from blind walking to targets presented with wire-frame graphics, lit and shaded graphics, and photographic panoramas showed no statistically significant differences [Thompson et al. 2004].

The source of the compression remains an open question. One possible explanation investigated in this paper is that the underestimation of distance may be arising from static torque forces resulting from mass distribution near the front of the HMD. With most HMDs, optics and associated circuitry create additional weight at the front of the HMD. This has the potential to influence the angle of declination to targets on the ground which might result in changes to the perceived distance to those targets. More specifically, afferent or visual information associated with unintended head orientation could result in a bias in the efferent signal for head orientation in a way that increases the sensed angle of declination, decreasing the perceived distance. It is also important to note that it is unknown how angle of declination is actually determined. It is possible that if efferent-only proprioception of head orientation is used, then the increase in pitch down head orientation could lead to a decreased sensed angle of declination, increasing the apparent distance.

If additional mass or moments of inertia are indeed influencing distance judgments, it is likely that a real world viewing condition using a mock HMD with mechanical properties identical to the real HMD would be susceptible to the same influences found in the virtual conditions. Although previous work has suggested minimal effects of field of view for blind walking judgments of distance, it is unknown how the field of view restriction commonly found in HMDs interacts with the HMD mechanics. Given that the freedom to rotate one's head was critical to the accuracy of judgments in Creem-Regehr et al.'s (2005) reduced FOV study, it is possible that the combined effect of reduced FOV and HMD mechanical properties would be different than the effect of the additional mass and moments of the HMD alone. For this reason, an additional condition tested distance judgments while wearing the inertial headband, which controlled for the mechanical properties of the HMD while allowing for a full field of view.

3. METHOD

3.1 Participants

116 University of Utah students participated in the experiment, each only experiencing one of the eight possible conditions (14-17 participants, approximately balanced for gender, in each condition). All were given eye tests prior to the experiment to ensure normal acuity and the ability to fuse stereo images.

3.2 Design

The experiment tested direct and triangulated blind walking to targets on the ground crossed with four viewing conditions: a virtual world condition with the HMD; a real world condition using the mock HMD; a real world condition using the inertial headband; and a real world condition with unrestricted viewing. For the direct walking condition, targets were placed at 4m, 6m, and 8m using 6 uniquely sized shapes of differently colored targets. In the triangulated walking conditions, targets were placed at 5m, 10m, and 15m. Triangulated walking allows investigation of target distances greater than is possible with direct walking in most tracked HMD spaces. Triangulated walking can also help to remove cognitive bias that might arise from subjects attempting to pre-plan walking or turning toward the intended target locations if the *turn toward target action* is directed by the experimenter. In other words, as the subject walks away from the initially viewed target, the experimenter instructs the subject to turn towards the target at a random moment in time. This encourages on-line spatial updating of target location and limits the ability of the subject to predetermine the actual amount they need to walk and turn since the angle is based on distance walked from the initial viewing location. The direct and triangulated walking tasks are illustrated in Figure 1.

3.3 Materials

All viewing conditions except that involving the actual HMD were conducted in an 18m x 11m meeting room, while the HMD condition used a virtual world modeled after this same room (Figure 2). The virtual viewing conditions were conducted in our laboratory using an NVIS nVisor SX HMD with a field of view 47 degrees horizontal by 38 degrees vertical and 100% binocular overlap (Figure 3). The nVisor has a resolution of 1280x1024 pixels in each eye and is driven by two clustered PCs. The position and orientation of the HMD was tracked using an Intersense IS-900 tracker, which uses inertial sensor readings (gyroscopes and accelerometers) with ultrasonic range measurements to compensate for drift. The manufacturer's published positional resolution and accuracy is 0.75mm (X,Y,Z) and 2–3mm, respectively. For orientation tracking angular resolution is 0.05 degrees while angular static accuracy is 0.25 degrees. The refresh rate for the virtual world viewing conditions was 60Hz and was locked to the refresh rate of the HMD display device. Latency effects were not subjectively apparent, though formal measurements of end-to-end system latency were not done.

Three viewing conditions were evaluated in the real space. For one of these conditions, a mock HMD was created from a replica shell of the nVisor SX HMD (Figure 4). Weights were added inside the mock HMD shell so that it closely approximated the mass and moments of inertia of the real HMD. The front of the shell used for the mock HMD was cut out and replaced by small viewing pyramids constructed from black foam core to approximate the field of view in the real HMD. These visual occluders could be moved a total of approximately 2.5cm with respect to the subject's frontal plane. This motion allowed for more closely matching the binocular field of view created by the visual occluders to each subject's facial dimensions. A second condition evaluated in the real room used the same design of head band as used in the real and mock HMDs. Weights were attached to this headband to approximate the mass and moments of the real HMD. These weights were sufficiently above eye level so as to not restrict field of view (Figure 5). In a control condition also conducted in the real room, subjects wore nothing on their heads.

Almost all HMDs in use today are tethered, with an attached cable supplying power and the video feed. Often, tracker information is returned through this same cable bundle. Often, these cables are relatively heavy and stiff. As a result, they affect the balance of the HMD and can restrict natural movement. To account for this, a cable similar to that used in the real HMD was attached to both the mock HMD and the inertial headband. During blind walking trials using the mock HMD and inertial headband, this (non-functioning) cable was managed in the same way as was done with the cable attached to the real HMD.

Not shown in Figures 3–5 is an occluding collar that subjects wore around their neck in all conditions. The collar was designed to block a person's view of the ground near their feet radially out to approximately 1.5 meters to avoid potential problems associated with the absence of a virtual body representation. We have previously shown that blind walking to floor targets in the real world remains accurate even when wearing this collar [Creem-Regehr et al. 2005].

3.3.1 *Mass and Moments of Inertia.* Mass is a measure of the amount of matter in an object. Moments of inertia are related to the distribution of matter in an object. Under static conditions, the mass of the HMD generates forces and torques on the user. Most obviously, the user feels the downward pressure due to the weight of the HMD. In addition, if the center of mass of the HMD is offset horizontally from the center of mass of the user's head, the user's neck must exert extra torque to offset the gravitational torque due to the mismatch. This occurs with the present HMD apparatus due to the location of the (relatively) heavy optics and circuitry located in front of the user's eyes; the user feels the imbalance and exerts a compensating torque to lift the front of the HMD. The user must exert additional forces and torques on the HMD when movement occurs, due to the inertial effects of the HMD mass and moments. Neck torques and other forces are needed to compensate for the effects of the mass of an HMD when translational acceleration or decelerations occur during walking or postural sway. For the experiments described here, this

Fig. 2. Real (top) and virtual (bottom) room conditions.

is relevant to both the direct and triangulated walking measures. Different neck and body torques are needed during turning motions due to the moments of inertia of the HMD. Both pitch and yaw torques are associated with the head movements needed to visually explore the real and virtual spaces, even while otherwise standing still. Yaw torques also come in to play during triangulated walking, which involves

Fig. 3. NVIS nVisor SX head-mounted display, which was used in the HMD conditions. Not shown in the figure is a neck collar used to occlude the area around the feet in order to avoid a potential confound when the body is not visible in the HMD conditions [Creem-Regehr et al. 2005].

Fig. 4. Mock HMD based on NVIS nVisor SX HMD shell used during real world viewing conditions. As with all of the other conditions the neck collar was used to restrict subjects from looking at their feet or the floor in the immediate vicinity of where they were standing.

Fig. 5. Inertial band, with similar mass and moments to the real and mock HMDs, but without field of view restriction or a sense of "wearing a helmet".

Parameter	Real HMD	Mock HMD	Error	Inertial Band	Error
$m\ (kg)$	1.088	1.088	0.0%	1.088	0.0%
$I_x\ (kg-m^2)$	0.001965	0.001710	-13.0%	0.002135	8.6%
$I_y\ (kg-m^2)$	0.009377	0.010106	7.8%	0.008477	-9.6%
$I_z\ (kg-m^2)$	0.011776	0.012911	9.6%	0.011041	-6.2%

Table I. Mass and moments of inertia for the real HMD, the mock HMD, and the inertial band. For the mock HMD and inertial band, the deviation of each parameter from the corresponding parameter for the real HMD is given.

substantial changes in facing direction at both the beginning and end of the first leg of the walk.

In the general case, the rotational inertia of a body is completely described by six quantities: the moments of inertia (I_x, I_y, I_z), which relate torques about three orthogonal axes embedded in the body to motion about those same axes; and the products of inertia (I_{xy}, I_{xz}, I_{yz}), which relate torques and motion about different axes. The importance of these inertial properties lies in the fact that, for a given torque exerted by the user, the presence of the HMD results in a lower angular acceleration. Conversely, for a given angular acceleration, the inertia of the HMD results in larger torques sensed and exerted by the user. These modified torque/acceleration relationships, as well as the modified mass/force/torque relationships described previously, may in turn modify the way in which an HMD user perceives his motion relative to a real or virtual environment.

The determination of the mass parameters of the real HMD and matching of the parameters of the mock HMD and inertial headband proceeded as follows. The mock HMD and inertial headband mass were increased to that of the HMD through the addition of small internal weights. The location of the center of mass was matched by relocating the weights until the mock HMD, inertial headband, and HMD exhibited the same point of balance when suspended from a string. The products of inertia I_{xy} and I_{yz} are zero due to the $x - z$ plane of symmetry of the HMD, and I_{xz} was assumed negligible due to the near-symmetry about the other two planes. The moments of inertia (I_x, I_y, I_z) were matched by adjusting the weight locations until the mock HMD and HMD exhibited similar periods of oscillation when attached to a pendulum and swung about the three axes. The results of the matching procedure are presented in Table I.

3.4 Procedure

Before beginning the experiment, subjects gave consent and were given written and verbal instructions. Subjects were instructed to view the environment and the target location until they felt confident they had a good mental image of the space. Then, they closed their eyes and either walked directly to the perceived location of the target and stopped (direct walking), or walked indirectly toward the target, turning and walking two steps toward the target when instructed by the experimenter (triangulated walking). Target distance and shape were randomized for each subject. Each subject was presented with a total of 15 trials during the experiment, with the first three being practice trials not used for data analysis, and with no feedback given on any trial.

3.5 Data Transformation

In the triangulated walking task, apparent distance was determined based on a trigonometric calculation that intersected one half line specified by the initial viewing position and facing direction with another half line specified by the location in which the subject turns to face the target and the direction the subject walks after making this turn. Variability in this measure is asymmetric. In the case where the first walked leg is to the right of the target, a small final heading error too far to the right will generate a larger error in apparent distance than a turning error of the same magnitude to the left. Since the statistical data analysis techniques that were used presume symmetrically distributed error, these techniques were applied to transformed data values $t = \arctan(d)/\alpha$, where d is the indicated distance for a given trial as determined by the intersection of original viewing direction and final pointing direction, as shown in Figure 1, and α was an empirically determined constant that minimized the statistical skew in t over all trials in all conditions. Once the statistics were computed on the t values, the inverse transform was applied in order to re-express the values in units of apparent distance to the target.

4. RESULTS

As shown in Figures 6 and 7, the differences among the viewing conditions were similar across the two walking measures. Distances were underestimated when viewing with the HMD in the virtual environment compared to estimations when viewing with the mock HMD, the inertial headband, or with no viewing restrictions in the real world. Furthermore, distances were underestimated in the mock HMD

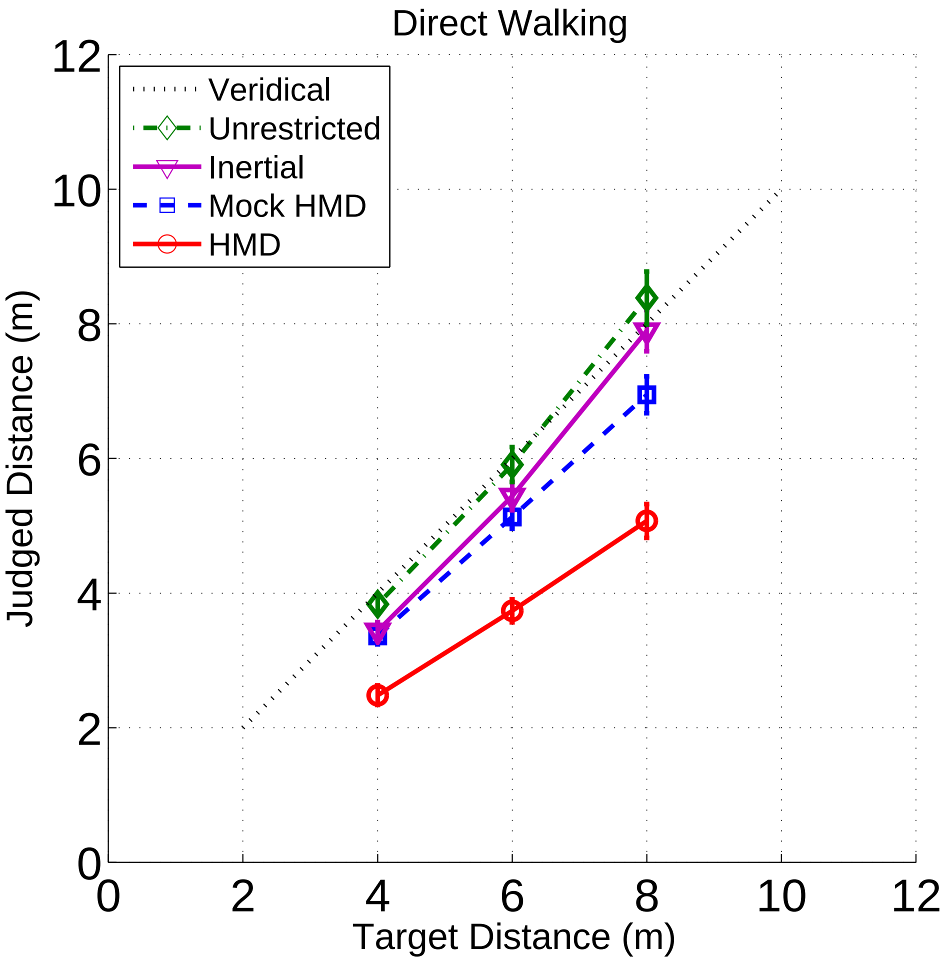

Fig. 6. Indicated distances based on direct blind walking to previously viewed targets. Error bars represent ±1 SEM. The dotted line represents veridical performance.

condition compared to the unrestricted real world, although performance was still significantly more accurate than in the HMD VE condition.

4(viewing condition) x 3(distance) ANOVAs with viewing condition as a between-subjects factor and distance as a within-subjects factor performed separately on the direct walking and triangulated walking measures confirmed a significant difference between the four viewing conditions (Triangulated: $F(3, 53) = 11.2, p < .01$; Direct: $F(3, 55) = 23.19, p < .01$). Distance estimations increased with increasing intended distance for all conditions (Triangulated: $F(2, 106) = 363.41, p < .01$; Direct: $F(2, 110) = 812.85, p < .01$). There was also a condition x distance interaction for both measures, explored in more detail below (Triangulated: $F(6, 106) = 2.18, p < .05$; Direct: $F(6, 110) = 11.52, p < .01$). The average distances walked were fit well by a linear function for each condition ($R^2 > .99$ for all conditions)

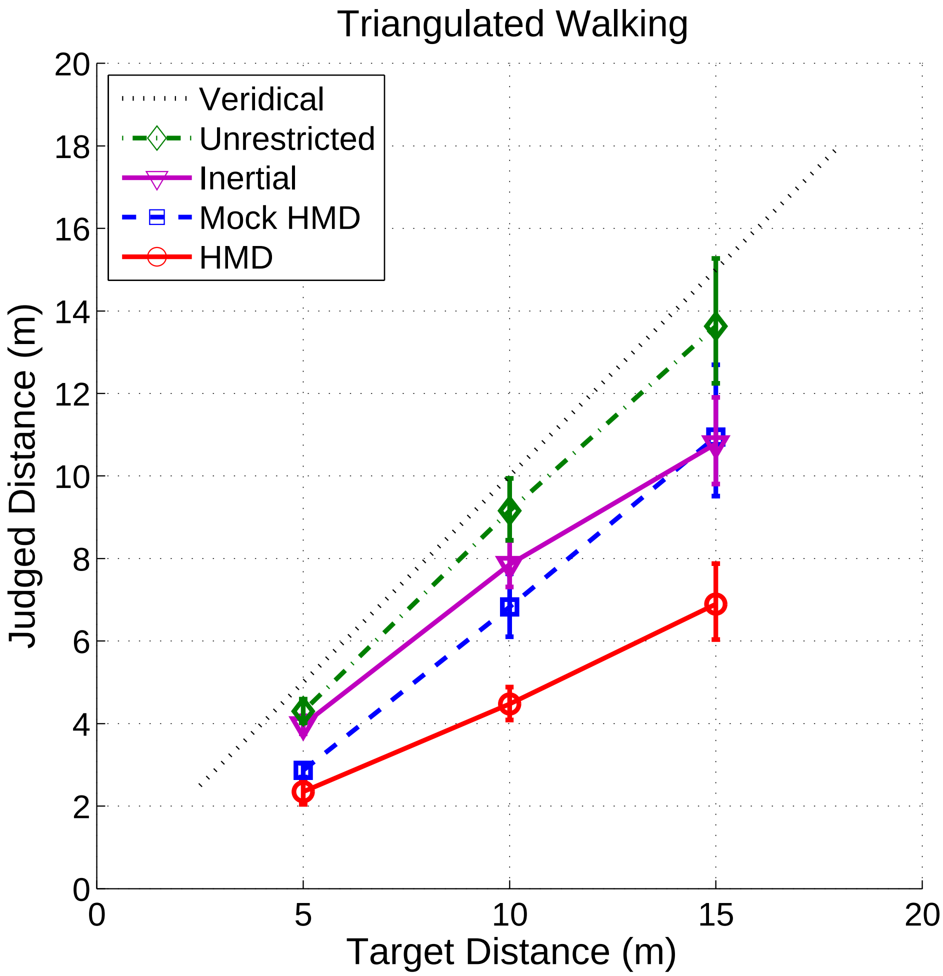

Fig. 7. Indicated distances based on triangulated blind walking to previously viewed targets. Error bars represent ±1 SEM. The dotted line represents veridical performance.

and led to the values presented in Table II, which reports both slope and intercept.

Planned orthogonal contrasts comparing the three restricted viewing conditions to the unrestricted real world condition indicated that judgments made with both the HMD in the virtual environment and the mock HMD in the real world were underestimated compared to the unrestricted real world condition ($p < .05$ for both Triangulated and Direct). However, estimations made with the inertial headband did not significantly differ from the unrestricted viewing condition (Triangulated: $p = .19$; Direct: $p = .13$). Scheffe post-hoc tests also confirmed that there was more underestimation in the HMD condition compared to the mock HMD and inertial headband conditions ($p < .05$ for all comparisons). To examine the viewing condition x distance interaction, univariate ANOVAs were performed separately

	slope	intercept
direct walking		
HMD	.647	-.121
mock HMD	.896	-.231
inertial band	1.115	-1.099
unrestricted	1.138	-.784
triangulated walking		
HMD	.455	.025
mock HMD	.807	-1.194
inertial band	.681	.721
unrestricted	.933	-.298

Table II. Linear fit to the mean indicated distances for each condition.

at each distance, using planned orthogonal contrasts to compare each of the three viewing manipulations to the unrestricted real world condition. In Direct walking at 4 m, distances were underestimated in all conditions relative to the unrestricted control ($ps < .01$). At 6 and 8 m, the HMD and mock HMD showed underestimation ($ps < .01$), but the inertial headband did not ($ps = .12, .29$, respectively). For Triangulated walking, a similar pattern at 5 and 10 m showed that the HMD and mock HMD conditions had significant underestimation compared to the control ($ps < .01$) but that there was no difference between the inertial headband and the control ($ps = .39, .22$, respectively). At 15 m, only the HMD condition was different than the control ($p < .01$, all other conditions $p > .20$). In all, the condition x distance interactions and corresponding changes in slope (Table II) reveal a somewhat more complex pattern of behavior across distance, but support the conclusion that while the mock HMD shows some compression of distance walked, the inertial headband had little effect overall. Furthermore, the amount of compression found in the HMD virtual environment condition is significantly greater than that found in the other conditions. Together, this pattern of data is suggestive of two conclusions. First, some compression of distance may be accounted for by the combined effect of a FOV restriction and the mass and moments of inertia of a traditional HMD. This is qualified by the second conclusion that the combined FOV/inertial effect does not fully account for the magnitude of compression seen in the distance estimations made with an HMD within a virtual environment.

For triangulated walking (Figure 7), the data for the unrestricted viewing condition appears to fall slightly below the veridical performance line, unlike our current results for direct walking and our previous findings ([Thompson et al. 2004]). One subject showed mean estimations that fell two standard deviations below the group mean and may be contributing to this apparent underestimation. We kept the subject in the data set because she did not fulfill any *a priori* exclusion criteria. When the data is analyzed without this subject, the unrestricted viewing condition for triangulated walking shows accurate performance along the veridical performance line.

5. DISCUSSION AND CONCLUSION

The apparent compression of virtual spaces as revealed through visually directed walking is a puzzling problem. We examined the possibility that the mechanical aspects of an HMD, with or without the additional common FOV restriction, contribute to the consistent underestimation effects seen across several laboratories. Two forms of mechanical effects were explored. An inertial headband added mass and moments comparable to a real HMD to the user's head, but did not restrict field of view or generate a sense of the user's head being inclosed in some device. A mock HMD mimicked the real HMD in shape, mass, and moments, but used cutouts allowing direct viewing of the environment rather displaying computer generated images. There was a small, but statistically insignificant underestimation in judgments made with the inertial headband relative to those made with no restrictions. This is in contrast to the mock HMD combining mass, moments, and field of view restrictions, which did show a reliable difference from the no restriction condition but with a magnitude of compression significantly less than what occurred with the real HMD.

Much of the previous work finding underestimation of absolute distance in HMD virtual environments has used blindwalking as a response measure. Blindwalking, established to be accurate on average in real environments, involves both perception of distance and the process of dynamically updating a representation of space with movement. We hypothesized that the mechanical and FOV characteristics of HMDs could influence either the visual estimation of distance, the indication of distance through walking, or both. We suggest that the HMD mechanical characteristics on their own cannot account for the distance compression at a level of explanation of either the visual distance estimation or the walking response for several reasons. First, there was no significant effect of the inertial headband on distance judgments overall, providing little support for the idea that the extra mass of the HMD might influence head pointing and have an effect on the resulting angle of declination used to compute absolute distance. Second, the results were consistent across the two blindwalking measures, direct and triangulated walking, which themselves differ in important aspects relating to translation and rotation of the body during locomotion. The conclusion that the compression effect is not a result of an interaction between HMD mechanics and the requirement of walking is also supported by our prior work showing similar effects for blind throwing as for walking [Sahm et al. 2005].

We did, however, find a significant underestimation of distance in the mock HMD when the FOV restriction was combined with the HMD mass and moments of inertia. Previous work suggests that a comparable FOV restriction to the one used here was not a significant factor in distance estimation when head rotation was permitted [Creem-Regehr et al. 2005; Knapp and Loomis 2004]. Creem-Regehr et al. (2005) demonstrated some underestimation of distance through blindwalking when head rotation during viewing was prevented. The present work allowed for head rotation during viewing but combined reduced FOV with additional mechanical restrictions. In both cases, a similar magnitude of distance compression was found, which did not reach the magnitude of compression seen within an HMD virtual environment. The current findings add to the small body of work suggesting that FOV restrictions have an influence on the accuracy of distance estimations when combined with other restrictions that influence head rotation (see also [Wu et al. 2004].

In sum, the conditions tested here suggest that with HMD viewing, a combination of the mass and moments, field of view restriction, and sense of "wearing" a helmet only partially accounts for distance underestimation and that the underestimation can not be explained by the mechanical aspects of HMDs alone.

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