

The Effects of Head-Mounted Display Mechanics on Distance Judgments in Virtual Environments*

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Abstract

In virtual environments that use head-mounted displays (HMD), distance judgments to targets on the ground are compressed, at least when indicated through visually-directed walking tasks. The same tasks performed in the real world yield veridical results over distances ranging from 2m to 25m. This paper describes experiments aimed at determining if mechanical aspects of HMDs such as mass and moments of inertia are responsible for the apparent distortion of distance. Our results indicate that the mechanical aspects of HMDs cannot explain the full magnitude of distance underestimation seen in HMD-based virtual environments, though they may account for a portion of the effect.

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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 wearing helmets with fixed masses, 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 is 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 [Durgin et al. 2002; Lampton et al. 1995; Loomis and Knapp 2003; Thompson et al. in press; Witmer and Sadowski 1998; Witmer and Kline 1998]. 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]. 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. Recent speculation about the perception of distance to targets on the floor has focused on the role of angle of declination coupled with eye height [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 wearing a mock HMD designed to match the mass and moments of inertia of the real HMD. Our results show that people wearing the mock HMD act as if the scale of the world has been compressed, though not enough to account for the full amount of the compression 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 [Rieser et al. 1990; Thomson 1983]. 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 [Loomis et al. 1992; Philbeck et al. 1997; Fukusima et al. 1997; Rieser et al. 1990].

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

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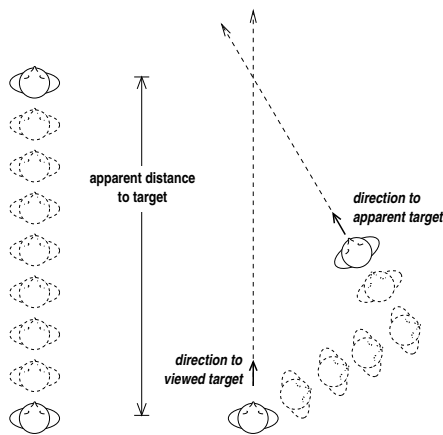


Figure 1: Visually directed actions involving direct and triangulated walking to targets.

beyond personal space [Beall and Loomis 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.

When visually directed actions are used as response measures for distance perception in 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 in most HMDs, but recent studies suggest this is not the case for blind walking to targets in action space [Knapp and Loomis in press], provided that participants are able to look around the environment [Creem-Regehr et al. 2003]. However, small field of view has been shown to degrade performance in search and walking tasks, but these studies did not study absolute, egocentric distance judgments [Arthur 2000]. Another possible explanation for the compression of space is the lack of graphics realism used in previous studies. However, graphics quality does not appear to be a major factor of the compression since results from blind walking to targets presented with wireframe graphics, lit and shaded graphics, and photographic panoramas showed no statistically significant differences [Thompson et al. in press; Willemsen and Gooch 2002].

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. This could influence the angle of declination which would result in a shorter perceived distance to targets on the ground plane. The triangulation task involves turning of the head and body which could be affected by mass and moments of inertia. If these factors 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.

3 Experimental Design

The experiment tested direct and triangulated blind walking to targets on the ground crossed with three viewing conditions: a virtual



Figure 2: Mock HMD based on NVIS nVisor SX HMD shell used during real world viewing conditions. A neck collar is used to occlude the area around the feet.

world condition with the HMD; a real world condition using the mock HMD; 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, and also removes the ability for subjects to pre-plan target location. The direct and triangulated walking tasks are illustrated in Figure 1. 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. Eighty-three (83) University of Utah students (42 male, 41 female) participated in the experiment, each only experiencing one of the six possible conditions. Each subject was presented with a total of 15 trials (3 practice) during the experiment.

The virtual viewing conditions were conducted in our lab with an NVIS nVisor SX HMD with a field of view 47 degrees horizontal by 38 degrees vertical and 100% binocular overlap. The nVisor has a resolution of 1280x1024 pixels in each eye and is driven by two clustered PCs. Real world viewing conditions were conducted with and without a mock HMD created from a replica shell of the nVisor SX HMD. We measured the mass and moments of inertia of the nVisor HMD, and created a mock HMD with similar mass, moments of inertia, and field of view. The front of the nVisor shell was cut out and replaced by small viewing pyramids constructed from black foam core to approximate the field of view in the real HMD. Approximately 2.5cm of lateral movement in the viewing frustums allowed for more closely matching the binocular field of view. Figure 2 shows the mock HMD. Subjects also wore a neck collar (shown in Figure 2) in the real and virtual 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 or the presence of an unrealistic avatar when looking down. The room used for all real world conditions was an 18m x 11m room. A model of this room was created for the virtual viewing conditions, and is illustrated in Figure 3.



Figure 3: Real (top) and virtual (bottom) room conditions.

3.1 Mass and Moments of Inertia

Mass is a measure of the amount of matter in an object, and may be quantified by simply weighing the object. The mass of the HMD is important in two respects. First, the force that the user must exert to support the static weight of the HMD is proportional to the total mass of the HMD. Second, the magnitude of the dynamic (inertial) force that the user must exert to accelerate the HMD is proportional to the mass of the HMD. The magnitude of the mass-related forces felt by the user is independent of the distribution of the mass. However, the distribution of the mass in the HMD is important for other reasons, the most obvious of which is related to the center of mass of the HMD. If the center of mass of the HMD is not collocated with the center of mass of the user's head, then the user's neck must exert a 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.

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.

Parameter	HMD	Mock HMD	Error (%)
m (kg)	1.088	1.088	0.0
I_x ($kg - m^2$)	0.001965	0.001710	-13.0
I_y ($kg - m^2$)	0.009377	0.010106	7.8
I_z ($kg - m^2$)	0.011776	0.012911	9.6

Table 1: Mass and Moments of Inertia

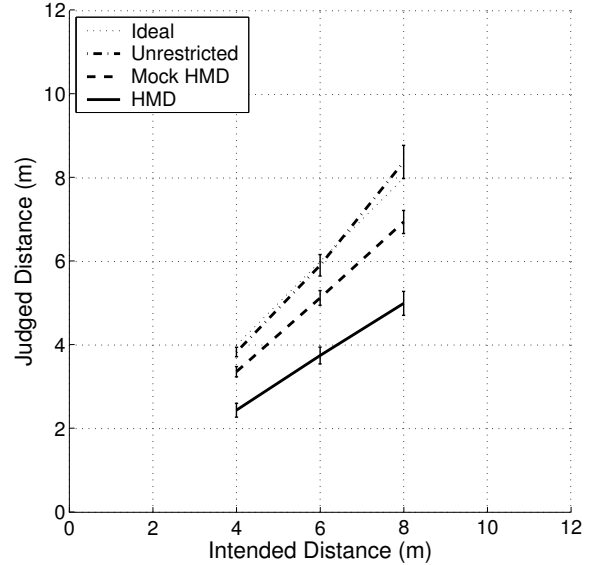


Figure 4: Direct walking. Error bars represent ± 1 SEM. The dotted line represents ideal performance.

The determination of the mass parameters of the real HMD and matching of the parameters of the mock HMD proceeded as follows. The mock HMD mass was 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 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 1.

4 Results

Distances were underestimated when viewing with the HMD in the virtual environment compared to estimations when viewing with the mock HMD or with no viewing restrictions in the real world. A 3(environment) x 3(distance) ANOVA confirmed a significant difference between the three environment conditions with a main effect of environment (Triangulated: $F(2, 37) = 10.40, p < .01$; Direct: $F(2, 40) = 27.50, p < .01$). Distance estimations increased with increasing intended distance for all conditions (Triangulated: $F(2, 74) = 240.05, p < .01$; Direct: $F(2, 80) = 536.74, p < .01$). As shown in Figures 4 and 5, although distance estimations were more accurate with the mock HMD in the real world compared to the HMD in the virtual environment ($p < .05$ for both Triangulated and Direct), the mock HMD estimations were also significantly

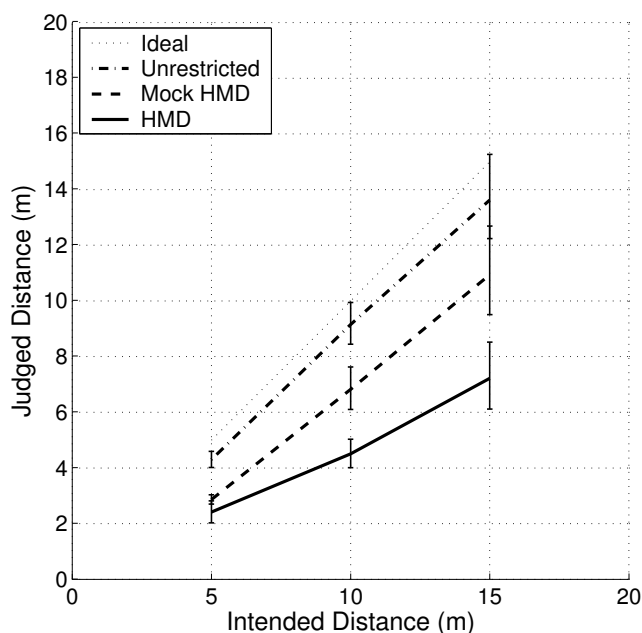


Figure 5: Triangulated walking. Error bars represent ± 1 SEM. The dotted line represents ideal performance.

lower than those in the unrestricted viewing condition ($p < .05$ for both Triangulated and Direct). This pattern of data is suggestive of some compression resulting from judging distances while wearing the mock HMD. For triangulated walking (Figure 5), the data for the unrestricted viewing condition appears to fall slightly below the ideal performance line, unlike our current results for direct walking and our previous findings ([Thompson et al. in press]). 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 ideal 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 viewing and estimating distances while wearing an HMD contributes to the consistent underestimation effects seen across several laboratories. We found greater compression in judgments made in the HMD virtual environment compared to judgments made in the real world while wearing the mock HMD, and greater compression in judgments made while wearing the mock HMD compared to those in the unrestricted viewing condition. These results suggest that the HMD itself cannot explain all of the compression seen in virtual environments and support the notion that other perceptual factors are likely to influence distance estimations in virtual environments. However, our results do indicate that there is a reliable effect of underestimation when viewing the real world with the mock HMD suggesting that mechanical aspects of HMDs account for some of the distance compression effects found in virtual environment research. Additional conditions involving further manipulations of mass and moments of inertia in the same

large room are needed to make stronger conclusions about the impact of the mechanical properties of the HMD on performance.

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