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.


Keywords: perception, virtual reality, head-mounted displays

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 underestimations 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 torque 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
condition using a mock HMD with mechanical properties identical by mass and moments of inertia. If these factors are indeed in-
ggets on the ground crossed with three viewing conditions: a virtual
uencing distance judgments, it is likely that a real world viewing
The experiment tested direct and triangulated blind walking to tar-
tasks involves turning of the head and body which could be affected
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 walk-
tasks, but these studies did not study absolute, egocentric dis-
tance 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 graph-
ics, and photographic panoramas showed no statistically significant
differences [Thompson et al. in press; Willemen and Gooch 2002].
The source of the compression remains an open question. One pos-
sible explanation investigated in this paper is that the underestima-
tion of distance may be arising from static torque forces resulting
from mass distribution near the front of the HMD. This could influ-
ence the angle of declination which would result in a shorter per-
ceived 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 in-
fluencing 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 tar-
gs on the ground crossed with three viewing conditions: a virtual
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 tar-
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 en-
vironment 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
or stepped (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-
tal 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 representa-
tion 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 1: Visually directed actions involving direct and triangulated walking to targets.](image)

![Figure 2: Mock HMD based on NVIS nVisor SX HMD shell used during real world viewing conditions. An neck collar is used to occlude the area around the feet.](image)
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 mismatch. This occurs with the present HMD apparatus due to the mismatch. 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.

### Table 1: Mass and Moments of Inertia

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HMD</th>
<th>Mock HMD</th>
<th>Error (%)</th>
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</thead>
<tbody>
<tr>
<td>$m$ (kg)</td>
<td>1.088</td>
<td>1.088</td>
<td>0.0</td>
</tr>
<tr>
<td>$I_x$ (kg·m$^2$)</td>
<td>0.001965</td>
<td>0.001710</td>
<td>-13.0</td>
</tr>
<tr>
<td>$I_y$ (kg·m$^2$)</td>
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<td>0.010106</td>
<td>7.8</td>
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<tr>
<td>$I_z$ (kg·m$^2$)</td>
<td>0.011776</td>
<td>0.012911</td>
<td>9.6</td>
</tr>
</tbody>
</table>

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

Figure 4: Direct 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.

References


