A Methodology for Quantifying Medium- and Far-Field Depth Perception in Optical, See-Through Augmented Reality

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Abstract

A fundamental problem in optical, see-through augmented reality (AR) is characterizing how it affects human depth perception. This problem is important, because AR system developers need to place graphics in arbitrary spatial relationships with real-world objects, and to know that users will perceive them in the same relationships. However, achieving this is difficult, because the graphics are physically drawn directly in front of the eyes. Furthermore, AR makes possible enhanced perceptual techniques that have no real-world equivalent, such as x-ray vision, where AR users perceive that graphics are located behind opaque surfaces. Also, to date AR depth perception research has examined near-field distances, yet many compelling AR applications operate at longer distances, and human depth perception itself operates differently at medium-field and far-field distances.

This paper describes the first medium- and far-field AR depth perception experiment that provides metric results. We describe a task and experimental design that measures AR depth perception, with strong linear perspective depth cues, and matches results found in the general depth perception literature. Our experiment quantifies how depth estimation error grows with increasing distance across a range of medium- to far-field distances, and we also find evidence for a switch in bias from underestimating to overestimating depth at ~19.4 meters. Our experiment also examined the x-ray vision condition, and found initial evidence of how depth estimation error grows for occluded versus non-occluded graphics.

Keywords: Augmented Reality Depth Perception, Optical See-Through Augmented Reality

CR Categories: H.5 [Information Interfaces and Presentation]: H.5.1: Multimedia Information Systems — Artificial, Augmented, and Virtual Realities; H.5.2: User Interfaces — Ergonomics, Evaluation / Methodology, Screen Design

1 Introduction

Optical, see-through augmented reality (AR) is the variant of AR where graphics are superimposed on a user’s view of the real world with optical, as opposed to video, combiners. Because optical, see-through AR (simply referred to as “AR” for the rest of this paper) provides direct, heads-up access to information that is correlated with a user’s view of the real world, it has the potential to revolutionize the way many tasks are performed. In addition, AR makes possible enhanced perceptual techniques that have no real-world equivalent. One such technique is x-ray vision, where AR users perceive objects which are located behind opaque surfaces.

The AR community is applying AR technology to a number of unique and useful applications [Azuma et al. 2001]. The application that motivated the work described here is mobile, outdoor AR for situational awareness in urban settings [Livingston et al. 2002]. This is a very difficult application domain for AR; the biggest challenges are outdoor tracking and registration, outdoor display hardware, and developing appropriate AR display and interaction techniques.

In this paper we are focused on AR display techniques, in particular how to correctly display and accurately convey depth. This is a hard problem for several reasons. Unlike virtual reality, with AR users see the real world, and therefore graphics need to appear to be at the same depth as co-located real-world objects, even though the graphics are physically drawn directly in front of the eyes. Yet current AR displays are compromised in their ability to display depth (for example, they often dictate a fixed focal depth), and it is not yet known if this is simply due to engineering limitations, or if the limits are more fundamental. Furthermore, there is no real-world equivalent to x-ray vision, and how the human visual system processes x-ray visual information is not yet understood, much less the depth accuracy limitations for applications such as the ones mentioned above.

Human depth perception delivers a vivid three-dimensional perceptual world from flat, two-dimensional, ambiguous retinal images of the scene. Current thinking on how the human visual system is able to achieve this performance emphasizes the use of multiple depth cues, available in the scene, that are able to resolve and disambiguate depth relationships into reliable, stable percepts. **Cue theory** describes how and in which circumstances multiple depth cues interact and combine [Landy et al. 1995]. Generally, depth cues are recognized [Howard and Rogers 2002]: (1) binocular disparity, (2) binocular convergence, (3)accommodation-focus, (4) atmospheric haze, (5) motion parallax, (6) linear perspective and foreshortening, (7) occlusion, (8) height in the visual field, (9) shading, and (10) texture gradient. Real-world scenes combine some or all of these cues, with the structure of the scene determining the salience of each cue. Although depth cue interaction models exist, these were largely developed to account for how stable percepts could arise from a variety of cues with differing salience. The central challenge in understanding human depth perception in AR is how stable percepts can arise from inconsistent, sparse, or conflicting depth cues, which arise either from imperfect AR displays, or from novel AR perceptual situations such as x-ray vision. Therefore, AR depth perception will likely inform both AR technology, as well as depth cue interaction models.

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2 Related Work

Depth cues vary both in their salience across real-world scenes, and in their effectiveness by distance. Cutting [2003] has provided a useful taxonomy and formulation of depth cue effectiveness by distances that relate to human action. He divided perceptual space into three distinct regions, which we term near-field, medium-field, and far-field. The near field extends to about 1.5 meters; it extends slightly beyond arm’s reach, it is the distance within which the hands can easily manipulate objects, and within this distance, depth perception operates almost veridically. The medium field extends from about 1.5 meters to about 30 meters: it is the distance within which conversations can be held and objects thrown with reasonable accuracy; within this distance, depth perception for stationary observers becomes somewhat compressed (items appear closer than they really are). The far field extends from about 30 meters to infinity, and as distance increases depth perception becomes increasingly compressed. Within each of these regions, different combinations of depth cues are available.

There have been a small number of studies that have examined depth perception with optical, see-through AR displays. Ellis and Menges [1998] summarize a series of AR depth experiments, which examined near-field distances of 0.4 to 1.0 meters, and studied an occluding surface (the x-ray vision condition), convergence, accommodation, subject age, and monocular, binocular, and stereo AR displays. McCandless et al. [2000] used the same experimental setup and task to additionally study motion parallax, AR system latency, and the effect of cutting a hole in the occluding surface. In all of these experiments, subjects used a method of adjustment technique: they manipulated the depth of a real object to match the depth of a virtual object. Rolland et al. [1995] discuss a pilot study at near-field distances of 0.8 to 1.2 meters, which examined depth perception of real and virtual objects. The study used a forced choice technique, where subjects must choose one object as “closer” or “farther” than a reference object. Rolland et al. [2002] ran further experiments that examined these topics, but used an improved AR display, and compared forced-choice to method of adjustment techniques. Livingston et al. [2003] discuss an experiment that examined graphical techniques such as drawing style, intensity, and opacity on occluded AR objects at far-field distances of 60 to 500 meters; they used a forced-choice technique.

In addition to the experiments reported above, a large number of visualization tools and interactive techniques have been proposed for viewing and manipulating objects in depth in virtual and augmented reality systems, including hidden or occluded (x-ray vision) conditions. Bane and Höllerer [2004] describe one current effort, which gives a set of far-field, x-ray vision techniques for visualizing the interior structure of buildings. Their paper also contains an extensive review of the work in this area.

3 AR Depth Experiment

When developing our experimental protocol, setting, and task, we pursued the following design goals:

- Study medium- and far-field distances, which interest us because they have not been well-studied in AR, different depth cues operate at these distances, and these distances are meaningful in our application domain [Livingston et al. 2002]. We studied distances between 5.25 and 44.31 meters.
- Determine the fidelity (ordinal or metric) of AR depth perception at these distances. Ordinal fidelity means subjects could only make judgments such as “in front of” or “behind”, which metric implies a continuous sense of depth. We therefore used a method-of-adjustment technique, which allows metric measurements, as opposed to a forced-choice technique, which would only allow ordinal measurements.
- Compare the occluded (x-ray vision) condition to the non-occluded condition.
- Require subjects to simultaneously attend to the real world and virtual objects in order to correctly perform the task. This addresses a criticism of some previous work [Livingston et al. 2003; Gabbard et al. 2005], where subjects could essentially ignore the real world and yet still perform the task.
- Ensure that our task is not 2D solvable, but requires depth perception to correctly perform. A 2D solvable task can be solved by attending to only 2D geometry. For example, if we used only height in the visual field to encode the depth of two virtual objects, then subjects could correctly determine which was farther by noting which had the greater 2D y-coordinate.
Table 1: Independent and dependent variables.

<table>
<thead>
<tr>
<th></th>
<th>independent variables</th>
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<tbody>
<tr>
<td>subject</td>
<td>8 (random variable)</td>
</tr>
<tr>
<td>referent</td>
<td>field of view</td>
</tr>
<tr>
<td>occluder</td>
<td>2, present, absent</td>
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<tr>
<td>distance</td>
<td>8, meters</td>
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<tr>
<td>repetition</td>
<td>10, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10</td>
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<table>
<thead>
<tr>
<th></th>
<th>dependent variables</th>
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<tr>
<td>absolute error</td>
<td>estimated distance – actual distance, meters</td>
</tr>
<tr>
<td>signed error</td>
<td>estimated distance – actual distance, meters</td>
</tr>
<tr>
<td>:+</td>
<td>subject overestimated target distance</td>
</tr>
<tr>
<td>:–</td>
<td>subject underestimated target distance</td>
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- Control the ratio of environmental illumination to AR display brightness. Even though our application domain of mobile AR calls for outdoor use, we needed to control this ratio because our AR system and display cannot adjust to or match outdoor illuminance values. Therefore, we found an indoor space (a hallway) that was large enough to study medium- and far-field distances, and we covered the windows with thick black felt.

3.1 Experimental Task

Figure 1 shows the experimental setting. We seated subjects 3.4 meters from one end of a 50.1-meter long hallway. Subjects looked down the hallway, through an optical, see-through AR display mounted on a frame. Because the display was rigidly mounted, each subject saw exactly the same field of view. Subjects saw a series of eight real-world referents, approximately positioned every 5.6 meters down the hallway (Figure 1). Each referent was a different color. The AR display showed a virtual target, which we drew as a semi-transparent rectangle that filled approximately half of the hallway. Subjects placed their right hand on a trackball; by rolling the trackball forwards and backwards, they moved the target in depth up and down the hallway. For each trial, our software drew the target rectangle at a random initial depth position in the hallway. The software drew the target rectangle with a white border, and colored the target interior to match the color of one of the referents (Figure 1). The software smoothly modulated the opacity of the color according to distance: close to the subject the color was more opaque, and it grew progressively more transparent with increasing distance. This was in addition to the transparency of the graphics induced by the AR display; Livingston et al. [2003] previously determined this to be an effective graphical technique for distance encoding. The software also printed a text label that named the color at the bottom of the display screen.

The subject’s task was to adjust the target’s depth position until it matched the depth of the referent with the same color (Figure 1). When the subject believed the target depth matched the referent depth, they pressed a mouse button on the side of the trackball. This made the target disappear; the display then remained blank for approximately one second, and then the next trial began.

For the display device we used a Sony Glasstron LDI–100B stereo optical see-through display, with SVGA resolution and a 28° horizontal field of view in each eye. We increased the display’s transparency by removing the LCD opacity filter, and we set the display brightness to its maximum setting. We ran the experiment on a Pentium IV 3.06 GHz computer with an Nvidia Quadro4 graphics card, which outputs frame-sequential stereo. We split the video signal, sending one signal to the AR display, and one to a monitor, so we could observe subjects’ progress. We implemented our experimental control code in Java.

3.2 Variables and Design

3.2.1 Independent Variables

Subjects: We recruited eight subjects from a population of scientists and engineers. Seven of the subjects were male, one was female; they ranged in age from 21 to 47. We screened the subjects, via self-reporting, for color blindness and visual acuity. All subjects volunteered and received no compensation.

Field of View: As shown in Figure 1, we placed the referents in the subject’s upper and lower field of view, by mounting the referents either on the ceiling or the floor. Our experimental control program rendered the target in the opposite field of view as the referents.

We manipulated field of view in this experiment because we earlier ran a four-subject pilot experiment with the same task, but with the referents exclusively in the lower field of view. The pilot data suggested that subjects consistently underestimated the target depth, and we hypothesized that this might be due to an implicitly tilted visual reference plane, called a horopter, against which matches are made. In the depth perception community it is well-known that the vertical horopter is tilted, with objects lying physically slightly closer in the lower field of view appearing equidistant to objects in the upper field of view [Tyler 1991]. If subjects in our experiment made depth judgments by matching against a tilted vertical horopter, it should show up as a main effect or interaction with field of view.

Occluder: As discussed above, we are interested in understanding AR depth perception in the x-ray vision condition. When the occluder was absent (Figure 1, (a) and (c)), subjects could see the hallway behind the target. When the occluder was present (Figure 1, (b) and (d)), we mounted a heavy rectangle of foamcore posterboard across the subject’s field of view, which occluded the view of the hallway behind the target. We carefully positioned the occluder so that it did not cut off the subject’s view of the bottom (top) of the referents, and yet so it fully occluded the target throughout the entire possible depth range.

Because the hallway’s linear perspective becomes quite compressed at 50 meters, we had to calibrate the position of the occluder and the display. In fact, the tightness of this positioning was our original motivation for rigidly mounting the display: without it, subjects could easily look over (or under) the occluder to see an unoccluded view of the target, by moving their head up or down only a few centimeters. In addition, our hallway contains a dark, wooden molding between the brown-colored lower walls and the cream-colored upper walls (Figure 1). In the occluded condition, when the referents were in the lower field of view (Figure 1 (d)), this molding formed a strong linear perspective cue that was missing when the field of view was reversed (Figure 1 (b)). Therefore, we carefully positioned and applied black gaf-
Figure 2: The general results from the first study, indicating where subjects placed the targets (blue line), versus the actual referent locations (red line).

Referent Distance: We placed the eight referents at the distances from the subject indicated in Table 1; these distances are measured from the front of the Glasstron AR display. We positioned the referents left and right in the visual field so that they were all visible from the subject’s position. As indicated in Table 1, we placed three of the referents adjacent to a wall and the last referent in the very center; we slightly offset the remaining four referents from the center. In person, it was easier to perceive the far referents than it is to see them in Figure 1.

We built the referents out of triangular shipping boxes, which measured 15.3 cm wide by 96.7 cm tall. We covered the boxes with the colors listed in Table 1; these are the eight chromatic colors from the eleven basic color terms, which are the colors with one-word English names that Smallman and Boynton [1993] have shown to be maximally discriminable and unambiguously named, even cross-culturally (the remaining color terms are ‘white’, ‘black’, and ‘grey’). We created the colors by printing single-colored sheets of paper with a color printer. To increase the contrast of the referents, we created a border around each color with white gaffer’s tape. We affixed the referents to the ceiling and floor with Velcro.

Repetition: We presented each combination of the other independent variables 10 times.

3.2.2 Dependent Variables

For each trial, subjects manipulated a trackball to place the target at their desired depth down the hallway, and pressed the trackball’s button when they were satisfied. The trackball produced 2D cursor coordinates, and we converted the y-coordinate into an estimated target distance, which we used to render the target rectangle. When a subject pressed the mouse button, we recorded the estimated target distance, and used this to calculate and record absolute error and signed error, using the formulas shown in Table 1.

3.2.3 Experimental Design and Procedure

We used a factorial nesting of independent variables for our experimental design, which varied in the order they are listed in Table 1, from slowest (subject) to fastest (repetition). We collected a total of 2560 data points (8 subjects * 2 fields of view * 2 occluder states * 8 distances * 10 repetitions). We counterbal-
importance for designers of AR x-ray vision techniques, it was when the occluder was present. Although this finding has practical depth cue beyond about 10 meters [Cutting 2003].

Menges determined that this occurred because the occluder estimated target distance closer to the subject. However, Ellis and in a near-field experiment, they found that an occluder pushed this result diverges from the findings of Ellis and Menges [1998];

The bias shift occurs at the 11.34 meter referent — the 5.25 meter referent is close enough that stereopsis is still available as a depth cue, but by 11.34 meters subjects have transitioned from using stereopsis to using linear perspective. The bias shift is another manifestation of the absolute error increasing with distance (Figure 5).

Figure 6 shows the effect of distance on signed error ($F(7,49) = 3.20, p = .007, \eta^2 = 7.31\%$). Signed error generally displayed the same effects as absolute error (Figure 5): signed error increased with distance, and linear modeling of all of the data (black line), and the data split into wall data (red line), and non-wall data (blue line), indicates that error and rate of error growth were reduced when referents were next to a wall. However, the $r^2$ values indicate that linear models do not explain as much variance as they did for absolute error (Figure 5); this is particularly true for the wall data. Comparing the relative magnitude of the confidence intervals between Figures 5 and 6 indicates there is more variability in signed error, because with absolute error positive and negative values with nearly the same magnitude are folded over into values that are nearly equal.

The most interesting finding from signed error, which is not seen in the absolute error results, is evidence of a shift in bias from underestimating to overestimating target distances (Figure 6). This begins at the 11.34 meter referent — the 5.25 meter referent is close enough that stereopsis is still available as a depth cue, but by 11.34 meters subjects have transitioned from using stereopsis to using linear perspective. The bias shift occurs at around 19.4 meters, which is where the black line in Figure 6 crosses zero meters of signed error. Before this point, subjects underestimated target distances (negative signed error); after this
repeated-measures design described in Table 1, except that we
and 6, we conducted an ANOVA analysis which followed the
Menges 1998; McCandless et al. 2000; Rolland et al. 1995; Rol-
AR depth studies that examined near-field distances [Ellis and
position
point, subjects increasingly overestimated target distances (positive
signed error). This bias shift has not been found by previous AR
depth studies that examined near-field distances [Ellis and
References are the only two that lie below the red regression line;
7 also shows an interesting effect for the two wall referents at
increasing distance which is similar to what has been found in a
large body of depth perception literature (Figure 3). Our experi-
ment has quantified how depth estimation error grows with in-
creasing distance (Figure 5) across a range of interesting medium-
to far-field distances. We have also detected evidence for a
switch in bias, from underestimating to overestimating distance, at
~19.4 meters (Figure 6), and finally, we quantified how depth
error grows for occluded versus non-occluded graphics (Figure 7).

However, like most controlled user studies, this one had many
limitations that restrict the generality of our findings. We list a
few limitations here; all of them suggest future experiments, some
of which we plan to conduct:

- We only examined a subset of the depth cues discussed in the
  Introduction, and features in the hallway, such as the ceiling
  lights and molding, gave very strong linear perspective cues (Figure 1). This is the likely the reason why there was not an
even higher cost for the occluded condition (Figure 7): subjects
were able to use linear perspective cues from the non-occluded
referents to help place the occluded graphics. However, there
are AR applications, such as visualizing building interiors,
which can use strong linear perspective cues [Bane and
Höllerer 2004]. We would like to run a similar experiment in a
large room instead of a hallway, where we could control the
strength of linear perspective cues with appropriately placed
props.

- Like most optical see-through AR user-based studies to date, a
  large limitation is the optical quality of our AR display itself:
although they have been widely used in AR research, the Sony
Glasstron was originally designed for personal use and general
desktop applications. We are interested in potentially building
an AR display out of off-the-shelf optical components, similar
to the one built by Rolland et al. [2002]. This is especially im-
portant for near-field depth experiments, where cues that are
strongly influenced by display optics, such as binocular dispar-
ity and accommodative focus, are dominant.

- In our task subjects only manipulated the depth of a virtual
target to match the depth of a real referent. We might find dif-
dent results if subjects matched a real target to a virtual refer-ent, like Ellis and Menges [1998] and McCandless et al. [2000].
We have already conducted a study where we compared matching
both real and virtual objects to real referents [Livingston et
al. 2005].

- A challenging AR visualization related to x-ray vision involves understanding how depth perception operates when users per-
ceive multiple, semi-transparent layers of occluded informa-
tion. Livingston et al. [2003] studied this issue, but only meas-
ured ordinal depth perception, and did not require subjects to
attend to the real world. We would like to conduct a similar

Figure 7: Subjects had more error in the occluded (x-ray vision)
condition (red line and points) than in the non-occluded condition
(black line and points), and the difference between the occluded
and non-occluded conditions increased with increasing distance.

Figure 7 shows an occluder by distance interaction on abso-
lute error ($F(7,49) = 2.06, p = .066; \eta^2 = .97\%$). When an
occluder was present (the x-ray vision condition), subjects had more
error then when the occluder was absent, and the difference be-
between the occluder present and occluder absent conditions in-
creased with increasing distance. Figure 7 also shows a linear
modeling of the occluder present condition (red line), which
explains $r^2 = 28.9\%$ of the observed variance, and a linear modeling
of the occluder absent condition (black line), which explains $r^2 =
29.3\%$ of the observed variance. The slope of the occluder pre-
sent (red) line is larger than the occluder absent (black) line; the
slopes (1) indicates that the occluded condition becomes increas-
ingly more difficult than the non-occluded condition with in-
creasing distance, and (2) estimate the magnitude of this effect.
Figure 7 also shows an interesting effect for the two wall referents
at 22.26 and 33.34 meters. When the occluder is present, these wall
referents are the only two that lie below the red regression line;
this pattern is not repeated when the occluder is absent. This in-
dicates that in the occluded condition, where most linear perspective
cues from the hallway are missing, subjects can still gain some
linear perspective by aligning the target with a wall (Figure 1); but
this is only helpful when the referent is against a wall. In the non-
 occluded condition there are enough perspective cues that subjects
do not attend as closely to the wall. Thus, Figure 7 shows that
most of the wall effect from Figures 5 and 6 comes from the oc-
cluded condition.

4 Discussion and Future Work

As discussed in the Introduction, AR has many compelling appli-
cations, but some will not be realized until we understand how to
place graphics in depth relative to real-world objects. This is
difficult because imperfect AR displays and novel AR perceptual
situations such as x-ray vision result in conflicting depth cues. Our
study contributes to the important task of understanding AR
depth perception.

To our knowledge, we have conducted the first experiment that
metrically examines AR depth perception at medium- and far-
field distances, which are important distances for a number of
compelling AR applications. We have demonstrated an experi-
mental task and design that measures depth perception, finding a
linear relationship between estimated depth variability and in-
creasing distance which is similar to what has been found in a
large body of depth perception literature (Figure 3). Our experi-
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study, based on the methods and task of the experiment reported here, that measures depth sorting ability metrically.

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