A Replication Study to Measure the Perceived Three-Dimensional Location of Virtual Objects in Optical See Through Augmented Reality

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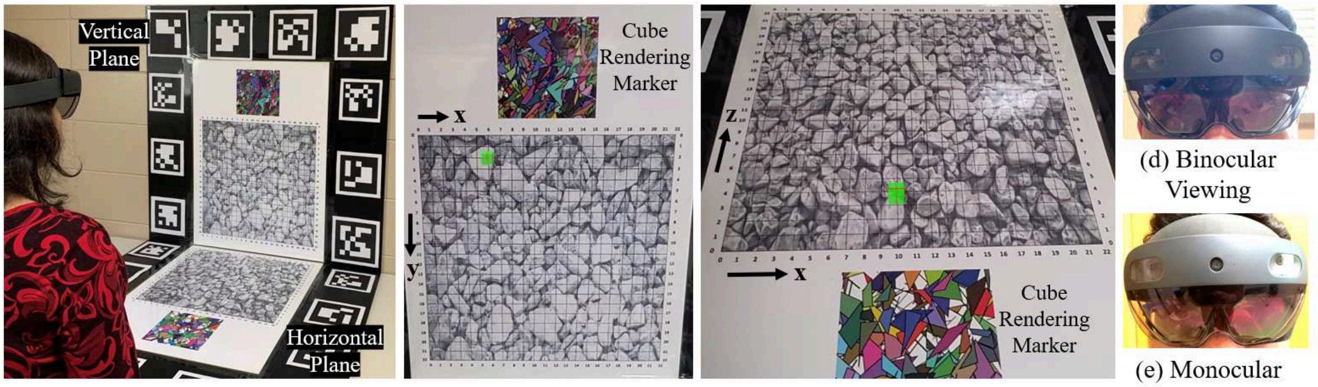

(a) Experimental Setup (b) Vertical Plane (c) Horizontal Plane (d) Binocular Viewing (e) Monocular Viewing

Figure 1: Experimental overview. (a) Participant is viewing the vertical and horizontal plane. (b) View of the green virtual cube marked with a pair of lines through the HoloLens 2nd generation AR display on the vertical plane, and (c) horizontal plane. Participants verbally reported the estimated perceived virtual cube's center location along the x, y, and z axis. (d) Two eyes are open in the binocular condition. (e) Only the dominant eye is open; the other eye is covered with an eye-patch in the monocular condition.

ABSTRACT

An important research question in optical see-through (OST) augmented reality (AR) is, how accurately and precisely can a virtual object's real world location be perceived? Previously, a method was developed to measure the perceived three-dimensional location of virtual objects in OST AR. In this research, a replication study is reported, which examined whether the perceived location of virtual objects are biased in the direction of the dominant eye. The successful replication analysis suggests that perceptual accuracy is not biased in the direction of the dominant eye. Compared to the previous study's findings, overall perceptual accuracy increased, and precision was similar.

Index Terms: Augmented Reality—Depth Perception—Optical see-through Display—Replication Study

1 INTRODUCTION

In optical see-through (OST) augmented reality (AR), users can see virtual objects superimposed on the real world environment, and it appears to users as if the real and virtual objects co-exist in the same space. A well-established goal while using OST AR is *locational realism*: virtual objects appear to be located precisely where intended in the real world. For example, consider a scenario where a surgeon uses an OST AR display to map a needle inserted to a tumor's position visualized through an AR *x-ray vision* application. In this case, it is important for the surgeon to clearly understand the location presented by the AR display. Similar contexts are also present among other fields, such as manufacturing, maintenance, and law enforcement, where AR applications require accurate and precise presentation and perception of the virtual objects' location.

Previously, Khan et al. [2, 3] proposed a new method to measure the perceived three-dimensional location of virtual objects presented through a Microsoft HoloLens 1st generation AR display. However, they observed an unexplained rightward bias on the horizontal plane. They stated that this rightward bias might be explained by eye dominance, which has not been previously considered. In addition, they called for a replication of their study to test the hypothesis that the perceived location of the virtual object is biased in the direction of the dominant eye. Therefore, the purpose of the current study was to partially replicate the experimental task of Khan et al. [2, 3], using the latest OST AR display (HoloLens 2nd generation), and including binocular and monocular viewing conditions. This tests the hypothesis. Besides, unlike the 1st generation, the Hololens 2nd generation OST AR display uses an eyetracking calibration method, which likely gives more accurate and precise hologram alignment and stability. Therefore, another purpose of the experiment was to examine whether a more modern OST AR display (HoloLens 2nd generation) increases overall perceptual accuracy and precision.

2 EXPERIMENT

In this experiment, the task and experiment reported by Khan et al. [2, 3] was partially replicated. Participants wore a HoloLens 2nd generation display and stood in front of the experimental table (see Figure 1a). The table supported a vertical plane (x,y) (Figure 1b) and a horizontal plane (x,z) (Figure 1c) mounted together, which could be used to measure perceived location in three dimensional (x,y,z) space. Both grid systems ranged from 1 to 22, and each grid cell was 2×2 cm. Participants saw a $2 \times 2 \times 2$ cm green virtual cube marked with a pair of intersecting lines, placed in one of the two planes (Figures 1b,c) at distances of 50 to 80 cm. There were 10 randomly chosen virtual cube locations for each plane. As a primary task, the participant estimated the grid coordinate of the cube

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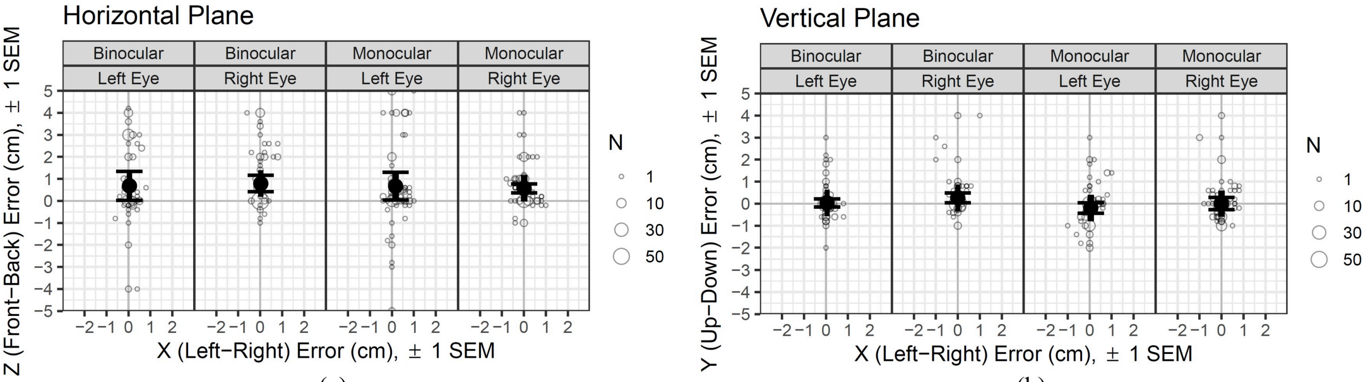

(a) (b)

Figure 2: Experimental error results. (a) and (b) show the result for the horizontal and vertical planes. The perceptual errors between the perceived and intended locations are shown in hollow circles and size indicate the number of errors on that location. Black points represent the total mean error and the error bars indicate the standard error of mean (SEM) which represent precision. Both (a) and (b) are divided into four facets according to the viewing conditions; the left two panels shows the results for the binocular viewing condition for left eye and right eye dominant participants, and right two panels show the result of the monocular viewing condition for left eye and right eye dominant participants.

center position along the (*x,y*) or (*x,z*) axis, and verbally reported it to the experimenter. During the monocular viewing condition, participants observed the virtual cube with the dominant eye, while the non-dominant eye was covered with an eye patch (see Figure 1e). In contrast, during the binocular viewing condition, participants observed the virtual cube with both eyes open (see figure 1d).

In our experimental design, we manipulated the variables of *plane* (vertical, horizontal), *viewing* (monocular, binocular), and *intended location* (1–10). We measured the perceived cube locations relative to the grid surface as a dependent variable. Each participant observed a total of $2\ (\textit{plane}) \times 2\ (\textit{viewing}) \times 10\ (\textit{intended location}) = 40$ trials. The experimental variables were properly counterbalanced between participants. We recruited 24 participants for our experiment, with an equal number of left eye (12) and right eye (12) dominant participants. Among them, 13 were male, and 11 were female, with a mean age of 24.38 years.

3 RESULTS

Horizontal Plane (Figure 2a) Under binocular viewing with left eye dominant participants, the *x* (left-right) axis has a precision of 0.44 mm SEM and an accuracy of +0.44 mm. The *z* (front-back) axis shows less precision (6.57 mm SEM) and less accuracy (+6.84 mm backward bias). Under binocular viewing with right eye dominant participants, the *x* (left-right) axis shows a precision of 0.37 mm SEM and an accuracy of +0.27 mm. The *z* (front-back) axis has less precision (3.74 mm SEM) and less accuracy (+7.87 mm backward bias). Under monocular viewing with left eye dominant participants, the *x* (left-right) axis has a precision of 0.63 mm SEM and accuracy of +1.68 mm. For the *z* (front-back) axis, precision drops to 6.30 mm SEM and has a backward bias of +6.67 mm. Under monocular viewing with right eye dominant participants, the *x* (left-right) axis has a precision of 0.68 mm SEM and an accuracy of +0.10 mm. The *z* (front-back) axis shows less precision (2.02 mm SEM) and less accuracy (+5.72 mm backward bias).

Vertical Plane (Figure 2b) In binocular viewing with left eye dominant participants, the *x* (left-right) axis shows a high precision of 0.35 mm and accuracy of +0.48 mm. For the *y* (up-down) axis, precision rises to 1.80 mm SEM and has a slight upward bias of +0.33 mm. Under binocular viewing with right eye dominant participants, the *x* (left-right) axis has a high precision of 0.23 mm and very high accuracy of -0.03 mm. The *y* (up-down) axis has a precision of 2.25 mm SEM and has a slight upward bias of +0.27 mm. Under monocular viewing condition with left eye dominant participants, the *x* (left-right) axis has a high precision of 0.58 mm SEM, and an accuracy of +0.48 mm. The *y* (up-down) axis shows less precision at 2.40 mm SEM, and a small downward bias of -1.98 mm. Under monocular viewing with right eye dominant participants, the *x* (left-right) axis has a precision of 0.66 mm SEM, and high accuracy of -0.04 mm. The *y* (up-down) axis has less precision (2.78 mm SEM) and high accuracy of close to zero millimeters.

4 DISCUSSION

We have successfully partially replicated the experimental task of Khan et al. [2, 3] to determine if the observed rightward bias in the horizontal plane is related to eye dominance. Unlike the previous experiment, we did not observe any high rightward bias; the judgments are generally accurate in both binocular and monocular viewing conditions, for both left and right eye dominant participants. In addition, a backward bias in the horizontal plane along the *z* (front-back) axis is observed, meaning participants observed the virtual object farther than intended (overestimation) in each viewing condition. This supports previous overestimation results in AR, such as Fischer et al. [1]. While examining whether there is an overall improvement of perceptual accuracy and precision with a HoloLens 2nd generation OST AR display, compared to the previous study's results, overall accuracy increased, while precision remained similar.

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