Distance Judgments to On- and Off-Ground Objects in Augmented Reality

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ABSTRACT

Augmented reality (AR) technologies have the potential to provide individuals with unique training and visualizations, but the effectiveness of these applications may be influenced by users' perceptions of the distance to AR objects. Perceived distances to AR objects may be biased if these objects do not appear to make contact with the ground plane. The current work compared distance judgments of AR targets presented on the ground versus off the ground when no additional AR depth cues, such as shadows, were available to denote ground contact. We predicted that without additional information for height off the ground, observers would perceive the off-ground objects as placed on the ground, but at farther distances. Furthermore, this bias should be exaggerated when targets were viewed with one eye rather than two. In our experiment, participants judged the absolute egocentric distance to various cubes presented on or off the ground with an action-based measure, blind walking. We found that observers walked farther for off-ground AR objects and that this effect was exaggerated when participants viewed off-ground objects with monocular vision compared to binocular vision. However, we also found that the restriction of binocular cues influenced participants' distance judgments for on-ground AR objects. Our results suggest that distances to off-ground AR objects are perceived differently than on-ground AR objects and that the elimination of binocular cues further influences how users perceive these distances.

Keywords: Augmented reality, Virtual environments, distance perception, depth cues

Index Terms: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual Reality; J.4 [Computer Applications]: Social and Behavioral Sciences—Psychology

1 INTRODUCTION

Due to recent advances in optical see-through head mounted displays, augmented reality (AR) has begun to permeate the domains of entertainment, education, and engineering. The improved quality and accessibility of this technology has made AR devices, such as the Microsoft HoloLens, targets for new application development. To illustrate, AR solutions have already been developed to aid architecture, design, and medical imaging [1, 5, 12, 22]. However, to optimally use this technology, it is essential that we understand how users perceive and interact with virtual objects in mediated reality. Recent reviews demonstrate widespread study of human behavior within AR over the last 15 years [2, 10]. However, open questions remain about human spatial perception in augmented reality and the depth cues that are used when virtual and real worlds coexist.

Our current work investigates the accuracy of observers' distance perception to virtual objects when the objects are presented on or off the ground in the real world. The ability to perceive absolute distances to objects in AR is critical to many applications that require an understanding of scale, such as environmental simulations for training and architectural design. To act accurately, a person must perceive spatial relationships of virtual objects in the same way that they would be perceived in the physical world. Prior research both in virtual environments (VEs) and AR has shown a tendency to underestimate distances [11, 19, 33, 34, 36]. In AR, accurate positioning of virtual objects has unique challenges, requiring computer visual input, visual markers, and virtual world anchors to build accurate perceptions and references of the real world. For example, the Microsoft HoloLens' spatial mapping capabilities, although impressive, require certain conditions to accurately visualize the real-world environment and place virtual objects within it.

Although a variety of studies evaluating distance perception in immersive technology have been conducted, little research has been done to examine the effect that an object's contact with the ground has on depth perception within augmented reality. Examining this effect is important, as previous real-world research has shown that depth estimates can be overestimated for objects that appear to be floating over a surface [26]. Since there is a demonstrated effect of the ground plane on distance estimations in the real world [13], it is important to consider similar ground contact effects on depth perception for virtual objects in AR.

2 BACKGROUND

2.1 Distance perception in real, virtual, and augmented environments

In this paper, we assess judgments of absolute egocentric distance to targets either on the ground or off the ground. Egocentric distance is defined as the distance between the viewpoint of the observer and a specified target location. A variety of measures can be used to assess absolute, egocentric distances, including but not limited to verbal reports of the distance in a specified metric, visually matching the distance with another extent, and walking without vision to the previously viewed target (termed *blind walking*). The current paper uses blind walking to measure egocentric distance perception, because judgments of absolute egocentric distance are accurate when assessed with blind walking in the real world up to approximately 15 meters [30]. However, research over the past 20 years assessing participants' abilities to blind walk to targets in virtual environments has shown underestimation of distance (see [7, 29] for recent reviews). This underestimation ranged from 40-80% of real world distances–depending on the lab and the measure of distance perception–and was generally present in most HMDs and tracking systems [7]. It has only been with the recent advent of commodity-level HMDs that distance underestimation in virtual environments has reduced. Studies evaluating distance estimation in these devices via blind walking have reported 10% or less underestimation [6, 8, 31].

Prior work assessing distance perception in AR showed mixed results regarding accuracy of distance judgments. For example, one

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study comparing blind walked estimates of the distance to objects in a virtual hallway compared to a visually matched real hallway with objects displayed through augmented reality found similar underestimation (60% of real distances) of AR judgments and VR judgments [14]. However, other work found that distance judgments made in AR were similar to those made in the real world [16,25,33]. Evidence from a study using a video see-through AR device suggests that stereoscopic cues and relative size cues can be particularly important for accurate distance estimation in AR [18]. Improvements in distance estimation can also sometimes be due to the training and feedback given to participants in these augmented environments [14, 34]. One particularly relevant study for the current work was conducted by Swan and colleagues [32]. They seated observers in a hallway and asked them to visually match distances between approximately 5 and 45 meters. But, in addition to the targets (which were always placed on the ground), the researchers also placed referent objects in the hallway in either the upper field of view or the lower field of view (i.e., on the ceiling or the ground). Distances were underestimated up to 23 meters, but past 23 meters they were overestimated. This finding was qualified by the location of the referents. When the referent objects were in the upper field of view, participants overestimated closer targets, but when the referents were in the lower field of view, participants underestimated closer targets. Such disparity in estimation could be due to the referents being on or off the ground plane, even though the targets were all on the ground plane. In the following section, we review studies that have investigated the effects of ground contact for perceived location.

2.2 Visual information for object contact with the ground plane and distance perception

Objects in the real world typically make contact with the ground plane, or are set on surfaces that contact the ground. Gibson's [13] ground theory of perception argued for the importance of the ground surface for terrestrial animals to perceive distance. In the absence of information to the contrary, an object silhouetted against a ground surface will appear to be in contact with the ground surface and at a depth from the viewer corresponding to the occluded portion of the ground [4]. The perceived distance may be influenced by an illusory decrease in angular declination below the horizon, which is an important visual cue for viewers standing on the ground that inversely relates to distance estimates made for objects on the ground surface [21]. Multiple different visual cues provide information about the contact of objects with a ground plane. A lack of these cues facilitates the ground contact effect for objects that are in fact above ground level. Many of these same cues can provide explicit non-contact information, thus inhibiting the ground contact effect. When this occurs, not only will the object be seen to be floating above the ground surface, but due to its 3-D position being constrained by the line of sight, it will appear to be nearer to the viewer than the occluded portion of the ground.

In many cases, shadows and interreflections (e.g., the result of light reflecting from the object surface to the ground surface) provide the strongest evidence for whether or not an object is in contact with a support surface [17, 20]. Binocular stereo may also be able to discriminate between contact and non-contact in two ways, but few controlled studies have directly tested these potential effects. One way is by indicating whether or not the three-dimensional location of an object and a surface viewed immediately below are compatible with contact. Alternatively, stereo might provide ordinal or relative depth information about the relationship of the bottom of an object and the surface immediately below in the view. Prior work has shown that stereoscopic viewing, shadows, and interreflections do influence participants' judgments of distance between a virtual block and a virtual table surface [15]. However, this study was conducted in *personal space* rather than *action space* (spaces that extend between 2–30 m), which is the focus of the current work [9]. Rand [26] demonstrated the importance of perceived ground location on absolute distance judgments in action space in the real world by placing targets on stands and then degrading viewing conditions so that the stand could or could not be perceived. When the stand was visible, viewers accurately judged distances to the targets. When the stands were not detectable, participants overestimated the target distance, consistent with the notion that they grounded the targets at a location where they were visually projected, not where they were physically located.

2.3 Overview of Current Study

In the current experiment, we varied ground contact of augmented targets (cubes) by assessing the absolute distance perception to those targets from an egocentric viewpoint. Our primary goal was to determine whether distances to the AR cubes would be perceived accurately and how ground contact or lack of it would affect these judgments. Given prior work suggesting that stereoscopic information can affect interpretations of object contact with a surface [15], we also manipulated whether the cubes were viewed monocularly or binocularly. Viewing the cubes monocularly will eliminate stereoscopic information for depth, which should interact with the presentation of the cubes as contacting the ground or not. Specifically, without binocular information for the near ground surface, it should be more difficult to localize the targets when off the ground, and more likely that observers would perceive the off-ground objects at the location where they visually intersect the ground (i.e., on the ground but farther away). Thus, we predicted the following:

H1: Distances would be underestimated as demonstrated in prior AR work.

H2: Distances would be judged to be farther for targets off the ground versus on the ground.

H3: Distances to off-ground targets would be judged as farther away with monocular compared to binocular viewing. Distance judgments would not change as a function of viewing condition for on-ground targets.

3 ASSESSING DISTANCE JUDGMENTS TO ON- AND OFF-GROUND OBJECTS

3.1 Calibration of Cube Placement

Traditional studies assessing depth perception often present targets to observers in very sparse environments in order to control for relative comparisons and alternate strategies for judging distance [23, 24]. However, this practice poses a problem for the HoloLens tracking system, which relies on stable objects in the environment to accurately and reliably place targets at correct distances on each trial. In order to determine whether a somewhat sparse laboratory environment would make reliable placement of targets difficult across participants and trials, we conducted a preliminary study to assess the placement accuracy and potential drift of our virtual targets with the Microsoft HoloLens across two different laboratory spaces. The studies took place at Vanderbilt University and the University of Utah. Those participants run at Vanderbilt viewed the targets in a second floor hallway with a railing on one side. Those participants run at Utah viewed the targets in a rectangular lab room (4m x 9.5m) without furniture. Ten participants, distributed across the two labs, viewed virtual cubes placed at 5 distances (4m–8m in 1m increments). All participants had normal or corrected-to-normal vision.

A custom AR environment was created for the HoloLens, which weighs approximately 579g and has a graphical field of view of 30° X 17° (i.e., graphical AR objects can appear within an eyebox of these dimensions). The environment was designed using Unity (version 2017.4.4) on a Windows 10 laptop and run as a standalone application. Participants used a Microsoft HoloLens to view virtual cubes (20cm x 20cm x 20cm) at distances of 4m, 5m, 6m, 7m, and 8m from an augmented green line. All of the cubes were assigned a marble texture and presented on the ground. A HoloLens clicker was used to toggle the visibility of the cubes such that only one cube was visible to the participant at any given point.

To try to increase accuracy and stability of cube placement, a scan of the testing environment was done and uploaded into Unity prior to building the application. After giving consent, participants were asked to put on the HoloLens and align themselves directly behind a virtually augmented green starting line on the floor. Once in this starting position, participants' next task was to align a real world cube with each AR cube before and after walking in the environment. If adjustments from the first alignment were necessary after the participants walked in the environment, the experimenter recorded the distance between the original and final placement of the real world cube.

The sparseness of the environment mattered in terms of reliable and accurate augmented cube placement. Mean drift for cubes in the Vanderbilt environment was 0.15 cm (*SD* = 0.31 cm) whereas mean drift distance for the Utah environment was 2.08 cm (*SD* = 3.10 cm). In addition, the program seemed more unstable in the Utah environment. This discrepancy could be explained by the structure of the hallway and railing in the Vanderbilt environment, which likely provided the HoloLens' sensors with more reliable reference points. In contrast, the open and sparse Utah environment may have hindered the HoloLens' ability to accurately sense and map the room.

In order to counteract this problem, visual features in the form of chairs were added to the Utah environment along the walls. Two additional participants were then run with these visual features in the Utah environment. Mean drift for the cubes was reduced to 0.48 cm (*SD* = 0.89 cm). Given these results, we determined that variability in distance judgments would dwarf slight placement issues with the HoloLens and render the effect of drifting null. Thus, drift error in these environments was deemed tolerable for further experiments.

4 DISTANCE PERCEPTION EXPERIMENT

The results from the calibration study indicated that AR cubes can be reliably placed at various distances with the HoloLens. Given this, the current experiment manipulated distance to the cubes (3m, 4.5m, and 6m) and viewing condition (monocular or binocular) as within-participants variables and presentation of the cubes as on or off the ground as a between-participants variable.

4.1 Participants

Participants were recruited from the University of Utah Department of Psychology participant pool. In total, we collected data on 33 participants, but 4 were excluded due to technical issues and 1 participant withdrew from the study. This left us with 14 participants in the on-ground condition (8 Male, $M_{\text{age}} = 21.29$, $SD = 4.44$) and 14 participants in the off-ground condition (7 Male, $M_{\text{age}} = 23.21$, $SD = 10.09$). An independent samples t-test revealed that the participants in the on- and off-ground conditions did not differ significantly in height ($p = 0.628$) or eye height ($p = 0.839$).

4.2 Materials and Methods

Participants completed one of two conditions (on-ground or off-ground targets) of the experiment in the same rectangular lab room (4m x 9.5m) used for the calibration study (see Figures 1 and 2). All the stimuli in the off-ground condition were displayed at 0.2m above the ground plane. Within each condition, the participants viewed a series of 18 cubes (20cm x 20cm x 20cm) presented at 3 distances (3m, 4.5m, 6m). The three cube distances were repeated 3 times in both the first and second block of trials. We used the same AR cubes that were used in our calibration study. Trials were blocked by viewing condition (monocular and binocular viewing). The order of viewing conditions was counterbalanced across participants. The experimental builds were programmed in Unity (Version 2017.4.4) on a Windows 10 laptop and run as independent applications on the Microsoft HoloLens.

Figure 1: An example of an AR cube trial as it was run in the real world laboratory space.

Figure 2: A participant viewing an AR cube with the HoloLens in the real world laboratory space.

After obtaining consent, participants' stereo vision was assessed with a random dot stereogram test. The experimenter then measured eye dominance by asking participants to look through a small hole in poster board and align their gaze to a target in the back of the room. While aligned with the target, the participants closed one eye and kept the other open. The eye for which participants could still see the target with when open was considered their dominant eye. After eye dominance was determined, the participant was given practice with the blind walking procedure in a different part of the laboratory. The experimenter stood beside the participant with their arm out for support and guided the participant to the other side of the room with their eyes closed. They then led them back to the starting location with the experimenter guiding them by their shoulders. Once the participant felt comfortable with blind walking and being led back to a location without vision, the participant put on the HoloLens with or without an eyepatch on (to correspond to viewing condition) and began the experiment.

On each trial, the participants first aligned their toes with the edge of an augmented green bar displayed on the floor. They then used the verbal command ”advance” in order to generate a cube. Participants were given as much time as they needed to view the cube and its distance from them before they blind walked. When the participant felt ready to blind walk, they used the verbal command ”ready” to make the cube disappear and then walked to where they previously saw the cube with their eyes closed. When the participants stopped, they remained at that location with their eyes closed while the experimenter measured the distance walked from the start line to their toes. The experimenter then guided the participant back to the start area in a circuitous pattern so that participants could not count steps or use any other strategy to determine distance walked. After the ninth trial, the start line changed color to indicate that the first block of the experiment was complete. At this point, the experimenter had participants either remove their eyepatch or place one on their non-dominant eye. The second block of trials followed the same procedure. At the end of the experiment, the experimenter collected the participants' height, eye height, and their responses to a brief debriefing.

Table 1: Mean blind walked distances for each condition

	On-ground		**Off-ground**		
Distance	Binocular	Monocular	Binocular	Monocular	Predicted Distance
300	256 (39.2)	247 (33.1)	272 (37.8)	279 (38.0)	342
450	386 (61.2)	374 (61.3)	419 (50.7)	426 (59.3)	513
600	531 (71.5)	517 (63.4)	546 (53.2)	570 (77.3)	684

Note: Values represent average blind walked distances in cm. Values in parentheses represent standard deviations. The predicted distances represent how far the off-ground cubes would appear to be if they were interpreted to be on the ground, and were calculated with the following equation: $PredictedDistance = EyeHeight_{avg} * CubeDistance / Eyeheight_{avg} - Cubeheight$

4.3 Data Analysis

In order to investigate the influence of cube distance, cube height, and viewing condition, we analyzed our results with a mixed model approach (see Appendix for model details). Mixed models are a form of generalized regression techniques that can account for both between-participant variability (in this case, the variability between the two cube height conditions) and within-participant variability (in this case, the variability within each participant across distance and viewing condition). The mixed models we ran were comparable to a repeated measures ANOVA (analysis of variance) with planned comparisons, but with the added advantage of model specification. This allowed us to include only the interactions that were hypothesized *a priori* which also increased our power to detect differences. Furthermore, they are well suited for nested experimental designs, i.e., repeated measures designs [27].

We designed our model to test four planned comparisons. These comparisons were 1) the difference in judged distance between on-ground and off-ground cubes across all other conditions, i.e., H2: the main effect of cube height; 2) whether the on/off ground manipulation differed by distance (the interaction between distance and cube height); 3) whether the on/off ground manipulation differed by viewing condition, i.e., H3: the predicted effect of monocular viewing on off-ground objects; and 4) the interaction between cube height and viewing order. Our fourth comparison was included to ensure that our results were not confounded by the order of viewing condition. Given that these comparisons were planned and orthogonal to each other (i.e., they test different conceptual questions), a correction for multiple comparisons was not necessary. We report the results of these comparisons below along with their respective unstandardized coefficients. The unstandardized coefficients (B) represent the expected difference of each comparison in raw units (cm). Practical significance is also estimated by reporting Cohen's d, which we calculated by dividing the unstandardized beta coefficients by the standard deviation of our outcome variable [28].

4.4 Results

H1: Distances to AR targets would be underestimated. As shown in Figure 3, both on-ground and off-ground targets were underestimated. On average, participants underestimated distances to on-ground cubes by 15% (Min = 13%, Max = 16%) and underestimated distances to off-ground cubes by 7% (Min = 6%, Max = 8%). Additionally, the figure shows that participants increased their judged distances as actual distance of the cube increased. Specifically, participants walked on average about 130 cm further to the 4.5 m cube (B = 128.92, SE = 6.19, t = 20.83, $p < .001$, d = 1.01) and about 270 cm further to the 6 m cube (B = 272.64, SE = 6.19, t = 44.04, $p < .001$, d = 2.14) relative to the distance they walked to the 3 m cube.

H2: Distances would be judged to be farther for targets off the ground versus on the ground. Our analysis supported this prediction. We found a significant main effect of cube height (B = 33.5, SE = 15.45, t = 2.17, p = 0.04, d = 0.26), which indicated that participants blind walked, on average, 33.5 cm farther to off-ground cubes than to on-ground cubes across all conditions. We also found that cube height interacted with the 3 - 4.5m distance effect (B = 17.74, SE = 8.754, t = 2.03, $p < 0.04$, d = 0.14). This indicates that the difference between the on- and off-ground conditions was greatest for the 4.5m distance.

H3: Distances to off-ground targets would be judged as farther away with monocular compared to binocular viewing. Distance judgments would not change as a function of viewing condition for on-ground targets. First, we did not find any interaction between cube height and viewing order. We also did not find a main effect of viewing order. Thus, the order in which the participants experienced the viewing conditions did not influence their behavior. Our main prediction was partially supported. Monocular versus binocular viewing led to opposite effects for on-ground and off-ground targets as indicated by a significant two-way interaction between cube height and viewing condition (B = 24.56, SE = 7.15, t = 3.435, $p < 0.001$, d = 0.19). As predicted, participants in the off-ground condition judged distances as farther (by about 13 cm) for all of the cubes displayed off the ground when in the monocular viewing condition compared to the binocular viewing condition (B = 12.81, SE = 5.05, t = 2.53, p = 0.01, d = 0.10). In addition, participants in the on-ground condition judged distances to be about 12 cm less in the monocular viewing condition compared to the binocular viewing condition (B = -11.75, SE = 5.05, t = -2.33, p = 0.02, d = -0.09) which did not support our hypothesis that viewing condition would have a null effect for on-ground targets.

5 DISCUSSION

The goal of this work was to examine the impact of varied ground contact on egocentric distance to targets in AR. Prior work in VR has shown underestimation of distance (though the extent of underestimation has declined with the advent of new head-mounted displays), but the few studies investigating distance perception in AR have been mixed. We focused on the role of object contact with the ground surface and the impact of stereoscopic (or lack of) information. Our results showed an overall underestimation of blind walked distance to targets across all conditions. As predicted, the off-ground targets were judged to be farther away, possibly due to a lack of information specifying that the objects were not in contact with the ground. This explanation is supported by the finding that with the reduced-cue condition of monocular viewing, off-ground targets were judged to be even farther. We found the unexpected additional result that targets on the ground were judged as closer when viewed monocularly. Potential reasons for this finding are discussed further below.

Our primary question was whether targets off the ground would be perceived for their actual egocentric location above the ground, or whether perceived distance would be based on their visual intersection with the ground. Previous work has demonstrated that when there are insufficient cues to suggest that a target is off the ground, distances will be perceived as if they are on the ground [13, 26].

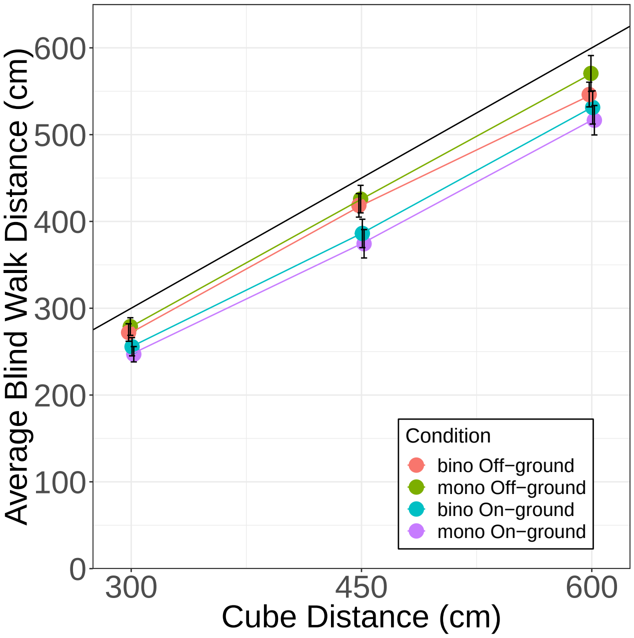

Figure 3: The figure above shows the average distance participants walked to the 3m, 4.5m, and 6m cube in each combination of viewing and cube height conditions. Error bars indicate ±1 standard errors.

Our current results are consistent with this effect. While there was overall underestimation in judged distance, targets off the ground were relatively overestimated compared to those on the ground, suggesting that their location may have been perceived as on the ground but farther away. Despite the current limitations in AR technology for shadows, future work should investigate whether any rendered shadows might affect the perceived location of targets off the ground. Methods for rendering shadows in AR to improve depth perception have been recently developed [11] and could be applied to our current question of ground contact and perception of depth. In addition, varying the height of off-ground objects might also be useful in terms of determining whether participants connect shadows to objects correctly. Placing objects on the ceiling might also be an important test for understanding how off ground locations and restricted vertical field of view could affect perceived locations of targets. Blind walking to targets on the ceiling in the real world has been shown to be accurate [35], but this accuracy could be affected by a more restricted vertical field of view in AR.

We found differences in distance estimation due to monocular versus binocular viewing. And we had predicted that further reducing visual cues for depth with monocular viewing would affect off-ground targets, in particular. While the off-ground targets were perceived as farther away, we found that the on-ground targets were also affected in that they were perceived as closer when viewed monocularly. There is anecdotal evidence that strong differences in spatial frequency, contrast, and chromaticity can lead to the appearance of non-contact, but no study has formally tested this hypothesis. However, this could have contributed to the effect observed in the current study for monocular viewing of on-ground targets. Our cubes were bright and textured in a way that made them stand in stark contrast against the dark ground plane (a dark carpet with fairly uniform texture). This large difference in appearance–particularly in brightness, contrast, and texture–between the real world surface and the virtual cube may have led to the cube being perceived as hovering above the ground plane even though it was in contact with the ground. In this case, the virtual cube on the ground would be pushed forward perceptually.

Future work will explore the effect of object-background visual similarity on the perception of surface contact and thus the on-the-ground contact effect. Additional work should also examine the generalizability of the monocular viewing effects (given the somewhat small effect sizes) by testing distance judgments in varied spatial environments and at different distances.

These results contribute to a growing body of work on depth perception in AR—much of which previously has focused on near locations—by using blind walking to assess perception of farther distances in *action space*. We have established that, while viewers underestimate distances to AR objects relative to the intended distance, their distance judgments systematically increased as cube distance increased for both on- and off-ground targets. Although this may have been assumed based on previous VR findings, the challenges faced with accurately calibrating the AR system and placing objects so that they appear stable and grounded at farther distances makes this first question necessary to address. The finding of underestimation in perceived distance may be a result of a combination of factors, including the severely reduced horizontal and vertical field of view of the HoloLens as well the lack of information for ground contact as discussed above. Both are areas in need of future research.

Beyond the importance of establishing the accuracy of perceived scale in AR spaces, studies of perception of distance may generally inform the application and use of AR for more complex spatial tasks such as navigation. If AR is to be used to facilitate spatial learning while navigating, it is critical to understand how the locations of AR features such as landmarks are perceived.

5.1 Study Limitations

Future work should attempt to replicate and extend the current results given a few limitations in methodology and design. While our findings suggest that AR targets off of the ground are perceived as farther away, we only compared one off-ground height to the ground condition. Therefore, we can only speculate that the height of AR objects would continue to effect distance judgments at various heights, particularly significant heights, as studied in Tlauka et al. [37]. Furthermore, participants may have judged distances more accurately if additional cube sizes or additional AR objects were placed in the environment to act as relative size cues. The effect of participants' height was also not thoroughly investigated. Future work could emphasize the exact relationship between participant height, AR object height, and distance judgments.

6 CONCLUSION

This research demonstrates that targets portrayed off the ground in AR may not be perceived to be in the same location as targets displayed on the ground plane, especially if viewed in conditions under which depth cues are reduced (such as monocular viewing). Other cues to the location of targets, such as shadows, should be added in the future to assess their contribution to accuracy of perceived location of targets. The current experiment provides an initial step toward understanding cues for perceiving depth in AR but also highlights the need for further research in depth perception within AR environments to assess contributions of other depth cues.

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A STATISTICAL MODEL AND ANALYSES

The mixed models we ran were designed to test the influence of cube height, viewing condition, and cube distance on participants' blind walk behavior. As stated above, mixed models are a form of generalized regression. In these models, continuous and categorical predictors can be included at different levels within a nested experimental design. Our model included predictors at the within-subject level (e.g., viewing condition, viewing order, cube distance) and at the between-subject level (i.e., cube height). Because all of our predictors are categorical, the B estimates reported in the main text represent the expected difference between each level of the variable (e.g., the expected difference in distance walked for cubes presented on and off the ground). The standard errors represent the variance that surrounds each estimate in cm. The t and p indicate the degree to which the fixed effect estimates are different from 0, or our null hypothesis. Cohen's d is also reported which indicates the size of the effects we observed. All analyses were estimated with restricted maximum likelihood and were conducted in R using the `lme4` package [3].

The equation below represents our primary model, where i represents a single observation and j represents a participant. This means that any predictor with the subscript ij indicates a variable that varies by within participants whereas a predictor with the subscript j indicates a variable that varies between participants. Each variable was entered as a categorical factor with 2 or 3 levels. Distance had 3 levels (3m, 4.5m, 6m). Cube height (on-ground & off-ground), viewing condition (binocular & monocular), and viewing order (binocular first and monocular first) had two levels. We specified interactions between cube height and distance (γ_{11} & γ_{21}), cube height and viewing condition (γ_{31}), as well as cube height and viewing order (γ_{41}). Additionally, we included a random intercept (μ_{0j}) for each participant which accounted for individual variability in blind walking behavior (i.e., the variability associated with repeated measures within each participant). These are not reported in the main text since they only control for within-subject variability and do not indicate relevant information about our experimental manipulations. Finally, contrast coding was used to allow for the planned comparisons described in Section 4.3.

$$\begin{aligned}
\text{BlindWalkDistance}_{ij} = \gamma_{00} + \gamma_{01} * \text{CubeHeight}_j + \\
\gamma_{10} * \text{Distance}(3vs.4.5\text{m})_{ij} + \\
\gamma_{11} * \text{CubeHeight}_j * \text{Distance}(3vs.4.5\text{m})_{ij} + \\
\gamma_{20} * \text{Distance}(3vs.6\text{m})_{ij} + \\
\gamma_{21} * \text{CubeHeight}_j * \text{Distance}(3vs.6\text{m})_{ij} + \\
\gamma_{30} * \text{ViewingCondition}_{ij} + \\
\gamma_{31} * \text{CubeHeight}_j * \text{ViewingCondition}_{ij} + \\
\gamma_{40} * \text{ViewOrder}_{ij} + \\
\gamma_{41} * \text{CubeHeight}_j * \text{ViewOrder}_{ij} + \mu_{0j}
\end{aligned}$$

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