Depth Perception in Soft-Edge Occlusion-capable Optical See-through Head-mounted Displays

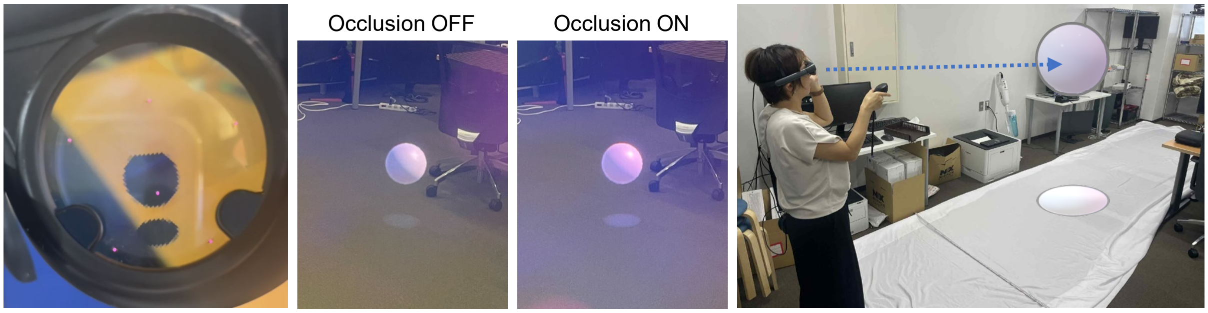
Gauthier Bertram[*,‡]
Ecole Centrale de Nantes

Takefumi Hiraki[†,‡]
University of Tsukuba
Cluster Metaverse Lab

Yuichi Hiroi[§]
Cluster Metaverse Lab

Étienne Peillard[¶]
IMT Atlantique

Jean-Marie Normand[‖]
Ecole Centrale de Nantes



(a) (b) (c)

Figure 1: (a) Object mask and shadow cast on the floor displayed on Magic Leap 2's occlusion layer. Note that in this photograph, the camera is focused on the occlusion layer, making the occlusion edges appear sharp, whereas they would normally appear blurred. (b) Difference in virtual object appearance with and without occlusion. (c) Experimental setup. Participants viewed virtual objects with varying parameters including occlusion and reported perceived depth.

ABSTRACT

Commercial optical see-through head-mounted displays (OST-HMDs) are becoming increasingly prevalent. While conventional OST-HMDs use optical combiners to overlay virtual objects semi-transparently onto the background, recent commercial products have introduced occlusion-capable OST-HMDs (OCOST-HMDs) that selectively block background light using occlusion masks. However, the depth perception characteristics of OCOST-HMDs, particularly the effect of occlusion on depth perception, remain insufficiently investigated.

This study evaluated the effect of soft-edge occlusion masks on distance perception accuracy for virtual objects using Magic Leap 2, a commercial OCOST-HMD. We measured participants' distance estimates while varying the presentation distance, vertical position, presence of drop shadows, and occlusion state of virtual objects. Our preliminary results confirmed that vertical position significantly affects distance perception, consistent with prior work. However, occlusion alone did not significantly improve distance estimation accuracy. These findings suggest that background occlusion for isolated objects provides limited effectiveness as a depth cue.

Index Terms: Augmented Reality, Optical See-through Head-Mounted Display, Depth Perception, Occlusion.

1 INTRODUCTION

Augmented Reality (AR) is fundamentally transforming how we interact with the physical world by overlaying digital information onto our direct view. For this integration to be seamless and effective, virtual objects must be perceived as stable and accurately positioned within the real environment. However, numerous studies have demonstrated that human spatial perception is systematically distorted when using head-mounted displays (HMDs) [56]. This perceptual discrepancy indicates that spatial judgments in AR depend on the complex interplay between viewing conditions and display technology.

To improve perceptual accuracy in AR, various depth cues have been investigated in prior research. The presence of drop shadows anchors virtual objects to surfaces and provides ground contact information, leading to more accurate distance judgments [10, 14]. Similarly, the vertical position of objects (i.e., floating versus grounded) significantly affects the perceived distance because the human visual system uses the height of objects relative to the ground as a cue to infer spatial layout [1, 48].

While the effects of shadows and vertical position are partially understood, occlusion remains an important yet underexplored factor. Occlusion is the visual phenomenon where one object blocks the view of another, which provides a powerful and deterministic cue for depth ordering [9]. Realistic occlusion is crucial to establish accurate perception of spatial relationships [15]. In OST-HMDs, where virtual objects are presented by adding light to the real scene, perceptual studies of occlusion have been hindered by technical constraints. However, recent commercial products have introduced occlusion-capable OST-HMDs (OCOST-HMDs), which capable of selectively blocking background light. Magic Leap 2 is a representative example, simulating virtual object occlusion through

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[*] e-mail: gauthier.bertram@eleves.ec-nantes.fr
[†] e-mail: hiraki@slis.tsukuba.ac.jp
[‡] These authors contributed equally to this work.
[§] e-mail: y.hiroi@cluster.mu
[¶] e-mail: etienne.peillard@imt-atlantique.fr
[‖] e-mail: jean-marie.normand@ec-nantes.fr

dynamic dimming. However, the perceptual characteristics of these devices, particularly how occlusion affects depth perception, remain insufficiently investigated.

In this study, we aim to provide the first preliminary analysis of the combined effects of object height, cast shadows, and hardware-enabled occlusion on absolute distance perception, using Magic Leap 2. The experimental protocol extends the work of Adams et al. [1], who examined absolute depth perception using video see-through (VST) and OST-HMDs, by incorporating an occlusion condition. Results confirmed that vertical position significantly affects distance perception, consistent with prior work. However, our results show that hardware-based occlusion did not significantly improve distance estimation accuracy when applied to isolated virtual objects. This suggests that background occlusion has limited utility as a depth cue without additional contextual information.

The contributions of this paper are as follows:

- First preliminary analysis of the combined effects of object height, drop shadows, and hardware-based occlusion on absolute distance perception in OCOST-HMDs
- Empirical evaluation of how dynamic dimming-based occlusion in Magic Leap 2 affects distance judgments
- Demonstration that while vertical position is a significant factor, hardware-based occlusion provides limited improvement in distance estimation accuracy for isolated objects
- Discussion of methodological limitations and guidance for future research

2 RELATED WORK

2.1 Vertical Position as a Depth Cue

The importance of ground surfaces in visual space perception is best explained by Gibson's foundational work [15]. Gibson argued that spatial perception is impossible without perception of a continuous background, and that visual space itself is defined by surface arrangements, adjacent surfaces, and objects positioned relative to them.

Empirical studies have demonstrated the importance of surface arrangement and adjacent surfaces for accurate spatial perception. Meng and Sedgwick [40] showed that when continuous ground surfaces are interrupted, the visual system cannot establish a reliable reference frame. Consequently, when surface discontinuities along the ground, such as gaps in the floor [50] or changes in texture gradients [40], are positioned between observer and target, distance perception accuracy decreases.

When cues linking objects to nearby surfaces are absent, observers determine spatial positions based on "optical contact", the point where the object's projected image contacts the image of the ground below [40, 42]. Consequently, when cues specifying that a target is above the ground are absent, targets positioned above the ground are perceived as being on the ground but farther away [42, 48]. This phenomenon has been demonstrated in both real [46] and virtual [6, 11] environments within action space (2 m to 30 m range [9]).

More recently, Salas-Rosales et al. [48] confirmed this effect in augmented reality, and Adams et al. [1] replicated it using Microsoft HoloLens 2 and Varjo XR-3. Specifically, they showed that without drop shadows, floating targets are perceived as farther than grounded targets.

2.2 Distance Perception in AR-HMDs

Systematic distance distortions have been reported across VR/AR-HMDs [56, 31, 7], varying with distance range and measurement method [16]. At near distances (<2m), many studies have reported overestimation [47, 53, 51, 27, 43, 5, 19, 49, 4]. This stems from the fixed focal plane of HMDs and may contribute to perceptual distortion at both near and far distances. In contract, in action space (approximately 2–30m), underestimation is frequently observed [52, 13, 17, 1, 29, 12, 55, 44]. These underestimations have been attributed to limited field of view and loss of peripheral information [26, 41], as well as device weight and environmental context [57, 34].

Overestimation has also been reported at near distances. Rolland et al. [47] first demonstrated near-distance overestimation in OST AR displays, pointing to interpupillary distance (IPD) mismatch and pincushion distortion as potential factors. Swan et al. [53] also found overestimation with collimated optics. Singh et al. [51] reported that overestimation occurs when focal distance is fixed at infinity, while underestimation occurs when focal distance matches target distance, suggesting that focal distance is a key factor determining the direction of bias.

Display calibration accuracy also significantly affects distance perception [30, 35]. Lee and Hua [35] investigated the effects of optical combiner configuration and IPD changes on near-field depth perception, showing that calibration errors cause systematic biases in perceived depth. Furthermore, Lee and Hua [36] proposed a rigorous three-stage display calibration method comprising focus calibration, geometric/distortion calibration, and eye position calibration, demonstrating that this approach can substantially reduce perceived depth errors.

2.3 Cast Shadows for Grounding Virtual Objects

Shadows play an important role in visual perception, indicating where objects are positioned in space by creating contact points between objects and adjacent surfaces [21, 38]. However, rendering drop shadows in augmented reality is challenging, especially for OST displays that render using additive light. Since darker color values become more transparent in these displays, prior research on drop shadows in AR has represented object shadows using rendering techniques such as emissive shadows or brightening the area around shadows [20, 23].

Previous studies have found that, in OST-HMDs, the accuracy of judging relative depth improves when floating targets are rendered with drop shadows [17, 14, 10]. Adams et al. [1] extended these findings to absolute distance measurement, confirming that distance judgments become more accurate in the presence of shadows.

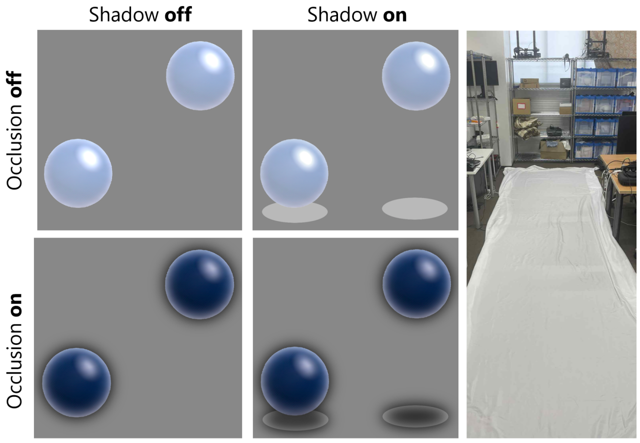
2.4 OCOST-HMDs and Effects on Depth Perception

To address the problem of semi-transparent rendering in conventional OST-HMDs, research has advanced on OCOST-HMDs that appropriately block light from the real world to give virtual objects opacity [32, 25].

OCOST-HMD implementations are broadly categorized as either hard-edge or soft-edge occlusion. In hard-edge occlusion, an image of the real scene is formed at an intermediate image plane, where precise occlusion at the pixel level is performed [32, 8, 58, 59, 60]. Hard-edge OCOST-HMDs optically align the virtual image plane with the mask plane. This results in sharp occlusion along the contours of virtual objects. However, this approach increases device size. In contrast, soft-edge occlusion uses a simpler configuration that places the occlusion mask directly in front of the eye [39]. This approach enables device miniaturization and a wider field of view by eliminating the need for complex imaging optics. The Magic Leap 2, released in 2023, is the first commercial product to adopt this approach.

Regarding the effects of occlusion on depth perception, occlusion primarily provides relative (ordinal) depth information and is most important when multiple overlapping surfaces compete for perceptual ordering [9, 60, 37]. However, it is unclear whether occlusion contributes to absolute distance judgments, particularly in the OCOST-HMD context. This study is the first to evaluate the

Magic Leap 2's soft-edge occlusion capability from this perspective.



(a) (b)

Figure 2: (a) Virtual sphere stimuli under four rendering conditions. Top row: occlusion off (standard OST rendering); bottom row: occlusion on (segmented dimming enabled). Left column: shadow off; right column: shadow on. Each panel shows grounded and floating positions. Note the soft-edge blur characteristic of the dimming region in the occlusion-on conditions. (b) Experimental setup with white carpet to control environmental depth cues.

Table 1: Experimental Variables

Type	Variable	Levels	Values
Independent	Observer	18	(random)
	Distance	3	3, 4.5, 6 m
	Shadow	2	present, absent
	Occlusion	2	on, off
	Height	2	0, 0.2 m
	Repetition	3	1, 2, 3
Dependent	Distance judgment	—	meters

3 EXPERIMENT

We conducted a within-subjects experiment using the Magic Leap 2 to investigate the effects of target distance, shadow, occlusion, and target height on distance perception in AR. The experimental protocol extended Adams et al. [1] by adding an occlusion condition. Following prior research, we used verbal report as an absolute measure of distance perception for targets presented at various distances within action space.

Based on prior research on depth perception in AR environments, we developed four hypotheses:

H1: Distance judgments will be underestimated in the AR display, consistent with prior research [1].

H2: When cast shadows are present, participants' distance judgments will become more accurate compared to conditions without shadows.

H3: When occlusion rendering is enabled, participants' distance perception accuracy will improve compared to conditions without occlusion.

H4: Floating objects will be perceived as farther away than grounded objects, but this difference will be reduced when depth cues (shadow and occlusion) are present.

3.1 Materials and Apparatus

Magic Leap 2 was selected as a soft-edge OCOST-HMD due to its wide field of view and low-latency tracking capabilities, which make it ideal for precise perceptual experiments. To ensure consistent visual conditions across trials, shadows and occlusion rendering were implemented directly in Unity.

The virtual object used a sphere with a diameter of 20 cm as the target object, similar to Adams et al. [1]. The sphere was rendered using Unity's standard shader and colored with a mid-gray (RGB value 128). Shadows were implemented as "cast shadows," where a virtual directional light source was placed directly above the object, casting the shadow directly below it, as shown in Fig. 2 (a). This technique, adopted in prior AR research [10, 14], is a simplified implementation that does not necessarily match the actual light source position in the environment. Adams et al. selected a shadow with a grayscale RGB value of 36 because HoloLens 2 cannot render black color. This study also adopted a similar approach for settings without occlusion masks.

The experiment was conducted in a laboratory room measuring 8 × 6 m, as shown in Fig. 2 (b). The laboratory setting was deliberately controlled to minimize environmental cues that could bias distance perception. A white carpet was installed to eliminate patterned textures that could serve as strong depth cues.

3.2 Participants

Eighteen volunteers (14 male, 4 female) participated in the experiment. The average age was 28.4 ± 9.5 years (Min: 19, Max: 58). All participants had normal or corrected-to-normal vision. Participation was voluntary, and written informed consent was obtained prior to the experiment. At the end of the study, participants were compensated with a 1,000 JPY Amazon gift card.

3.3 Design

We employed a 3 (target distance: 3 m, 4.5 m, 6 m) × 2 (target height: 0 m, 0.2 m above the ground) × 2 (shadow: present, absent) × 2 (occlusion: on, off) within-subjects factorial design. Each of the 24 unique conditions was repeated three times, yielding a total of 72 trials per participant. With 18 participants, a total of 1,296 trials were collected for analysis. Table 1 summarizes the variables in these experiments.

3.4 Procedure

Participants estimated the distance of each virtual sphere verbally in meters. Responses were recorded manually by the experimenter. No feedback was provided, and all trials were completed consecutively within approximately 30 minutes per session.

3.5 Statistical Analysis

We used a linear mixed-effects model (LMM) to investigate the influence of distance, shadow, occlusion, and target height on participants' distance judgments. Linear mixed models are a form of generalized linear regression that assume normally distributed dependent variables. They are suitable for repeated-measures designs and can account for both within-subject and between-subject variation.

The general regression equation is shown in Eq. 1:

$$\begin{aligned} Y = {} & \beta_0 + \beta_1(\text{shadow}) + \beta_2(\text{occlusion}) + \beta_3(\text{height}) + \beta_4(\text{distance}) \\ & + \beta_5(\text{shadow} \times \text{height}) + \beta_6(\text{occlusion} \times \text{height}) \\ & + \beta_7(\text{shadow} \times \text{occlusion}) + \beta_8(\text{shadow} \times \text{occlusion} \times \text{height}) \\ & + \mu_0 \end{aligned} \tag{1}$$

Table 2: Linear Mixed-Effects Model Results

Effect	β	**SE**	p
Intercept	0.146	0.060	**.016***
Distance	0.869	0.014	<**.001*****
Shadow (present vs. absent)	0.015	0.010	.133
Occlusion (on vs. off)	0.008	0.010	.448
Height (floating vs. grounded)	0.067	0.017	<**.001*****
Shadow × Height	−0.032	0.012	**.008****
Occlusion × Height	−0.011	0.012	.361
Shadow × Occlusion	0.005	0.010	.617
Shadow × Occ. × Height	0.008	0.012	.513

Note: * $p < .05$, ** $p < .01$, *** $p < .001$

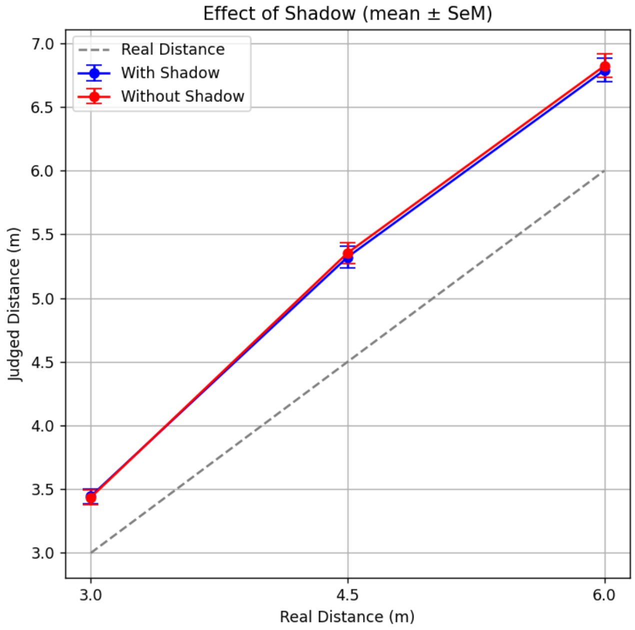


Figure 3: Effect of shadow on judged distance (mean ± SEM) across target distances. The dashed gray line indicates veridical performance (judged = real).

4 RESULTS

Distance judgments were recorded and analyzed in meters.

The linear mixed model results and condition-wise distance judgments are shown in Table 2.

4.1 H1: Distance Judgments

Overall, participants systematically *overestimated* distances in AR, diverging from H1 and prior reports of underestimation. Distance scaling was preserved, as participants increased their estimates with increasing physical distance. At 3.0 m, judgments averaged 3.42 m (SEM = 0.06), corresponding to +14.0% overestimation. At 4.5 m, judgments averaged 5.24 m (SEM = 0.07), a +16.4% error. At 6.0 m, judgments averaged 6.92 m (SEM = 0.08), a +15.3% error.

These results demonstrate consistent overshooting across all distances, contrasting with prior findings that reported 15–20% underestimation in both OST and VST AR displays [1]. The intercept of the linear mixed-effects model was significantly greater than zero ($\beta = 0.146$, $p = .016$), confirming this positive bias. The reasons for this overestimation will be discussed in detail in Sec. 5.1.

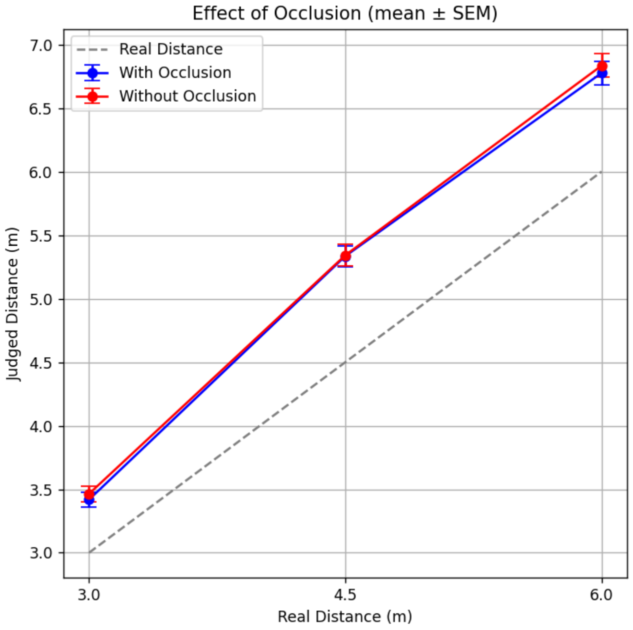


Figure 4: Effect of occlusion on judged distance (mean ± SEM) across target distances. The dashed gray line indicates veridical performance (judged = real).

4.2 H2: Effect of Shadows

H2 predicted that cast shadows would enhance accuracy. However, no significant main effect of shadows was observed ($p = .133$). Figure 3 shows parallel curves for shadow and no-shadow conditions. These findings diverge from previous research [1], which reported that cast shadows reduced underestimation, particularly for floating objects.

Interestingly, while shadows did not yield a robust main effect, they interacted with target height (Sec. 4.4). This suggests that shadows may still play a role in disambiguating floating objects, but the effect was subtle under our conditions. Thus, H2 was not supported as a main effect, but evidence of context-dependent influence remains.

4.3 H3: Effect of Occlusion

H3 predicted that occlusion would improve distance judgments by providing an additional depth cue. Our analysis did not support this prediction. The two conditions overlapped substantially, with differences less than 0.01 m on average (Figure 4). The main effect of occlusion was not significant ($p = .448$).

These null findings suggest that the segmented dimming technology of the Magic Leap 2 may not provide sufficiently salient occlusion cues for metric judgments. Unlike hard-edge occlusion rendering, dimming merely reduces background luminance without producing sharp contours. Participants may have perceived dimmed regions as unnatural shading rather than true occlusion, limiting its utility as a depth cue. Furthermore, in the controlled laboratory environment with minimal clutter, occlusion provided little additional information beyond existing geometric cues. Thus, H3 was not supported.

4.4 H4: Effect of Height

Consistent with H4, target height exerted a robust effect on distance judgments. Floating targets were consistently judged as farther away than grounded ones. This main effect was statistically

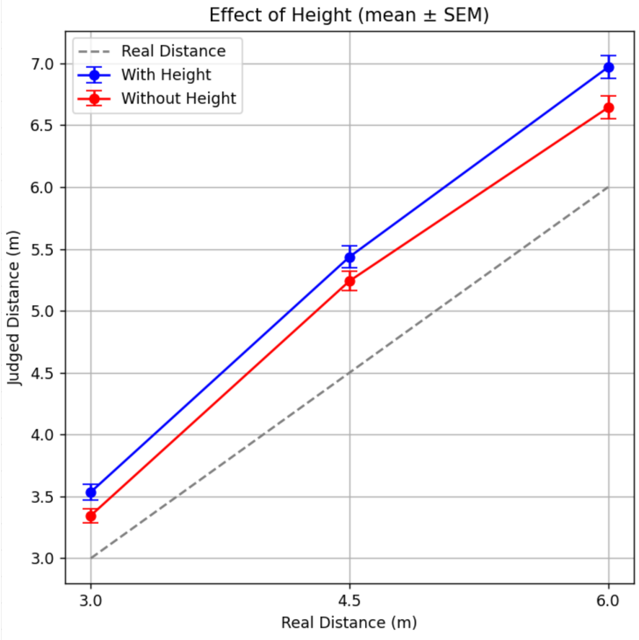


Figure 5: Effect of target height (on-ground vs. floating) on judged distance (mean ± SEM) across target distances. The dashed gray line indicates veridical performance (judged = real).

significant ($\beta = 0.067$, $p < .001$). Figure 5 illustrates the difference across distances.

Importantly, height interacted with shadow presence. This interaction was significant ($\beta = -0.032$, $p = .008$). Thus, while shadows did not have a strong overall effect, they provided a modest anchoring cue for elevated targets. This is consistent with Adams et al. [1], while the direction of bias in our study was reversed (overestimation).

5 DISCUSSION AND FUTURE WORK

This study investigated how shadow, occlusion, and target height affect distance perception in AR using the Magic Leap 2. While prior work has consistently reported underestimation of egocentric distances in AR action space, our findings revealed systematic overestimation. This unexpected reversal prompts reconsideration of depth perception biases in AR and highlights the multifactorial nature of perceptual distortion.

5.1 H1: Overestimation in contrast to Prior Findings

Across all distances, participants judged targets as an average of +15.6% farther than their physical positions. This finding contrasts with the large body of prior work documenting distance underestimation in AR action space [52, 56, 13, 1].

Several device- and context-specific factors may explain this divergence. First, focal distance effects may contribute. Singh et al. [51] reported that overestimation occurs when focal distance is fixed at infinity, while underestimation occurs when the focal distance matches target distance. Lee and Hua [36] demonstrated that virtual image plane focal distance systematically affects perceived depth. Although both HoloLens 2 and Magic Leap 2 employ diffractive waveguide optics, differences in their fixed focal planes may affect vergence-accommodation relationships and contribute to different bias patterns.

Second, methodological differences are most likely responsible for the reversal. Verbal report is known to be susceptible to anchoring effects [54], and without familiarization, participants may have used different internal references. Additionally, verbal report and action-based measures are known to show different bias patterns [3]. If future studies using both verbal report and perception-action tasks in similar settings show different bias directions, our findings may simply reflect measurement method characteristics. The perceptual matching method [51, 36] is considered more reliable than verbal report, and future research should consider adopting this approach.

5.2 H2: Shadows as Limited but Context-dependent Cues

H2 predicted that cast shadows would improve distance accuracy. However, shadow showed no significant main effect, with mean errors nearly identical with and without shadows. Prior work [1] found a significant main effect of shadow, though the effect was small at approximately 2%. They noted that this small effect was less than predicted by prior research [2, 10, 14, 17] and theory, citing verbal report variability and spherical target use as possible factors. Spherical targets in particular may be less effective at conveying surface contact and shadow cues compared to angular objects [48]. Adams et al. discussed that other shapes such as cubes [48], traffic cones [31], or hockey pucks [7] may have been more effective. In our study, the main effect itself was not significant, yielding even more limited results.

One possible explanation is the limitations of contrast enhancement through soft-edge occlusion. Unlike an occlusion mask, these shadows are displayed pseudo-visually through additive lighting. Devices like the HoloLens 2 use global dimming to uniformly darken the entire field of view and maintain contrast ratios. However, images without occlusion, or with soft-edge occlusion, on the Magic Leap 2 prevent the background behind virtual objects from becoming completely dark. Prior research has shown that shadow effectiveness depends on perceptual plausibility and opacity [33, 45]. This likely reduces the additive contrast of shadows, diminishing their perceptual prominence. Accurately measuring the relationship between contrast ratio and perception is a task for future research.

5.3 H3: Occlusion as an Ineffective Depth Cue

H3 predicted that occlusion would improve judgments. However, no significant difference was found between occlusion and no-occlusion conditions. The Magic Leap 2's segmented dimming employs a soft-edge occlusion approach. Perceptual research by Hu et al. [22] has shown that physically blurred edges tend to be perceived as relatively sharp when gazing at far distances. However, our results suggest that this perceptual completion did not contribute to improved distance estimation accuracy.

Importantly, no real objects requiring occlusion were present in this experiment. Prior research has shown that occlusion is most important when multiple overlapping surfaces compete for perceptual ordering [9, 60, 37]. Because no occlusion targets existed in our experimental setup, the occlusion function primarily tested changes in the appearance of isolated virtual objects, and improvement may be possible with perceptual ordering of multiple objects.

5.4 H4: Robust Effects of Height and Shadow–height Interaction

Consistent with H4, target height significantly affected distance judgments. Floating objects were judged as significantly farther away than grounded objects, replicating robust biases observed in real, virtual, and AR environments [6, 46]. One important difference between this study and Adams et al. [1] is the shadow-height interaction. Prior work [40, 42] predicted that without shadows, distance judgments of floating and grounded objects would differ, but this difference would shrink with shadows. However, they did not observe this interaction and cited insufficient statistical power as a possible reason why.

We observed an interaction partially consistent with this prediction. Shadows slightly mitigated overestimation for floating objects (+19.5% to +18.4%) but had little effect on grounded objects. This is consistent with prior research showing that cast shadows restore contact information for floating targets [42, 10, 14]. Our ability to detect this interaction may be due to the increased trial counts resulting from the addition of the occlusion condition, which improved statistical power. Alternatively, the direction of the overall bias (overestimation v.s. underestimation) may have influenced the detection of the interaction.

5.5 The Role of IPD and Participant Population

Inter-pupil distance (IPD) may be an additional relevant factor that explains the unexpected overestimation. Most prior AR studies recruited primarily Western participants with mean IPDs of approximately 63–65 mm [57]. In contrast, our sample consisted primarily of Asian participants with smaller mean IPDs (60–62 mm). If the headset's optics and calibration algorithms are optimized for Western norms, then users with smaller IPDs may experience exaggerated stereo disparity. This makes the scene appear larger and can lead to overestimation.

Lee and Hua [35] investigated in detail the effects of IPD mismatch on near-field depth perception, showing that IPD mismatch effects vary depending on the position of the virtual image plane. Although we did not measure individual IPDs, future research should include such measurements in order to explicitly test how IPD mismatch contributes to overestimation.

5.6 Comparison between Hard-Edge Occlusion

Perceptual comparison between hard-edge occlusion approaches [32, 59, 60] and soft-edge occlusion would also be valuable. While perceptual research by Hu et al. [22] suggests that soft edges may be perceptually sufficient in some cases, effects on distance perception remain untested. Alternative approaches such as light attenuation displays (LAD) [24, 28, 18], which differ from conventional occlusion mask approaches, should also be evaluated from a distance perception perspective.

6 CONCLUSION

This paper investigated how object height, drop shadows, and hardware-based occlusion affect absolute distance perception in AR using the Magic Leap 2 across 1,296 trials. We obtained the following results: (1) participants overestimated distances by approximately 15–16 % across all conditions, (2) object height showed a robust effect, with floating targets judged as farther than grounded targets. (3) while the main effect of shadow was not significant, a shadow-height interaction was observed, with shadow slightly reducing overestimation for floating targets. (4) occlusion showed no reliable effect, and the Magic Leap 2's segmented dimming function did not improve distance accuracy in this setting.

This study serves as a preliminary investigation. Methodological constraints including limitations of verbal report and absence of real objects requiring occlusion limit the generalizability of these findings. Nevertheless, comparison with prior work demonstrates that AR distance perception is sensitive to device-specific factors, environmental settings, and methodological choices. These findings highlight the importance of systematically evaluating depth cues and device functions to understand the perceptual reliability of emerging AR technologies, providing guidance for future research in this field.

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