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Effect of Luminance Contrast and Background Complexity on Depth Perception in Optical See-Through AR

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Abstract:

OST-AR systems overlay virtual imagery onto real-world backgrounds, where luminance contrast may affect spatial discrimination. This study investigates how contrast ratio and background complexity influence depth accuracy. Forty-four participants performed a 3D placement task under three contrast ratios (low, medium, high) and two background conditions (uniform vs. cluttered). High contrast rendering reduced mean depth error from 16.8 mm to 9.1 mm in cluttered environments. Usability scores improved by 34.5% under optimized contrast. Contrast-aware rendering significantly improves depth perception in visually complex environments.

Keywords: *Optical see-through AR; luminance contrast; background complexity; depth accuracy; visual perception; usability*

INTRODUCTION

Optical see-through augmented reality (OST-AR) presents virtual information while preserving direct visual access to the physical environment. This characteristic makes it particularly suitable for applications that rely on accurate spatial interpretation, including surgical navigation, industrial inspection, equipment maintenance, and task guidance in complex field settings [1]. In these scenarios, users must continuously judge the spatial relationship between virtual content and real objects under changing environmental conditions. Although recent developments in display optics, registration pipelines, and tracking algorithms have improved system performance, depth perception in OST-AR remains less stable and less accurate than in natural viewing [2,3]. Persistent depth errors have been associated with vergence–accommodation conflict, fixed focal distance, calibration limitations, and residual registration mismatch between virtual and physical elements [4]. These factors indicate that spatial perception in OST-AR is constrained not only by geometric alignment, but also by the way virtual content is visually presented within the real scene. Recent work has demonstrated that the visualization design of both targets and interaction tools can systematically influence depth perception accuracy and usability in optical see-through AR, highlighting the critical role of visual representation beyond geometric registration [5]. This evidence suggests that depth perception should not be understood solely as a consequence of

display hardware or tracking precision. Instead, visual presentation parameters may alter how reliably users discriminate spatial position, especially when the task requires fine alignment or precise placement. Among these parameters, luminance contrast is particularly important because it determines the perceptual separation between virtual content and the surrounding real background [6,7]. In OST displays, virtual imagery is optically superimposed onto the real world rather than fully replacing it. As a result, the effective visibility of virtual objects can be weakened by ambient light, reflective surfaces, background texture, and variations in scene brightness [8,9]. Under such conditions, even a geometrically well-registered virtual object may be difficult to perceive clearly if its contrast relative to the environment is insufficient. Luminance contrast plays a central role in defining the apparent clarity of object contours, edge sharpness, and boundary salience. When contrast is reduced, virtual elements are more likely to blend into the background, making their shape and position harder to resolve [10,11]. This issue is especially critical in OST-AR because depth-related decisions are often made under partial visual competition between real and virtual stimuli. Prior perception studies have shown that contrast level influences positional discrimination, visual precision, and confidence in tasks requiring accurate spatial judgment [12,13]. In mixed or augmented environments, reduced contrast may also impair the stability of binocular matching and increase uncertainty in estimating the relative depth of virtual content. The resulting perceptual ambiguity can degrade placement accuracy even when the user remains aware of the target location. From an application perspective, such degradation is not a minor display-quality issue; it may directly affect task safety, operating efficiency, and user trust in AR-guided systems. The influence of contrast becomes more complicated when the real background is visually complex. Real environments rarely provide a uniform visual field. Instead, they typically include textured surfaces, overlapping structures, variable illumination, specular reflections, and competing edges that attract attention [14,15]. These factors can reduce the salience of virtual overlays and interfere with the extraction of depth-related visual cues. Research in immersive visualization and human–computer interaction has shown that cluttered backgrounds can lower localization accuracy, prolong response time, and increase perceptual workload [16,17]. In OST-AR, this problem may be even more pronounced because virtual objects do not fully occlude the real scene and must compete with naturally visible background details at all times. Consequently, the perceptual effect of luminance contrast cannot be evaluated in isolation. Its influence is likely to depend on the structure of the surrounding environment and on how strongly the background masks or disrupts the visibility of the virtual object. This interaction between contrast and background complexity is closely related to visual saliency. Spatial judgment in OST-AR depends not only on binocular disparity and geometric consistency, but also on how effectively the virtual target attracts attention relative to the background [18,19]. A virtual object with insufficient contrast may lose perceptual priority in a cluttered scene, leading to delayed recognition, unstable depth estimation, or higher placement variability. By contrast, an object rendered with stronger luminance separation may remain perceptually distinct even when the environment contains distracting visual patterns. This suggests that depth accuracy in OST-AR is shaped by both low-level perceptual factors and scene-dependent visibility conditions. Understanding this relationship is important for rendering design because contrast settings that work well in a simple laboratory background may not remain effective in real operating environments such as clinics, workshops, or maintenance sites. Existing studies have examined contrast-related issues in display ergonomics, virtual environments, and augmented interfaces, but direct evidence linking graded luminance contrast to objective depth error in OST-AR remains limited [20,21]. Many prior experiments have focused on detection threshold, subjective comfort, visual fatigue, or general usability rather than metric spatial accuracy [22,23]. In addition, several studies rely on simplified visual conditions, binary contrast comparisons, or small participant samples, which makes it

difficult to determine how depth error changes across different contrast levels and environmental contexts [24]. As a result, current knowledge is insufficient for identifying contrast settings that can reliably support accurate depth placement in practical OST-AR use. A more systematic analysis is therefore needed to clarify how luminance contrast and background complexity jointly affect depth perception in optical see-through augmented reality. Evaluating multiple contrast ratios under both uniform and cluttered background conditions can provide a clearer account of whether improved contrast consistently reduces spatial error, and whether this benefit is preserved when the visual scene becomes more demanding. Against this background, the present study investigates depth placement accuracy and usability in OST-AR under three luminance contrast ratios and two levels of background complexity. The study aims to quantify how these factors influence objective spatial performance and user experience, and to determine whether contrast optimization can serve as a practical rendering strategy for improving perceptual reliability in real-world OST-AR tasks. By addressing this issue, the work provides empirical support for contrast-aware visual design in applications where precise depth judgment is essential.

2.Materials and Methods

2.1 Participants and Experimental Environment

Forty-four adults (22 females and 22 males; age range 20–35 years, mean ± SD: 27.8 ± 3.6 years) took part in the study. All participants had normal or corrected-to-normal vision and stereoacuity better than 60 arcsec, confirmed using a standard stereo test. Individuals with binocular vision disorders or uncorrected refractive errors were excluded. The experiment was conducted in a laboratory with stable ambient lighting between 300 and 350 lux. An optical see-through head-mounted display with a fixed focal distance of 2.0 m was used. Two background conditions were prepared: a uniform matte surface with minimal texture and a cluttered scene containing tools, printed patterns, and textured panels. Virtual targets were presented at 0.5, 0.8, and 1.1 m from the participant's eye position, covering common near and mid-range working distances.

2.2 Experimental Design and Control Conditions

A repeated-measures design was applied to reduce the effect of individual differences. Each participant completed a 3D placement task under three luminance contrast levels (low, medium, and high) and two background conditions (uniform and cluttered). Contrast level was defined as the luminance difference between the virtual target and its immediate background. This was adjusted by modifying target brightness while keeping color constant. The medium contrast condition served as the reference because it reflected the default display setting. The low contrast condition simulated reduced visibility, and the high contrast condition increased edge visibility and object separation. The order of contrast and background conditions was balanced using a Latin square scheme. Each condition included 18 trials distributed across the three depth levels. Short breaks were provided between blocks to reduce visual strain.

2.3 Measurement Procedures and Quality Control

Participants adjusted the depth of a virtual marker until it appeared aligned with a fixed physical reference point along the viewing axis. A handheld controller was used for depth adjustment. Absolute depth error was recorded in millimeters as the difference between the final virtual position and the actual reference depth. Task completion time was measured from target appearance to alignment confirmation. After completing each condition, participants rated usability on a 7-point Likert scale. Before data collection, interpupillary distance was calibrated individually to ensure accurate stereo presentation. Spatial alignment was verified using a calibration grid displayed in the central field of view. Trials affected by tracking instability, visual artifacts, or response times exceeding three standard deviations from the participant's mean were removed from analysis.

2.4 Data Processing and Statistical Modeling

Absolute depth error E for each trial was calculated as

$$E=|D_v-D_r|,$$

Where D_v is the final virtual depth and D_r is the physical reference depth. Mean error values were computed for each participant under each contrast and background condition. To assess the effects of contrast and background complexity, a linear model was applied:

$$E_{ij}=\alpha+\beta_1 C_i+\beta_2 B_j+\beta_3(C_i\times B_j)+\varepsilon_{ij},$$

where C_i represents contrast level, B_j represents background condition, and $\varepsilon_{ij}$is the residual term. The interaction term $C_i\times B_j$ was included to test whether contrast effects differed between background types. Residual plots were examined to confirm normal distribution and stable variance. Statistical significance was defined at $\alpha = 0.05$. Data analysis was performed using R (version 4.3).

3.Results and Discussion

3.1 Depth error decreased with higher contrast, especially in cluttered scenes

Depth placement accuracy improved as luminance contrast increased, and the magnitude of improvement depended on the background condition. In the uniform background, error declined from low to high contrast, but the change was moderate because the target contour remained visible even at reduced contrast. In the cluttered background, low contrast led to larger depth errors and greater variability, indicating strong masking from textured regions and competing edges. High-contrast rendering reduced mean depth error in cluttered scenes from 16.8 mm to 9.1 mm, showing that stronger target–background separation restores depth precision in visually complex environments. This pattern is consistent with the known behavior of transmissive OST displays, where real-world light lowers effective contrast and reduces boundary visibility [25,26]. Fig. 1 illustrates how optical see-through displays render virtual content under real illumination compared with conventional displays, highlighting the role of luminance transmission in spatial perception.

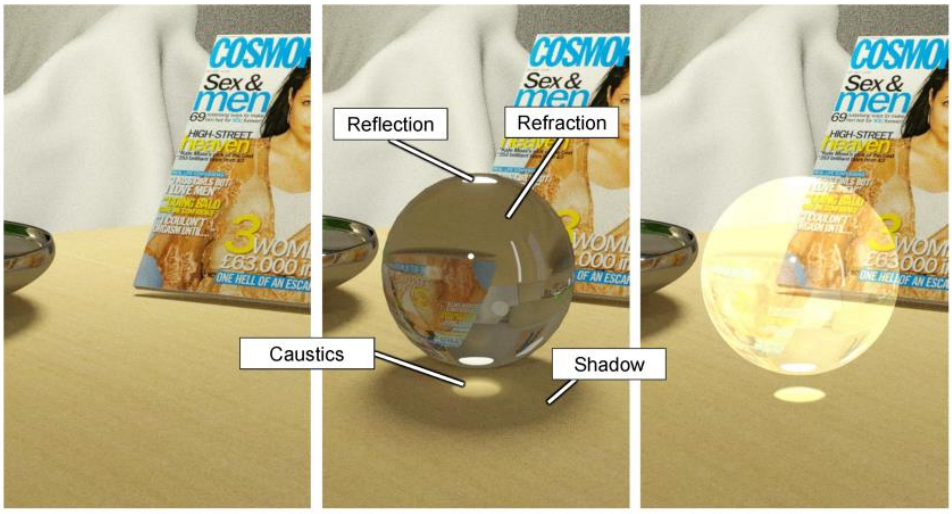


Fig.1.**Virtual object appearance in transmissive OST displays under real-world lighting conditions.**

3.2 Improvements in task time and usability under optimized contrast

Task completion time decreased as contrast increased, and the reduction was most evident in cluttered scenes. Under low contrast in clutter, participants performed repeated small adjustments before confirming alignment, which extended the final placement phase. Increasing contrast stabilized the virtual boundary against textured backgrounds and reduced these correction cycles. Usability ratings improved by 34.5% under optimized contrast, indicating better clarity and

reduced effort during task execution. These results show that contrast influences not only final depth accuracy but also the efficiency and stability of manual placement [27,28]. In practical OST workflows, reduced correction steps translate directly into lower fatigue and faster completion.

3.3 Role of visibility and geometric stability

The stronger contrast benefit in cluttered environments can be explained by visual masking and edge competition. In optical see-through systems, perceived contrast depends on local background luminance and texture. When the background contains dense patterns and sharp edges, low-contrast virtual contours blend with real features, weakening segmentation and increasing uncertainty during depth matching. High contrast enhances edge salience and improves separation between virtual and real elements. However, accurate depth judgment also depends on stable geometric registration. Parallax-related misalignment can shift the apparent virtual boundary relative to the physical reference point, limiting precision even when visibility is high [29]. Fig. 2 shows how placing the display focus plane near the working distance reduces parallax-induced misalignment, providing context for the interaction between visual clarity and optical stability.

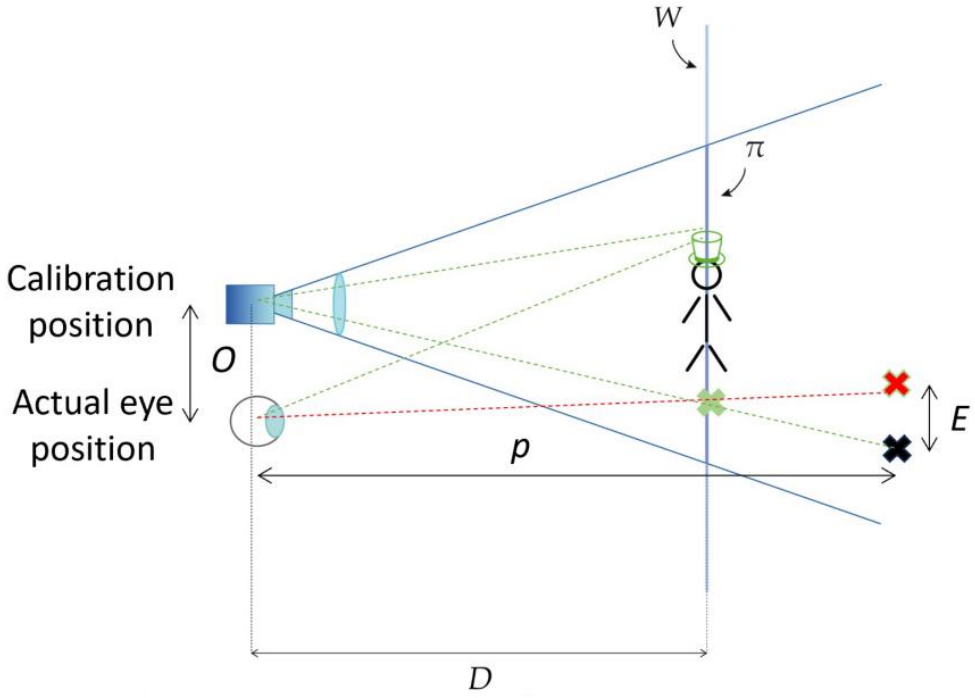


Fig.2.**Optical diagram showing reduced parallax misalignment when the focus plane is positioned near the working distance.**

3.4 Comparison with previous findings and design implications

Previous studies in OST-AR report reduced spatial reliability when virtual content has low visual strength relative to the background. The present results extend this evidence by showing a clear interaction between luminance contrast and background complexity. Contrast adjustments had limited effect in simple scenes but produced substantial accuracy and usability gains in cluttered environments. This interaction suggests that contrast settings should be adapted to local scene conditions rather than fixed at a constant level. Contrast-aware rendering can increase target–background separation in textured areas while avoiding excessive brightness that may cause glare or wash out fine details. The study was conducted with two background types and a fixed depth range, and real-world environments may introduce variable lighting and dynamic distractors. Future work should evaluate adaptive contrast strategies under broader illumination conditions and longer task durations to confirm stable performance in applied settings.

4.Conclusion

This study examined the influence of luminance contrast and background complexity on depth perception in optical see-through augmented reality. The findings indicate that increasing contrast improves depth placement accuracy, with the strongest effect observed in cluttered scenes where background textures reduce target visibility. High-contrast rendering lowered mean depth error from 16.8 mm to 9.1 mm in complex environments and increased usability ratings, demonstrating both performance and user-experience benefits. These results show that visual appearance parameters are central to spatial precision in OST systems and should be considered alongside geometric alignment and focal design. The interaction between contrast and background structure confirms that depth accuracy depends on effective separation between virtual content and real-world features. In practical applications, contrast-aware rendering can be incorporated into display pipelines to enhance clarity and reduce correction effort during manual tasks. The study was conducted under controlled lighting and within a limited depth range, and performance may differ under variable illumination or dynamic backgrounds. Future work should evaluate adaptive contrast strategies across wider ambient conditions and longer usage periods to establish stable guidelines for operational deployment.

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