Can You See It? Evaluating Color Visibility in Simulated Outdoor Environments

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Abstract

Evaluating color visibility in outdoor augmented reality (AR) is challenging due to the visual complexity and variability of real-world environments. Outdoor scenes feature diverse textures and lighting conditions, limiting the applicability of visibility evaluation methods developed for simple or static backgrounds. This work introduces a methodology for evaluating AR cue color visibility in an outdoor environment by sampling visibility across realistic scenes and identifying design considerations for evaluating color visibility under dynamic, visually complex conditions.

Index Terms: Outdoor Augmented Reality, Color Visibility

1 Introduction

Augmented reality (AR) can support navigation, situational awareness, training, contextual information access, and a range of other applications in outdoor settings. In outdoor settings, virtual content competes with rich background textures, colors, and lighting variations that can reduce the perceptual salience of AR cues [3]. Prior work shows that the contrast of AR cues affects user trust and reliance [2], motivating the need to better understand how visual properties, such as color and contrast, behave in visually complex real-world environments.

Prior work has examined the visibility and legibility of augmented information in AR by manipulating hue or brightness or by using task-based metrics such as accuracy and response time [5, 4]. While informative, these approaches often conflate perceptual visibility with task-related factors and may not isolate how visible virtual content is against real-world backgrounds. Similarly, common display-based contrast metrics (e.g., CIELAB ΔE) quantify differences between isolated colors but may not reliably predict perceptual visibility in outdoor AR environments with complex textures, illumination, and spatial variation.

In this work, we present an initial methodology for empirically evaluating color visibility in dynamic, outdoor AR. We discuss various study design challenges that we faced and iteratively addressed through pilot testing, and we ultimately put forth design considerations required to isolate perceptual visibility from non-perceptual influences.

2 Materials and Methods

Simulated augmented reality was used to evaluate color visibility across outdoor environments that are difficult to access consistently for in-situ user studies. Stereoscopic 360° video of real outdoor scenes was presented in VR, ensuring identical environmental conditions across participants while avoiding variability due to location, weather, or time of day. This approach preserves the visual complexity of outdoor scenes while supporting consistent, systematic visibility evaluation [7]. Video content was recorded at three outdoor locations (a beach, an urban setting, and a woodland scene) to capture a range of environmental structures and background textures representative of common outdoor AR contexts (Figure 1).

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Figure 1: Left: Woodland Environment. Middle: Beach Environment. Right: Urban Environment

Traditional visibility evaluation in augmented reality often relies on discrete trials with explicit responses, which are time-consuming and limit visibility sampling in visually complex outdoor environments [3, 5, 4]. To enable dense sampling of color visibility, we adapted the Continuous Psychophysics method introduced by Bonnen et al. [1], which uses continuous target tracking to assess visual sensitivity without verbal reports and has been shown to produce results comparable to traditional psychophysical tasks [6]. In its original formulation, the method employs a Gaussian luminance target with added noise and Brownian motion to support moment-to-moment assessment of perceptual sensitivity [1].

In this work, the continuous tracking paradigm is extended from a 2D display spanning approximately 6.5° of visual angle to a three-dimensional simulated AR setting with a bounded tracking region of approximately 30° in VR. Within this setting, participants track a moving target using a ray cast from a handheld controller, with tracking precision varying with the perceptual visibility of the target, enabling continuous assessment of color visibility. To support this extension, the target was rendered as an unlit sphere, sized to remain trackable without being visually dominant, and moved using randomized directions and distances at an easy-to-follow speed to traverse diverse regions of the background environment.

The experiment used a Varjo XR-4 [1] head-mounted display with a per-eye resolution of 3840×3744 pixels and a 120° by 105° field of view, driven by an Origin EON17-X laptop running the Unity-based application with real-time rendering and data logging. The outdoor scenes were captured using an Insta360 Pro 2 camera [2], recording 8K stereoscopic 360° video.

[1] https://varjo.com/products/xr-4

[2] https://www.insta360.com/product/insta360-pro2

3 Evaluation Observations and Design Adjustments

During pilot exploration conducted by four of the authors, three key design dimensions emerged as critical for ensuring that participant tracking behavior reflected perceptual visibility: target motion, target appearance, and target hue and lightness selection.

3.1 Target Motion

Target motion predictability emerged as a challenge during initial evaluations. When the target moved in straight segments with constant velocity and direction before changing course, participants could anticipate upcoming positions, and their tracking behavior became less dependent on moment-to-moment visual perception, reducing sensitivity to changes in target visibility caused by background variation.

Two target motion algorithms were evaluated to reduce predictability in tracking behavior. The first used destination-based motion, sampling successive relative displacements from a Gaussian distribution and moving the target toward each destination at a constant velocity, which increased positional variability while remaining easy to follow. The second used a Brownian walk, in which Gaussian velocity perturbations were sampled at 60 Hz and added continuously to the target's velocity, producing irregular, time-varying trajectories that further reduced predictability and mitigated ceiling effects. Based on pilot testing, the Brownian walk was selected for subsequent evaluations because it more effectively limited predictive tracking while maintaining stable task performance

3.2 Target Appearance

During early evaluations, participants could often track the target accurately even at low visibility because parts of the target's boundary remained visible against the various textures in the environment. To reduce reliance on this boundary information, we decreased the target size to shorten the visible outline. However, pilot testing showed that even very small targets could still be tracked independently of visibility, as the target's motion continued to reveal enough boundary information for tracking.

Given the limitations of size-based adjustments, alternative target designs were explored that modified boundary structure rather than overall size. In addition to a solid circular target, designs with gradual transparency at the boundary were considered to reduce the prominence of the target boundary [1]. Based on pilot observations, an image sprite depicting a circle with radially decreasing transparency, with a diameter of approximately 1 cm and presented at a viewing distance of 2.5 m, was selected for subsequent evaluations. By softening the visual transition between the target and the background, this design reduced boundary salience and allowed greater sensitivity to changes in target visibility across different regions of the environment.

3.3 Color Selection

Target colors were defined in the HSL color space to enable controlled manipulation of hue and lightness, allowing systematic variation in how light or dark each target appeared. An initial target design space included six hues, corresponding to the primary (red, green, blue) and secondary (yellow, cyan, purple) colors, and five lightness levels (20%, 35%, 50%, 65%, and 80%). Given constraints on experimental duration, this design space was refined through pilot testing, which indicated that not all hue and lightness combinations produced distinct differences in tracking behavior. Based on these observations, the target set was reduced to three hues drawn from the secondary colors and three lightness levels (20%, 50%, and 80%). Intermediate lightness levels (35% and 65%) did not consistently differ from adjacent levels and were therefore excluded to focus on more distinct lightness conditions (Figure 2).

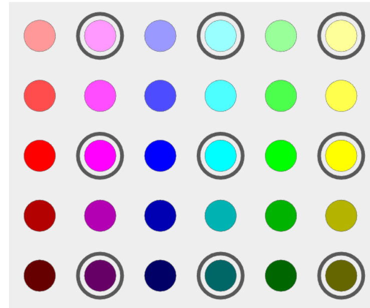

Figure 2: Grid of hue and lightness levels considered and the selected hues and lightness levels circled

4 Limitations and Conclusion

This work demonstrates that evaluating color visibility in outdoor AR benefits from careful design of target motion, appearance, and color parameterization so that tracking behavior reflects perceptual visibility in visually complex environments. A limitation of this approach is that interactions between real-world lighting and augmented visuals cannot be fully replicated when AR is simulated in VR. Within these constraints, this work focuses on visibility as it is experienced across an entire environment and provides design insights that can support future efforts to evaluate and design color-based AR cues for outdoor use.

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