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Transparency and Scission in Augmented Reality

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Abstract

Optical see-through Augmented Reality (OST-AR) is a developing technology with exciting applications including medicine, industry, education, and entertainment. OST-AR creates a mix of virtual and real using an optical combiner that blends images and graphics with the real-world environment. Such an overlay of visual information is simultaneously futuristic and familiar: like the sci-fi navigation and communication interfaces in movies, but also much like banal reflections in glass windows. OST-AR's transparent displays cause background bleed-through, which distorts color and contrast, yet virtual content is usually easily understandable. Perceptual scission, or the cognitive separation of layers, is an important mechanism, influenced by transparency, depth, parallax, and more, that helps us see what is real and what is virtual. In examples from Pepper's Ghost, veiling luminance, mixed material modes, window shopping, and today's OST-AR systems, transparency and scission provide surprising – and ordinary – results. Ongoing psychophysical research is addressing perceived characteristics of color, material, and images in OST-AR, testing and harnessing the perceptual effects of transparency and scission. Results help both understand the visual mechanisms and improve tomorrow's AR systems.

The Familiar Magic of Optical Blending

Imagine a crisp, yet visibly transparent image of someone you know, floating ghostlike in thin air within your environment, moving with smooth animation, lifelike color, and convincing realism. Do you picture this experience relying on advanced head-mounted AR glasses? Or, could it simply be the result of a reflection from a windowpane? The visual experience of an optical blend of two scenes is familiar, even banal, yet the potential of personalized AR systems that seem just over the horizon – use cases like telepresence, AI-guided maintenance, surgery, and education, not to mention collaborative gaming in real-world spaces – is compellingly futuristic and appealing.

Optical blends via beamsplitters, or indeed simply panes of glass, have a long history in visual trickery. Despite the familiarity of shop windows and the ease of ignoring reflections in glass, fooling people with reflections has been a common tactic since the "smoke and mirrors" of Victorian phantasmagoria theatre. Pepper's Ghost, the reflection of an off-stage actor illuminated by a spotlight who would appear supernaturally transparent while intermingling with the corporeal actors onstage, is perhaps the most immortal example [1]. This enduring effect has been employed long enough to qualify for retirement in Disney's Haunted Mansion, where spinning dancers appear wraithlike to riders passing by. In a particularly famous modern moment, a simple Pepper's Ghost setup reanimated Tupac Shakur for an impossible post-murder collaborative Coachella concert with Dr. Dre and Snoop Dogg, elevating his spirit to the role of guardian angel of hip-hop [2]. Honoring these traditions, the author's keynote for the 2022 AIC Conference was delivered as a ghostly transparent reflection [3].

The utility of optical blending has not gone unnoticed by vision researchers, even those not explicitly studying transparency. For example, veiling luminance, introduced by optically blending a uniform source of light with a normal scene, was studied by Gilchrist and Jacobsen, who found that people can easily ignore the veil and correctly perceive the obscured lightness relationships [4]. Pont et al., at HVEI in 2012, presented their innovative approach to "mixed material modes," using a beamsplitter to create visual blends of material characteristics including velvet and gloss [5].

Optical Blends, Decoupled via Scission

A pioneering investigation of the interaction of veiling luminance, transparency, and scission – the cognitive separation of layers that may explain how optically-blended stimuli may be perceived as distinct layers – was made by Grace Moore Heider in the 1930s [6]. Her influence can be traced through the work of Fabio Metelli, who carefully described how spatial edge and lightness relationships lead to percepts of transparency [7]. Transparency and scission are also clarified in Barton Anderson's studies of layered representations [8][9] and Frederick Kingdom's review of lightness, brightness, and transparency [10].

Despite compelling visual examples of optical blending, 2D figures that elicit transparency, and well-researched explanations of scission and transparency, it remains difficult to precisely describe the visual experience of color and material in AR.

Augmented Reality Systems

Head-mounted AR systems are typically much more complex than a simple beamsplitter, using freeform or diffractive optics as an optical combiner with tiny projectors to bring transparent images directly to the user's eyes. Further, they necessarily include multiple sensors, cameras, radios, and efficient processors, as well as batteries and heat dissipation strategies, in a delicate engineering balance of performance, weight, and cost. Visual optical details are outlined in a display textbook by Hainich and Bimber [11] and AR human factors are reviewed by Chen et al. [12].

It is important to emphasize the distinction between optical see-through AR (OST-AR) and video see-through AR (VST-AR). OST-AR systems utilize physically transparent displays, hence the relevance of beamsplitters and Pepper's Ghost, and for this reason they cannot selectively remove the influence and "bleed-through" of the background scene on the displayed AR content. Recent examples of AR glasses allow variable attenuation of the overall transparency (e.g. XREAL series [13]), which can reduce the impact of external light but thereby also remove the mix of real and virtual that makes AR compelling. The alternative, VST-AR, uses opaque displays, similar to a VR headset, on which a video composite of AR content and live-view video of the user's surroundings is displayed. Precise alpha matting allows VST-AR systems to display AR content that completely occludes background scene elements or that introduces transparency computationally. This major benefit is tempered somewhat by the mediating effect of viewing the real world through cameras – even done well, the temporal lag and geometric distortion has the potential to be distracting or uncomfortable. Recent examples of VST-AR systems include Apple's Vision Pro [14] and Meta's Quest 3 [15]. Further background is provided in Murdoch's recent book chapter [16].

Visual Perception and Cognitive Scission

One of the fascinating things about vision and color is that physics informs, but doesn't fully predict, perception. Joseph Gabbard et al. were early investigators of OST-AR, creating a model of the physics of blending real and virtual stimuli and anticipating the need for more perceptual research [17]. The physics are simple: the proximal stimulus, or light reaching the eye, is the sum of the real-world light transmitted by the optical combiner and the displayed light reflected by the optical combiner.

However, there's physics, and then there's perception. To investigate the perceptual side of AR, many visual experiments have been conducted at RIT. Nearly all of them have used large custom-built beamsplitter-based AR setups rather than head-mounted AR products, primarily because the custom setups allow precise calibration and control over the real and virtual visual stimuli. Early research at RIT uncovered large colorimetric differences between proximal stimuli and visually-matched stimuli. Matching AR stimuli across different real-world backgrounds, observers consistently discounted the background, meaning they did not "fully correct" for the physical bleed-through of the background into the transparent stimuli [18][19]. This was interpreted as evidence of scission: that viewers recognized the layered structure and separated the optical mix into its foreground (AR) and background (real) components, at least to some extent. Another study showed that observers could be induced to discount the AR foreground when the visual task asked them to match brightness of real-world background objects [20]. These studies also showed that the magnitude of discounting could be affected by cues to the layer structure, such as visual complexity and object continuity. Though not formally studied, it was observed that depth cues including stereo disparity and motion parallax have a strong effect on the cognitive understanding of layers.

Color Appearance, Mediated by Scission

A big-picture goal of RIT's research is to create a color appearance model (CAM) for AR stimuli that takes into account transparency and blending. Generally, CAMs incorporate colorimetric or cone-referenced descriptions of stimuli along with parameters for adaptation and surround effects, and they predict correlates of perceptual characteristics such as hue, lightness, brightness, chroma, and colorfulness [21]. For AR, a CAM can be updated either by altering the stimulus description or by manipulating the output computations.

An early attempt at a simple model of scission and discounting has proved durable through many experiments: Hassani and Murdoch's weighted foreground-background blending model. Somewhat counter-intuitively, because it is meant to explain a cognitive process, it operates in the stimulus domain, computing an effective stimulus as a weighted sum of AR foreground (FG) and real-world background (BG) contributions. The sum is shown here using tristimulus values for example, but equivalently could be cone signals, spectral radiance, or any linear scene-referred quantity:

$$XYZ_{eff} = \alpha\, XYZ_{FG} + \beta\, XYZ_{BG} \tag{1}$$

where the weights α and β would both equal unity for a physical sum, but can be varied to account for discounting. In Hassani's foreground-matching experiments, generally $\alpha > \beta$, with $\alpha{:}\beta$ ratios equal 2:1 to 3:1, indicating that the background contribution is discounted when observers are comparing foreground stimuli. In Murdoch's background-matching work, $\alpha < \beta$, indicating foreground discounting. $\alpha{:}\beta$ ratios ranged from approximately 1:1.5 to 1:1, depending on how "oversized" the AR overlay. A larger overlay corresponded to more foreground discounting, presumably because the layering cue was stronger. The situation resulting in nearly 1:1 weighting was the only case where the AR overlay was tightly fit and aligned to the real-world object, effectively removing any cues to its existence, eliminating scission, and making the proximal stimulus the only cognitive explanation.

In a later experiment, correspondence between transparent AR color patches and physical Munsell color samples was made [22]. Here, depending on the background and AR surround, fitted $\alpha{:}\beta$ ratios seemed to vary widely, confounding efforts to easily predict α and β for use in an AR CAM. In retrospect, the variations observed were likely the result of ambiguity that the observers could not resolve: for example, a "pink" proximal stimulus could be interpreted either as a red AR stimulus diluted by a bright background, an undiluted AR pink, or anything in between! This has not reduced the appeal of the $\alpha{:}\beta$ model; yet unpublished work comparing AR presentations with simultaneous contrast effects seems to show again good evidence for its utility.

An AR CAM remains a primary goal, despite the challenges of pinpointing the discounting parameters. Current work is focused on efficient descriptions of the foreground/background scene combinations and heuristics for the α and β parameters that are robust over recent experiments and relevant AR applications.

Luminance, Contrast, and Image Quality

Luminance and transparency are intertwined in OST-AR: brighter AR stimuli have the effect of lowering the visible contrast of background elements, making the AR layer appear more opaque. Lili Zhang and Murdoch showed through psychometric scaling experiments that steps of perceived brightness and perceived opacity are essentially equal [23]. An unfortunate epilogue says that it is nearly impossible to display black objects in AR, worsening still with brighter backgrounds.

With visibility and image quality in mind, several research groups have looked for image processing improvements that don't rely on a CAM. Yunjin Zhang et al. created and tested a color contrast enhancement method that aims to make the AR content more visible based on the local characteristics of a given real background [24]. Lee et al. suggest a gamut-mapping approach to attempt to restore the AR image to the intended range and contrast in spite of the background [25]. At RIT, recent work to find practical solutions to improve visibility and image quality include image tonescale manipulations [26] and border treatments (please see the author's concurrent HVEI paper [27]). The influence of these on perceived contrast and the combined effect on overall image quality is still being investigated.

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Author Biography

Michael J. Murdoch is an Associate Professor and Director of the Munsell Color Science Laboratory at RIT. He has more than 25 years of experience in color and imaging including research at Kodak and Philips. He conducts research on color appearance in augmented reality systems, displays, and LED lighting. He holds a BS in chemical engineering from Cornell, an MS in computer science from RIT, and PhD in human-technology interaction from Eindhoven University of Technology.