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From Polaroid to Augmented Reality: The Enduring Advantages of White Borders

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Abstract

Ubiquitous throughout the history of photography, white borders on photo prints and vintage Polaroids remain useful as new technologies including augmented reality emerge for general use. In contemporary optical see-through augmented reality (OST-AR) displays, physical transparency limits the visibility of dark stimuli. However, recent research shows that simple image manipulations, white borders and outer glows, have a strong visual effect, making dark objects appear darker and more opaque. In this work, the practical value of known, inter-related effects including lightness induction, glare illusion, Cornsweet illusion, and simultaneous contrast are explored. The results show promising improvements to visibility and visual quality in future OST-AR interfaces.

Introduction

The photography industry was forever changed in April, 1972, when Polaroid unveiled the much-anticipated SX-70 folding SLR instant camera, and with it the instant print film whose square images with thick white borders have become a vintage classic [1]. The distinctiveness of Polaroid's square images surrounded by a white border, extra wide at the bottom, was not designed for its appearance, but rather as an essential watertight package for the instant developing chemistry contained inside. The wider bottom edge stored the chemistry until the print came out of the camera, rollers squeezing it into the square image in the process.

White borders were not news. For more than a century, most photographic prints had white borders. As with Polaroid, this was not an aesthetic choice, but an artifact of the darkroom printing process in which silver-halide photographic paper was held flat in an easel with a metal edge. The opaque metal prevented the paper edge from being exposed to light, which in the negative printing process resulted in the border remaining paper white. Over the years, borderless prints from countless minilabs became the norm, though darkroom artists and photo aficionados still choose white borders for their vintage appeal and more "artsy" appearance.

Today's imaging landscape still includes silver-halide photographic prints, along with white-bordered Polaroid and Fujifilm instant prints, but it is dominated by digital imaging and advanced display modalities including head-mounted displays (HMDs) implementing virtual reality (VR) and augmented reality (AR). In this environment, a white border is strictly optional. Interestingly, in optical see-through (OST) AR, white borders are again practically useful, albeit for a whole new purpose: improving the appearance of transparent content. Transparent AR struggles to make dark images visible, but the darkening effect of white borders, outer glows, and similar effects, is shown to provide some relief.

In the following sections, the novel perceptual attributes of OST-AR are reviewed, then a summary of appearance effects induced by white borders and gradients is provided. A visual experiment is described, including image stimuli production, experimental methods, and analyses. **Figure 1** provides an illustration of the visual effects discussed.

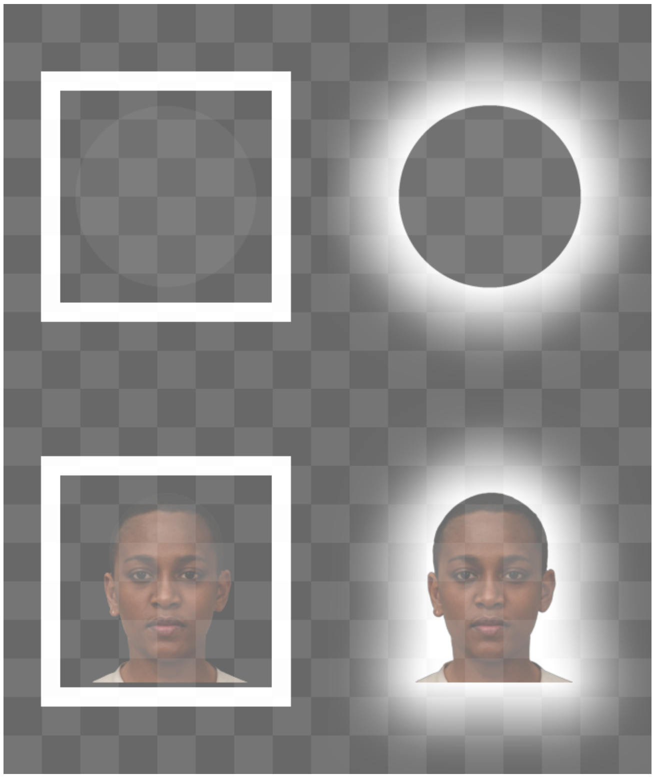

***Figure 1**: Simulation of additive optical combination of OST-AR images (disks and faces) with borders overlaid on a checkered background, where the visibility of the checkerboard gives a strong transparency cue. The pairs of circles and faces are identical. The left images have thick borders, which appear to darken the checkerboard within but have little effect on the disk and face; the right images have an outer glow, making the disk appear dramatically darker and the face and hair appear darker, more visible, and more opaque.*

Perception in OST-AR

The physical transparency of the display and optical combiner in an OST-AR system means that the real-world background behind bleeds through the displayed image. However, users of AR systems generally have no trouble interpreting the transparent stimuli, due to perceptual scission, which is the cognitive separation of the transparent foreground and real-world background layers. Scission can be enhanced with depth cues such as stereo disparity and motion parallax, as well as via image complexity and object continuity. A full accounting of recent findings in this area is provided in a recent book chapter by Murdoch [2].

Scission between the transparent foreground and background can result in visual discounting, which usually means that the foreground contributes more to the perceived color and lightness, and the background contributes less, than would be expected from the physically additive combination of foreground and background [3]. However, the opposite is possible, meaning the foreground is discounted, if the cognitive focus is on the background due to visual task or visual complexity [4]. Predicting the amount and polarity of discounting in arbitrary situations remains a topic of research.

Because the OST-AR display is physically transparent, there is a direct relationship between display luminance and perceived opacity [5]. Brighter transparent stimuli reduce the contrast in any background elements, making them less visible in general, and contributing to scission. An inescapable problem, however, is that black is invisible, and the darker the stimulus, the more transparent it appears. Practically, this creates an unwelcome bias in presenting realistic images of people: it is more difficult to display a realistic and visible image of a person with a more melanated, or darker, skin tone than one with a lighter skin tone (see **Figure 1** and **Figure 2**).

Spatial Lightness Effects

The human visual system has remarkable abilities to discern the material property of lightness (for the sake of this discussion, brightness relative to white, or equivalently perceived reflectance) in the face of diverse illumination environments, object shapes and shading, and other visual complexity. Fascination with human visual deftness has inspired a century or more of lightness induction research. Many spatial lightness effects have been catalogued and quantified over the years, including some ubiquitous demos or illusions, and several of these, related to white borders, are quite advantageous in OST-AR systems. A few relevant findings are summarized here, many of which are cited in Gilchrist's rich tome *Seeing Black and White* [6].

In the 1940s, Hans Wallach studied the brightness constancy using dark disks surrounded by bright annuli, in a darkened environment [7]. Without the annulus, an illuminated disk in the dark appears luminous rather than reflective, but the annulus provides an anchor that makes the disk appear opaque and reflective. He found that matching the luminance ratio of the disk to its brighter annulus generally predicted matches across luminance levels, but he noted deviations, for example that brighter or narrower annuli induced the perception of a darker disk. Gilchrist refers to anchoring in lightness perception, corresponding to Wallach's observation that the bright annulus is generally perceived as white, regardless of absolute luminance [6]. Irvin Rock extended the idea of maximum luminance anchoring to white to the analogous minimum luminance anchoring to black [8], which seems extremely relevant to media adaptation such as the perception of a full range of lightness in low dynamic range images in newsprint, and a similar effect in AR.

Simultaneous contrast is often demonstrated to show the contextual nature of color perception – the familiar comparison of a pair of center-surround figures, in which the physically-identical centers appear to diverge from the surrounding color. Choosing among numerous references for this effect, the lightness, hue, and colorfulness directions were quantified well by Luo et al. [9]. They found that a white surround was found to depress the lightness of the mid-gray center by 5 to 15 CIELAB L* units, or approximately 0.5 to 1.5 Munsell value units.

The visual system tends to fill in spaces based on edge interfaces. The Cornsweet illusion, originally studied using rotating disks with printed black and white patterns of varying edge details, is a well-known effect in which two identical uniform gray areas may be perceived as different in lightness if at their interface a pair of density gradients are made to meet at a discontinuity [10]. Related phenomena of Mach bands and simultaneous lightness contrast are also discussed in the aforementioned books as well as many others.

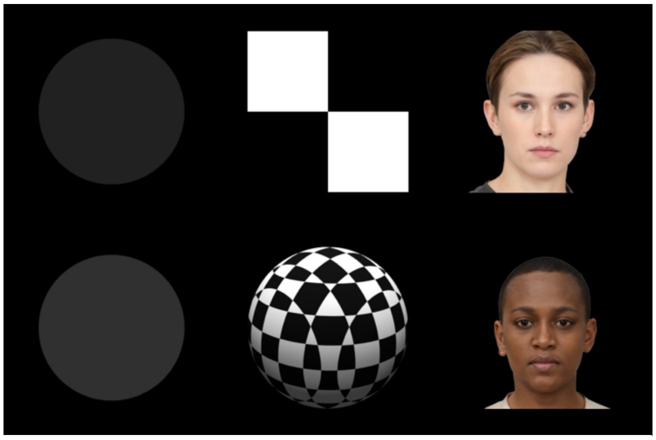

Figure 2: *Six source images used for the experiment. In the left column, darker and dark uniform disks; in the center column, square checker and sphere checker; and in the right column, lighter face and more melanated face.*

The effect of lightness gradients similar to Cornsweet's was also observed to create strong lightness increases and decreases. Agostini and Galmonte showed that a gradient could increase the magnitude of the simultaneous contrast effect – increasing a darkening effect from less than one-half to almost a full unit of Munsell value [11]. Later, they and others described a series of similar effects including low- and high-frequency gradients that can change the polarity of apparent lightness changes [12].

Based on the lightness induction effects described throughout the literature, the exploration of the utility of bright borders in OST-AR was begun, with the hope that a simple bright edge or a gradient could help reduce the apparent brightness of dark, transparent stimuli. A systematic study of border, image content, and background was made.

Methods

An experiment employing the method of adjustment was designed, with six source **images**, eight different **border** treatments, and three **backgrounds**. Images were presented in pairs with and without border treatments, and observers adjusted the black level of the bordered image to visually match the brightness of the non-bordered reference image. Typically, the observers raised the black level of the bordered image to compensate for its darkening effect; thus, it can be inferred that the magnitude of black level lift is equivalent to the visual darkening effect of the border.

Images and Border Generation

Six source **images** were selected, as shown in **Figure 2**: representing the most basic stimuli, related to Wallach's early work, two uniform dark disks of 1.5% and 3% luminance factor were generated. Next, to include a full black-to-white range in the images, a synthetic square checkerboard and a rendered sphere with a checkerboard albedo pattern were created. Finally, because human faces are essential for many AR use cases, and because darker skin tends to be more difficult to see in transparent AR, two faces were selected: one with lighter skin tone and one with more melanated skin tone, approximately Monk 03 and 07, respectively [13]. Each image was given a uniform black background using a custom alpha matte generated computationally or, in the case of the faces, using Photoshop. These images comprised the reference images.

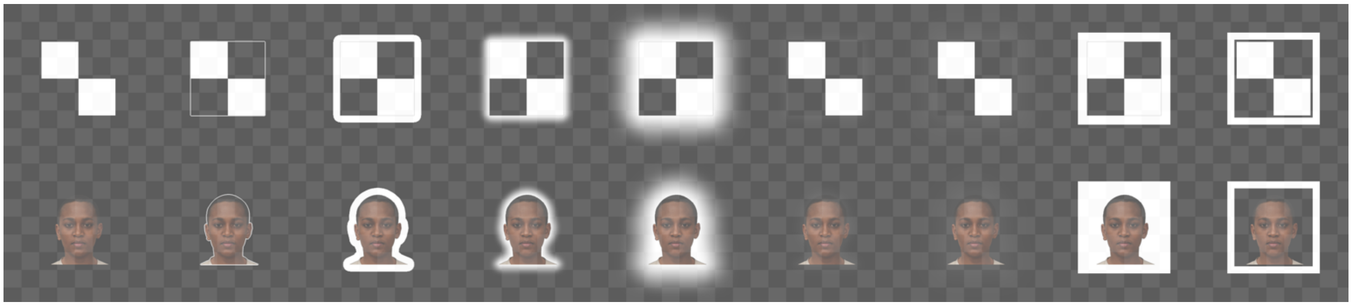

***Figure 3**: Border variations shown with simulation of additive combination with a checkered background, using the square checker and more melanated face images. At far left, the reference images with no border are shown. Following, left to right, the eight border variations in order are: narrow border, wide border, narrow bright glow, wide bright glow, narrow dim glow, wide dim glow, box surround, and frame border.*

Eight variations of **borders** were generated, six of which followed the contours of the images' alpha mattes, and two of which were a fixed square size. The contoured borders were generated in MATLAB using morphological imaging. The borders are shown in **Figure 3**, applied to the square checker and more melanated face images for illustration. The figure simulates the additive combination of the bordered images on the transparent display with a checkered background behind, similar to the appearance seen in the experiment. The darkening effect of the borders on the images is apparent, especially on the square checker image with thick bright glow (top center). Similar effects are observed between the square checker and melanated face images, though the effects appear slightly smaller with the face image.

Border Variations

Starting with 240-pixel square images, the narrow and wide contoured borders were created by dilating the alpha matte using a disk structuring element with radius 2 and 20 pixels, respectively, with a luminance factor of 1. The narrow and wide glow borders were created by dilating the alpha matte using a disk structuring element with radius 18 and 52 pixels, then applying a Gaussian blur with sigma equal to the dilating radius and size twice the dilating radius. Bright glow and dim glow variations had a max luminance factor of 1 and 0.1842, respectively (corresponding to L* 100 and 50). The box surround filled the space outside the alpha matte with a uniform field of luminance factor 1, and the frame border had the same outer dimensions but was 20 pixels in thickness. Note that the frame border, especially with the square checker image, seems to have a narrow black line just inside the white border, but in fact that is just the space between the image and the border, through which the background is visible.

Black Level Lift

For the method of adjustment task, variations in black level were pre-computed for all six images. After converting the images from sRGB to XYZ tristimulus factor with range [0, 1], the XYZ values were linearly compressed upward, leaving the peak Y fixed and lifting the minimum XYZ values. The transformation applied was: $Y' = mY + b$, where b is the black level, and $m = 1 - b$. Black levels from -5% to 15% with steps of 0.5% were computed, 41 levels in total. In rare cases where the negative lift resulted in negative values (such as the black part of the square checker), they were clipped to 0. Identical borders were added to each set of images after black level lift, so that the borders were unaffected by this transformation. The 41 black levels for each of the 48 combinations of image and border were converted back to sRGB and saved for use in the experiment, along with the 6 reference images.

Display and Background

Images were presented on a desktop AR system described in previous papers [4][14]. The system is centered on a beamsplitter, which reflects an LCD display and transmits objects in a lightbooth behind it, resulting in the displayed images appearing transparent, floating in the volume of the lightbooth. Measured in reflection through the beamsplitter, isolated from the lightbooth, the display has a D65 white point with a maximum luminance of 179.3 cd/m^2 and a minimum luminance of 0.81 cd/m^2.

The lightbooth was empty, with a printed paper checkerboard covering the back wall and floor for a consistent background. It was illuminated by D65 LED bulbs. The opening of the lightbooth was viewed through a pane of glass with one part of the glass covered with a neutral density ND 0.6 gel filter, providing attenuation of nominally 0.6 density or 2 stops of light, with measured transmittance of 0.278. Measured in transmission through the beamsplitter, the checkerboard luminance values (light and dark checkers) were 143 and 126 cd/m^2 behind the glass, and 39.5 and 35.1 cd/m^2 behind the glass and ND filter.

Three **background** variations in the experimental presentations were created. First, a black background was created, with the light booth lights off, and images were presented in front of the (invisible) ND filter; this results in an image black-to-white range equal to the display, 0.81 to 179.3 cd/m^2. With the lightbooth lights on, images were shown in front of the ND filter, creating a second background of a medium checker, which in front of the brighter checker resulted in an image + background luminance range of 40.3 to 219 cd/m^2. The third background, a light checker, was created by presenting images in front of the bare glass (no ND filter) with the lights on, resulting in an image + background luminance range of 143 to 322 cd/m^2.

Presentation and Observer Task

Observers were presented with pairs of images: a reference image with no border, and the same source image with a border variation and with a randomized starting black level. Observers were asked to: *"Adjust the image to match in brightness, focusing on the darkest parts of the image. If you find it impossible to make a good brightness match for all parts of the image, try to match the darkest parts."*

Presentation of images and borders was completely randomized, but the backgrounds were blocked so that all image × border combinations were completed for a single background before moving on. The order of background blocks was balanced over observers: there are six possible permutations of three backgrounds, and these were used sequentially.

Results

Eight observers completed the experiment, equal in M/F split, ranging in age from 15 to 50. Each background block of 48 matches took 15-20 minutes, for a total experiment time of 45-60 minutes. The observers' adjusted black level, selected via method of adjustment among the pre-computed black level variations, was the dependent variable, where a higher adjusted black level corresponds to a larger darkening effect of the border. The adjusted black level was affected by independent variables of **image** (6), **border** (8), and **background** (3). These 144 presentations, seen by all eight observers, resulted in 1,152 total observations.

An ANOVA was computed using MATLAB with these three independent factors, the 2-way interactions of **image** × **border**, **image** × **background**, **border** × **background**, the 3-way interaction of **image** × **border** × **background**, and **observer** as a random factor. All except the 3-way interaction were significant at the $\alpha = 0.05$ level, as is shown in Table 1.

Table 1: ANOVA table for 8 observers of all presentations.

Source	Sum Sq.	d.f.	Mean Sq.	*F*	*p*
Image	22,147	5	4,429	174.3	<0.001
Border	11,460	7	1,637	64.4	<0.001
BG	295	2	147	5.80	0.0031
Obs (random)	3,137	7	448	17.6	<0.001
ImagexBord	7,385	35	211	8.30	<0.001
ImagexBG	1,969	10	197	7.75	<0.001
BordxBG	824	14	59	2.32	0.0039
ImagexBordxBG	1,327	70	19	0.75	0.9398
Error	25,436	1,001	25		
Total	73,979	1,151			

Main Effects

While the picture is somewhat incomplete given the significant interaction effects, boxplots of the main effects are shown in **Figure 4**. In the top plot, comparing **images** over all borders, backgrounds, and observers, the two disk images (1 & 2) show the strongest darkening effect, indicated by the highest adjusted black values. The square checker (3) and sphere checker (4) images show median adjusted black levels just above and just below zero, respectively. The lighter face image (5) shows black levels similar to the square checker, and the more melanated face image (6) slightly higher.

In the middle plot, comparing **border** types, the highest adjusted black levels and widest interquartile ranges are seen with the wide bright glow (4) and box surround (7). The wide border (2) and narrow bright glow (3) show similar medium black levels, and the two dim glows (5 & 6) and frame border (8) show similar low black levels. The narrow border (1) shows the lowest adjusted black levels, with median approximately zero.

Comparing **backgrounds** in the bottom plot, the black background (1) shows the lowest median and narrowest interquartile range. The medium and light checkerboard backgrounds (2 & 3), respectively, show increasing median and interquartile ranges.

Interaction Effects

A strong interaction effect was noted between **image** and **border** – essentially, the darkening effect per **border** type is similar in pattern, but differences are magnified or attenuated depending on **image**. **Figure 5** includes a subset of images and borders that illustrate the diversity observed in the experiment. The effect on adjusted black for the dark disk image (far left) shows dramatic increases for the wide bright glow and box surround borders, and the trend over border is similar in shape but attenuated in magnitude for the two face images. The results from the sphere checker image are all quite close to zero, indicating that no border type elicits a darkening effect with this image.

There is also an interaction between **image** and **background**, as shown in **Figure 6**. The dark disk image (far left) shows an overall higher magnitude of adjusted black level with a slightly increasing trend over background brightness. The other images show much lower magnitude and different trends with background.

Figure 7 shows the interaction between **border** and **background**. The narrow border (far left) shows very little darkening effect regardless of background, while the wide bright glow (second from right) shows a strong trend of increasing adjusted black level with background brightness. This trend is mimicked at lower magnitude for the box surround (far right).

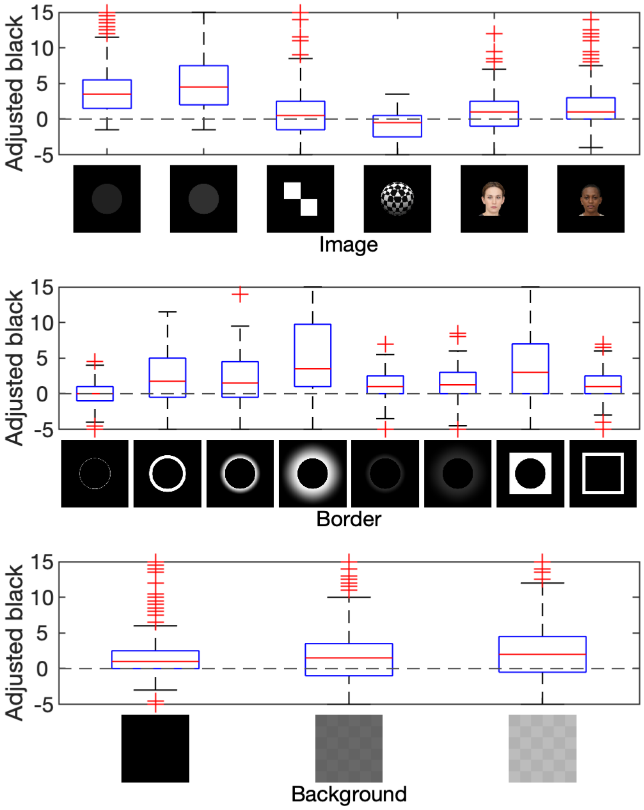

Figure 4: *Boxplots of adjusted black level results for main factors, where the blue boxes show the interquartile range (25th to 75th percentile), the red lines median values, black whiskers 1.5x the interquartile range, and red '+' indicating individual observations beyond the whiskers. The top plot shows results per* ***image****, the middle plot per* ***border****, and the bottom plot per* ***background****.*

Discussion

This small study clearly shows that simple borders surrounding dark stimuli in OST-AR can provide strong perceived darkening effects. The strongest effect, for the dark disk image with wide bright glow (in the far-left pane of **Figure 5**) has a median adjusted black level of 12%. That means that with the glow, the disk of 15% luminance factor matches in brightness – or in other words, looks as dark as – a non-bordered disk of 3% luminance factor. In CIELAB L* terms, these values are 46 and 20, roughly Munsell value 4.6 and

2: very large visible differences, and a very strong darkening effect! Perhaps this should be named the Corona Effect because of its likeness to a solar corona during an eclipse.

It is difficult to compare the present results with many of the previous literature discussed earlier, especially given the variety of stimulus images used herein. The nearest previous study is perhaps the work of Agostini and Galmonte, which showed that a white glow effect could decrease the apparent lightness of a mid-gray (Munsell 5.5) patch by about one unit of Munsell value. Compared to this, the value decrease mentioned above (from 4.6 to 2) is larger – perhaps because of the exaggeration caused by layer scissioning, or perhaps because the starting value is different. In all comparisons the mixed effect of simultaneous lightness contrast, border, and scission are difficult to separate.

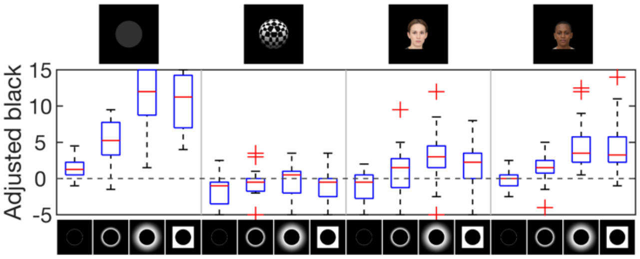

*Figure 5: Boxplots of adjusted black level indicating interaction effects, showing four **border** variations (narrow border, narrow bright glow, wide bright glow, box surround) grouped for each of four **images** (darker disk, sphere checker, lighter face, more melanated face).*

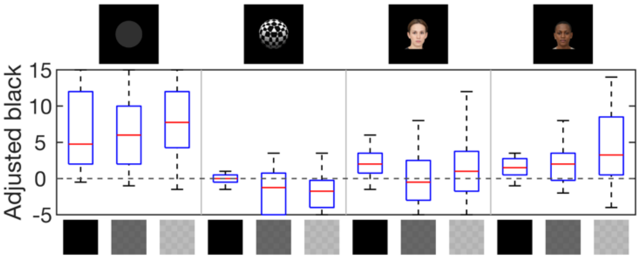

***Figure 6**: Boxplots of adjusted black level indicating interaction effects, showing three **backgrounds** (black, medium checker, light checker) grouped for each of four **images** (darker disk, sphere checker, lighter face, more melanated face).*

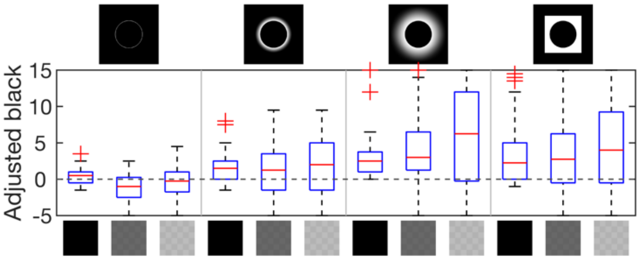

***Figure 7**: Boxplots of adjusted black level indicating interaction effects, showing three **backgrounds** (black, medium checker, light checker) grouped for each of four **border** variations (narrow border, narrow bright glow, wide bright glow, box surround).*

There is a large effect of image content, apparent in **Figure 4**, **Figure 5**, and **Figure 6**: in general, the darkest images create the strongest effect, but it is not simply mean luminance driving the difference. It appears that the presence of bright regions, even in relatively dark images, tend to reduce or eliminate the effect. The dark and darker disks show the strongest effects in all cases, even with the widest interquartile ranges in the boxplot results. Correspondingly, observers mentioned that the disks were the most difficult to match, and that sometimes they raised the black level to the maximum available and it wasn't quite enough. Interestingly, the checker sphere image, which contains a full range of white to black pixels, shows the weakest effect of border (**Figure 5**) and a possibly inverted effect of background (**Figure 6**). Observers noted that the sphere checker image was ambiguous, depending on what part of the image they looked at: they could match either the black at the top of sphere or the shadow region at bottom, but it was difficult to match both simultaneously. This ambiguity does not manifest itself as large boxplot ranges.

An important finding is that the darkening effect generally increases with background luminance, which may indicate that the Corona Effect is larger with transparent AR stimuli than on simple 2D displays. The ANOVA found a significant effect of background on adjusted black level (albeit in the presence of interaction effects), and a post-hoc test showed that the light checker background was significantly higher than the other two. The difference in adjusted black level is seen in the bottom plot of **Figure 4** and for several variations in **Figure 6** and **Figure 7**.

Future Work

The present study focused on quantifying the amount of darkening effect caused by bright border treatments, using a brightness matching technique. Clearly, there is an effect on perceived brightness (or lightness), but future work is warranted to determine the effect on visibility of details in the dark stimuli, perceived opacity of the transparent stimuli, and overall image quality. Are the distortions introduced by bright borders worth it for brightness and visibility advantages, or do they reduce image quality on balance?

A future study could focus on the glowing border types while looking more closely at the effect of border size and brightness, and it could also include stimuli in more realistic contexts for OST-AR applications. There is a good chance that an adaptive border strategy, depending on the luminance and contrast of the background as well as the AR images, would be beneficial, requiring more experiments to design and verify. Further work could also address efficiency in rendering the borders in a shader paradigm.

Conclusion

The present study shows that bright edge treatments, similar to white borders in photography or outer glow effects, provide a visual darkening effect to low-luminance, transparent AR stimuli. Darkening effects of up to 12% luminance factor were observed, equivalent to 20+ units of CIELAB L*. The darkening effect depends strongly on image content, stronger with darker images, as well as border type, strongest with a wide bright glow. The observed darkening was expected based on lightness induction literature, but the effect is notably larger in transparent stimuli with bright backgrounds than in 2D displays, making it especially valuable for use OST-AR applications to make darker objects and more melanated skin tones appear more visible and natural.

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