Gaze-Contingent Manipulation of Color Perception

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ABSTRACT
Using real time eye tracking, gaze-contingent displays can modify their content to represent depth (e.g., through additional depth cues) or to increase rendering performance (e.g., by omitting peripheral detail). However, there has been no research to date exploring how gaze-contingent displays can be leveraged for manipulating perceived color. To address this, we conducted two experiments (color matching and sorting) that manipulated peripheral background and object colors to influence the user's color perception. Findings from our color matching experiment suggest that we can use gaze-contingent simultaneous contrast to affect color appearance and that existing color appearance models might not fully predict perceived colors with gaze-contingent presentation. Through our color sorting experiment we demonstrate how gaze-contingent adjustments can be used to enhance color discrimination. Gaze-contingent color holds the promise of expanding the perceived color gamut of existing display technology and enabling people to discriminate color with greater precision.

Author Keywords
Eye tracking; gaze-contingent displays; color perception; simultaneous contrast; local contrast enhancement

ACM Classification Keywords
H.1.2 Models and Principles: User/machine Systems; I.3.3 Computer Graphics: Picture/Image Generation

INTRODUCTION
Inexpensive and easy-to-use eye tracking (e.g., Eye Tribe[1], Gazepoint[2]) is entering the mass market for gaming hardware through dedicated products, such as the Sentry Eye Tracker [37], and has long been used in marketing and user experience research [40]. Building on stand-alone eye tracking, gaze-contingent rendering and gaze-contingent multi-resolution displays are appearing in the wild [8] and in applications that aim to enhance immersion and realism [9].

Other facets of gaze-contingent displays (GCDs) have received less attention; in particular, gaze-contingent color manipulation has yet to be adequately explored. GCD-based luminance manipulation has been developed for displaying High Dynamic Range (HDR) images [32]; however, there is no quantitative evidence of its benefits yet and GCDs have yet to be extended to properties of color beyond luminance. We propose that gaze-contingent color manipulation can be used beyond gaze-based luminance adjustments to virtually enhance the entire gamut of a display in both luminance and chromaticity.

Gaze-contingent (GC) color manipulation could allow us to virtually expand the perceivable color gamut of a display (e.g., allowing more vivid colors in photographs) and increase user color discrimination abilities (e.g., improved color differentiability in information visualization tasks that involve color).

To explore GC color manipulation, we conducted two experiments to provide insights into how GCDs can influence color appearance. Both experiments used gaze-contingency to manipulate simultaneous contrast (SC), which is the phenomenon in which the color of an object's surroundings influences our perception of the object's color (see Figure 1).

In our first experiment, participants manipulated the color of a target patch to match a reference patch in both static and gaze-contingent conditions. We found that gaze-contingent color presentation preserved the SC effect in general but also found minor differences in the magnitude of the SC effect between the static and gaze-contingent conditions.

In our second experiment, participants sorted colored patches into a gradient using both static and gaze-contingent presentation techniques. We found that gaze-contingent techniques allowed participants to sort colors with fewer errors than in the naive static condition, although not directly through SC background manipulation.

This paper makes three contributions. First, we provide the first quantitative analysis of the effects of gaze-contingent color manipulation. Second, we provide data that supports the feasibility of techniques that (a) use simultaneous contrast to extend the apparent display gamut and (b) manipulate peripheral patches to improve color differentiation. Finally, we provide general insights into how color changes in the visual periphery can influence the perception of color on a GCD, which has implications for the use of GCDs in general and color manipulations specifically.

BACKGROUND
This section provides basic information on color perception, simultaneous contrast, and the CIE L*a*b* color space.

Color Perception
Color perception is a process in which the visual system interprets light-wave stimulation in the eye to differentiate

[1] https://theeyetribe.com/, retrieved September 25, 2015
[2] http://www.gazept.com/, retrieved September 25, 2015

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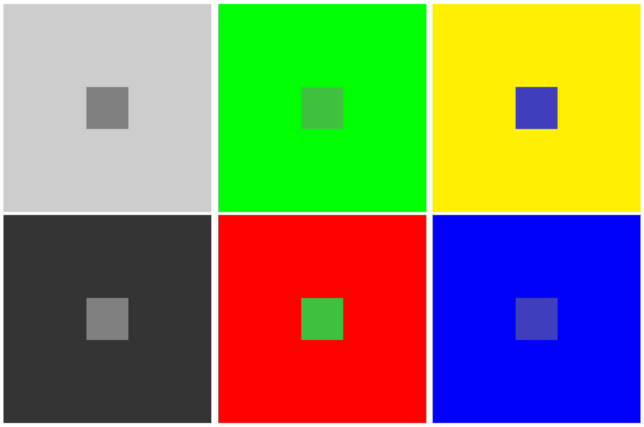

Figure 1. Simultaneous contrast: Central patches in the top row contain the same color as the patches of the bottom row but are perceived differently (in chromaticity and lightness) due to their surround.

between objects with varying reflective properties [13]. Although the spectrum of light that an object reflects into our eyes can vary substantially depending on the sources of light and the environment, we are able to reliably identify objects and their color [10]. This stability, often referred to as *color constancy* [13], is achieved through a combination of perceptual processes which we are generally unaware of until certain anomalous situations or stimuli make them obvious or puzzling, such as the recent "Dressgate" viral phenomenon [41].

At the core of our work is one of these perceptual anomalies: simultaneous contrast (SC). SC refers to how the appearance of a color patch is often influenced by the color that surrounds it (see Figure 1) and has been previously explored using color matching experiments in which participants compare patches of colors surrounded by different colors (e.g., [2, 18]).

SC and other color perception phenomena are described in Color Appearance Models (CAMs) that predict the appearance of a color given extrinsic viewing conditions [10]. A range of CAMs exist, including the application-oriented CIECAM02 [26], the comprehensive Hunt's model [16, 17], and other recent computational approaches [28]. These CAMs assume static viewing conditions, so they might not generalize to the temporally-dynamic conditions of gaze-contingent color manipulations, motivating our first experiment.

Color spaces

Color perception research requires precise ways to represent colors, typically by using *color spaces* which are multidimensional coordinate spaces in which each unique color maps to a unique location. In this paper, we use the 1976 CIE L*a*b* color space (CIELAB) [33, 34] because it is approximately perceptually uniform (Euclidean distance corresponds to perceptual difference), is well-known, and is based on opponent color channels [10, 13] which are closely related to simultaneous contrast effects [10]. CIELAB describes colors using lightness (L*: dark to bright), an a* axis (green to red), and a b* axis (blue to yellow), as shown in Figure 2.

RELATED WORK

Color perception has been applied to the development of graphics [1], interfaces [20], visualizations [12, 36], and image compression [35, 39]. Of particular importance to our work are *tone mapping* and *gaze-contingent displays*.

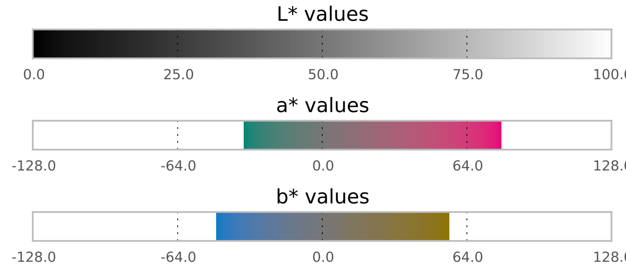

Figure 2. Sample gradients along the CIELAB axes (relative to D65). The L* gradient assumes a* = b* = 0, the a* and b* gradients assume L* = 50 and a* = 0 or b* = 0 respectively. Colors are truncated to sRGB.

Tone Mapping

When moving images between devices, tone mapping is used to adjust the colors of the image so that they are displayable or printable on the target device (e.g., displaying an image from a camera with a wide color gamut and HDR sensors on an LDR display with a smaller color gamut [32]). The two main approaches to tone mapping are global and local. Global operators are applied to each value in an image equally, e.g., by logarithmic transformation. Local tone mapping operators take into account the surround for each point in the image. To preserve the overall impression of a scene and create a realistic rendition of the HDR data, many advanced tone mapping techniques use knowledge of visual perception to influence how colors are perceived, e.g., by using simultaneous contrast to make colors appear brighter through an adapted surround [4, 19]. Most tone mapping approaches produce a static image; examples of gaze-contingent tone mapping are reviewed next.

Gaze-contingent Displays (GCDs)

GCDs leverage real-time eye tracking to manipulate display content in reaction to the user's eye gaze. GCDs have been used to reduce the computational cost of rendering [6, 14, 22, 27, 31]), to compensate for visual problems such as scotoma [6], or to add additional depth cues [25, 38].

There have also been attempts to use GCDs to influence brightness and luminance perception. Jacobs et al. [7] simulated loss of acuity, aftereffects and other visual phenomena with a GCD and found that brightness perception can be altered. Cheng and Badano [3] describe a gaze-based luminance and contrast algorithm for medical imaging, but do not provide an evaluation. Yamauchi, Mikami and Ouda [42] investigated global tone mapping operators driven by parameters derived from the focal area and compared them in a subjective task, but their comparison had no baseline nor showed statistically-reliable effects. Similar gaze-contingent tone mapping approaches have been proposed (e.g., [24, 30]), but without empirical evaluation. As a result, there is no evidence that gaze-contingent tone mapping provides any benefit over static tone mapping.

Our work furthers the state-of-the-art in gaze-contingent perceptual manipulation in two main ways: 1) we provide reliable empirical evidence about the perceptual effects and feasibility of gaze-contingent manipulation of color, and; 2) we extend the idea beyond luminance to also include chromaticity.

OVERARCHING GOALS AND RESEARCH QUESTIONS

We aim to lay the foundation for the use of gaze-contingent displays to achieve a *perceived* gamut that is wider than what the same display could produce without gaze contingency. For example, consider the range of sRGB colors in the a* axis (center row, Figure 2). Existing knowledge of the simultaneous contrast effect [2] tells us that the green sRGB color displayed at the left end of the a* axis can be perceived equivalently (i.e., *matched* in color-matching experiments) to a green further left on the axis (not displayed in the figure) *if a suitable surrounding color is provided* for the original green. We call this a *color shift*. For example, the left-end green can be made to appear more green by surrounding it with a contrasting color (e.g., red) even if the green being perceived or, more precisely, the green that we would have to generate to match our original green's perception is actually out of the gamut that the display can produce. In simplified terms, the more contrasting the surrounding color is (the redder or further right in the a* axis in our example), the further the SC models predict the color will shift outside the existing gamut.

We can achieve this effect on static displays for a single color by manipulating the colors in the surround to have higher chromatic contrast (e.g., make them more red in our green example above); however, to actually enlarge the perceived gamut of a display, we have to be able to manipulate the colors in the surround for any color at the edge of the gamut. A gaze-contingent display could help us shift the surrounding colors according to the position of gaze, but this assumes that the simultaneous contrast effect is robust to gaze-contingent changes in the display. This leads to our first research question (addressed in Experiment 1): Does gaze-contingent presentation of color preserve the simultaneous contrast effect, and if so, to what extent? Assuming that gaze contingency manifests SC, our second research question (addressed in Experiment 2) is: Do GC-based techniques increase a user's ability to discriminate colors?

COMMON TERMINOLOGY AND GC-MANIPULATIONS

Accurate reproduction of color in this document requires calibrated media (i.e., a color-calibrated display). Descriptions of colors in this paper are in CIELAB coordinates. Ideally our experiments would test the different manipulations at samples covering the whole CIELAB space at regular intervals, but this is unfeasible at this stage for our multi-technique comparison and is not necessary at the proof-of-concept stage. Instead, we sample the space at two points of each of the CIELAB axes by testing our hypotheses with colors on the L* axis at low and high values (dark and light greys), the a* axis at the green (low) and red (high) ends, and the b* axis at the blue (low) and yellow (high) ends (Figure 2 provides a reference). When testing each axis, the other axes stay at default values which are L*=50 and a*=b*=0. This means that if we refer to a color by one of its values (e.g., a*=43) its full coordinates are L*=50, a*=43, b*=0, or $(50,43,0)$.

Our experiments use uniform color patches as stimuli as is customary in color science and color appearance model research. Patches will be denoted by P with a subscript modifier that denotes their role in the experiment (e.g., P_{match} for a patch that the participant controls to match another patch). Patches have a color which can vary depending on the experiment circumstances and the gaze of the participant. Patches appear within a background B that also has a precisely-identified color. Both patches and background colors can be *static* or *gaze-contingent (GC)*. If they are gaze-contingent, they will change color depending on whether the participant is looking at the patch (*attended* patch – the coordinates of the gaze location are within the boundaries of the presented patch) or not (*unattended* patch).

In general we investigate two types of gaze-contingent color manipulations: background manipulation and peripheral patch manipulation. Background manipulation changes the color of the background area(s) depending on which area is looked at, i.e., a global change in the scene. This will be used to explore inducing different degrees of simultaneous contrast in different areas of the screen. Unattended patch manipulations change the color of patches that are not currently being looked at, i.e., a local peripheral change of specific objects. This will be used to explore increasing contrast between objects, e.g., to make peripheral objects easier to differentiate from the attended one.

REPLICABILITY

The analyses presented in this paper were performed in Python/R on a Vagrant virtual machine. We provide configuration files to recreate the virtual machine, as well as the data and code of the analyses (ACM DL). We hope that making our data and analyses available in this way will promote openness and reliability, and encourage other researchers to use our data to further analyze our experiments and to facilitate replication.

STATISTICAL APPROACH

The main statistical outcomes take two forms: effect sizes of factors from omnibus tests of repeated measures linear models and pairwise comparisons between conditions.

The factor effects from the repeated measures linear models are reported as η_p^2 (proportion of explained variance when excluding other factors). For the pairwise comparisons, we report effect sizes as mean paired differences M_D in CIELAB units and as standardized mean changes d_{diff} (M_D divided by the standard deviation). M_D is useful as it gives an impression of change between two variables in color units, while the standardized values are useful to make the effect sizes comparable regardless of the measure and experiment. Together with the 95% confidence intervals (CI) generated through the Bias-Corrected Accelerated Non-Parametric bootstrapping algorithm[3] they allow us to interpret the results and their reliability without depending on p-values and significance testing, which are strongly argued against in the current statistical and psychological literature (see [5, 21] for more details).

Although we do not discuss them in detail, we do report ANOVA omnibus significance test results (with repeated measures linear models over the experimental factors) for completeness and reference for those accustomed to these procedures. When the data was found to be not spherical (i.e., failed Mauchly's test), we applied a Greenhouse-Geisser correction that can be identified by the non-integer values in the resulting tests' degrees of freedom.

[3] https://github.com/cgevans/scikits-bootstrap

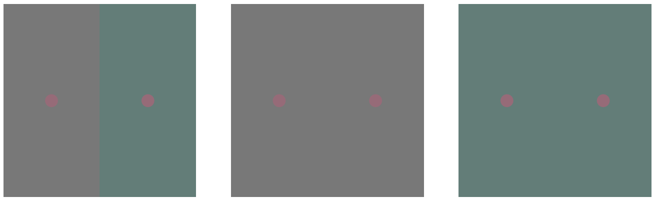

Figure 3. Example stimuli from Exp. 1. Left shows a static trial; each patch has its own background. Center and right show a GC trial with the left (matching) patch and the right (reference) patch being attended.

EXPERIMENT 1 — COLOR MATCHING

The goal of Exp. 1 is to test whether SC persists with gaze-contingent presentation of color when an object's color or its background change while the object itself is unattended. To test this we use a standard color matching experimental paradigm and compare several GC presentation conditions to a static one. We hypothesize that:

H1.1: Gaze-contingent simultaneous-contrast presentations of color patches will result in color shifts of the matched colors.
H1.2: Color shifts of the matched colors will be similar in GC conditions and the static condition.

Rejecting H1.1 implies that GC-SC is an unpromising avenue for our goal. H1.2 tells us whether we can use existing CAMs (e.g., [16, 17]) to predict color appearance.

Stimuli & Task

In each trial we presented a display that contained two circular color patches: the reference patch on the right P_{ref} and the adjustable matching patch on the left P_{match}. Each patch had a local background color (B_l and B_r) (see Figure 3). The rest of the screen was white (the display white point). Each color patch had a diameter of 2° visual angle and the patches were separated by 15° visual angle. Each half of the background had a width of 15° horizontally and 30° vertically.

We used a color matching task common in color appearance research (e.g., [15, 10]). The participants used a physical slider to control the color of P_{match} until it matched the appearance of P_{ref}. The available color range controlled by the slider depended on the trial (e.g., a range from green to red for a* trials). We instructed participants to compare the appearance of the patches by directly looking at them and collected eye tracking data to verify that this instruction was followed.

Experimental Design & Manipulations

We chose five experimental factors in a $3 \times 2 \times 2 \times 2 \times 3$ design with a single repetition per participant, resulting in a total of 1728 trials (72 per participant). These factors controlled the appearance and behaviour of the stimuli as follows:

Color Space Axis (C_{dim}) – To provide a degree of generality we explored the three axes of CIELAB. We look at each axis independently; that is, each trial shows colors from only one axis. Colors in one trial were thus either reddish/greenish (a*), yellowish/blueish (b*) or greys (L*).

Reference Patch Color (C_C) – For each axis, participants matched colors at one of the two ends of each axis. We refer to these reference patch colors as "low" and "high". The two values were equidistant to the center value in CIELAB space $(50, 0, 0)$, but were not at the very edge of the display gamut for methodological reasons; if the perceived reference color was shifted outside the display's physical gamut, we would not be able to provide a range that contained a match. The color values used were 42.18 (■) and 57.81 (■) for L*, and -20 (■ / ■) and $+20$ (■ / ■) for a* and b*.

Reference Patch Background Color (C_B) – To manipulate the reference patch color's appearance through SC, we manipulated the background color. The background could be one of two colors that we chose from within the range defined by the two reference extremes in each axis (previous paragraph). One of these background colors was near to the reference color and one was far, enabling the experiment to differentiate between different levels of simultaneous contrast intensity (e.g., background colors that are more distant should shift the perceived reference color more strongly away from the background color, towards the outside of the gamut). The background colors were 46.09 (■) and 53.91 (■) for L*, and -10 (■ / ■) and $+10$ (■ / ■) for a* and b*, respectively.

Background Manipulation (B_M) – This factor compared two presentation modes for the background: *static* and *gaze-contingent (GC)*. In the static condition, the display was divided in the middle as shown in Figure 3. The background to the left (around the matching patch) was neutral $(50, 0, 0)$ and the background to the right had the reference patch background color. In the GC background condition, B_l and B_r had the same color resulting in a uniform background, but the color varied with the participant's gaze location. When looking at (or to the right of) the reference patch, the background had the *reference patch background color* and when looking at (or to the left of) the matching patch, the background was neutral grey. The background was linearly interpolated between the reference patch background color and the neutral grey when looking between the patches.

Reference Patch Manipulation (C_δ) – So far we have assumed that viewers switch gaze between the reference patch and the matching patch to compare colors, and that they use their impression of the color of a patch while it is centered on the fovea to accomplish the matching task; however, it is also possible that viewers use information from their peripheral vision to perform matching. To control for this possibility, we introduced a manipulation that affects only the GC condition; the color of the reference patch was changed by an offset C_δ when unattended (by adding the offset to the CIELAB coordinate). The color of the patch was linearly interpolated between its base value and the modified value as in the Background Manipulation above. We chose two different values for the offset, one negative and one positive (both along the trial's axis), resulting in three possible levels of C_δ: one negative, one zero (static) and one positive. The values used for L*, a* and b* respectively are: $-3.91/+3.91$, $-10/+10$, $-10/+10$.

Apparatus

We used a monocular EyeLink 1000 eye tracker that provided gaze data at 1000 Hz with a nominal 1.4 ms delay. The tracker was installed in a tower mount configuration with a chin rest that kept the participant's face at a stable distance from the screen (40 cm).

The display was an Iiyama HM204DT 22 inch CRT display with a resolution of 1280 px × 1024 px running at 100 Hz. We calibrated the color output of the screen by using a PR-650 SpectraScan spectroradiometer to measure the screen through the eye tracker's hot mirror. We took measurements for the white point, R/G/B primaries and 25 luminance values along each R/G/B channel. These values were used to create a monitor calibration profile for PsychoPy[4], ensuring linear luminance values along each R/G/B channel, as well as a monitor-specific RGB color space specification for color computations.

Participants controlled the matching patch color through a custom-built physical input slider and a capacitive plate that served as a button to confirm input. The slider controlled the color along the same axis being tested (e.g., the slider made the matching patch go between green and red when testing a*, blue and yellow when testing b*, and between dark and light when testing L*).

The experiment took place in a darkened room with the area surrounding the display covered with a matte black surface to avoid visual distraction from the monitor's face plate.

The experimental software was built using PsychoPy [29] and colors were calculated using Colour [23]. We provide the code for this experiment in the supplemental material.

Participants

24 participants (15 female, aged 18 to 65, M=25.54, SD=10.66) took part in the experiment. All had normal or corrected-to-normal vision, 14 were right-eye dominant, 19 were right-handed. Eye dominance was determined using the Miles test, acuity with a Snellen chart, and absence of color vision deficiency with the Ishihara test using hidden digit plates. An additional six participants were tested but excluded from the analysis due to severe problems with the eye-tracking. Another participant was excluded because they did not follow the experimental instructions.

Procedure

After a brief introduction and obtaining written ethical consent (in compliance with the local committee) participants answered a demographic questionnaire and performed the vision tests. Then participants learned the five-point gaze-calibration procedure through a tutorial which also explained the basic task. The time spent on the tutorial and calibration (about 5 to 10 minutes) allowed for adaptation to the screen and room.

Each trial began with a fixation cross in the center of the screen and started when the participant looked at it. The participant controlled the matching patch's color with the slider according to our instructions (exact phrasing is available through the supplemental materials). Once a trial was complete, the participant had to reset the slider position to the bottom of the input device before proceeding to next trial.

Trial order was randomized for each participant. After half the trials, there was a break. After the break we checked the eye tracker calibration for changes in accuracy and re-calibrated if the average error was more than 1 degree. No change in room lighting happened during the break. The experiment took about 60 minutes. After the trials were complete, the participant was debriefed and compensated.

[4] http://www.psychopy.org/general/monitors.html

Measures and Statistical Analysis

The main raw measure for each trial was the CIELAB coordinate of the matching patch color along the given axis, which was recorded along with the specific condition (i.e., the reference patch color and its manipulations). We also recorded gaze-patterns to validate participant behavior.

To detect SC, we derived a measure called *simultaneous contrast effect* (δC) calculated as the difference (in CIELAB units) between the colors matched for a given reference color when using the two different backgrounds of the *reference patch background color factor* (C_B). This value will be non-zero if SC exists as different background colors will have changed the appearance of the reference patch color.

For completeness, we also computed a measure we call *absolute color appearance* ($\overline{C}$) which was the average across both background colors (C_B) of the matched color (all other conditions being equal), giving us an SC-independent measure. This allows us to make simple comparisons in CIELAB units between conditions (for H1.2). For example, by looking at absolute color appearance we can learn how much more green the green reference patch appears in the GC condition than in the static condition.

We noticed some severe outliers that appeared to be caused by resetting the slider before confirming the input. To address this, we trimmed the data to 3σ in each cell, affecting 17 trials ($\sim$1% of all trials).

Results

We report results by measure: simultaneous contrast effect (δC) and then absolute color appearance ($\overline{C}$).

Simultaneous Contrast Effects

We analyze δC per axis. Large δC values indicate a large shift in matched color due to SC. Results of the omnibus RM analysis are summarized in Table 1. The intercept of the model has a special meaning as it tells us whether SC appeared at all.

The large effect size of the intercept for the L* axis (M=−3.56 CI[−3.81, −3.30]) indicates that SC was present overall. All other factors and interactions had small effects. This means that the static and gaze-contingent manipulations were not very different in terms of SC effects. We did not observe large effect sizes in factors or interactions related to gaze-contingent manipulations. This is evidence that gaze-contingent manipulations did not negate simultaneous contrast.

We observe a small effect for the interaction $B_M \times C_C$, which could indicate a systematic (if small) difference between GC and static background manipulation for specific colors. The GC condition showed a larger SC effect than the static condition for the dark end of the L* axis (Figure 4). The effect sizes for the GC-vs-static difference are M_D=−1.1, d_{diff}=−0.43 for low and M_D=−0.12, d_{diff}=−0.050 for high.

Results on the a* axis are similar to those on the L* axis. The intercept (measure of SC effect) is weaker than in L* (although clearly present M=−3.43 CI[−4.22, −2.69]).

Factors	df	$\widetilde{df}$	F	p	η_p^2
*Results for L**					
$(Intercept)$	1.00	22.00	219.52	<0.01	0.75
B_M	1.00	22.00	4.93	0.04	0.03
C_C	1.00	22.00	0.40	0.53	<0.01
C_δ	2.00	44.00	0.68	0.51	<0.01
$B_M \times C_C$	1.00	22.00	5.17	0.03	0.02
$B_M \times C_\delta$	2.00	44.00	2.63	0.08	0.01
$C_C \times C_\delta$	2.00	44.00	0.12	0.89	<0.01
$B_M \times C_C \times C_\delta$	2.00	44.00	3.26	0.05	0.01
*Results for a**					
$(Intercept)$	1.00	22.00	44.04	<0.01	0.24
B_M	1.00	22.00	1.33	0.26	<0.01
C_C	1.00	22.00	12.98	<0.01	0.11
C_δ	1.51	33.25	1.99	0.16	<0.01
$B_M \times C_C$	1.00	22.00	0.29	0.59	<0.01
$B_M \times C_\delta$	2.00	44.00	0.06	0.95	<0.01
$C_C \times C_\delta$	2.00	44.00	0.56	0.57	<0.01
$B_M \times C_C \times C_\delta$	2.00	44.00	0.91	0.41	<0.01
*Results for b**					
$(Intercept)$	1.00	22.00	198.78	<0.01	0.56
B_M	1.00	22.00	4.47	0.05	0.02
C_C	1.00	22.00	45.58	<0.01	0.22
C_δ	2.00	44.00	1.33	0.27	<0.01
$B_M \times C_C$	1.00	22.00	12.92	<0.01	0.05
$B_M \times C_\delta$	2.00	44.00	0.23	0.79	<0.01
$C_C \times C_\delta$	2.00	44.00	2.37	0.10	0.02
$B_M \times C_C \times C_\delta$	2.00	44.00	0.59	0.56	<0.01

Table 1. Results of the repeated measure ANOVA of simultaneous contrast effect in Experiment 1, split by CIELAB axis.

As in L*, GC-related factors did not show effects. The effect on C_C simply shows that SC is not homogeneous along the axis, a result in agreement with exiting CAMs.

The SC effect is also evident in the b* axis through the intercept with M=−7.28, CI[−8.17, −6.37]. As in a*, the C_C effect shows that SC varies along the axis.

In b* there are two interactions with small effect sizes. $B_M \times C_C$ and $C_C \times C_\delta$ are plotted in Figure 5. The former shows that the SC effect is slightly reduced in the GC condition for the high color case M_D=4.7, d_{diff}=0.47. The latter, which suggests that different values of peripheral offset (C_δ) affect the low and high ends of the axis differently, is probably of little practical importance judging from the CIs and the small differences.

Absolute Color Appearance

This section looks at the $\overline{C}$ measure, which ignores the SC contrast effect to focus on absolute color appearance shifts. Results of the omnibus RM analysis are summarized in Table 2. The large effect of C_C is trivial since if we show a different color, people will match it to a different color.

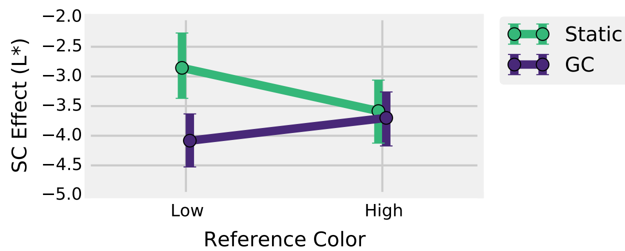

Figure 4. Plot of the $B_M \times C_C$ interaction on the L* axis for SC effect.

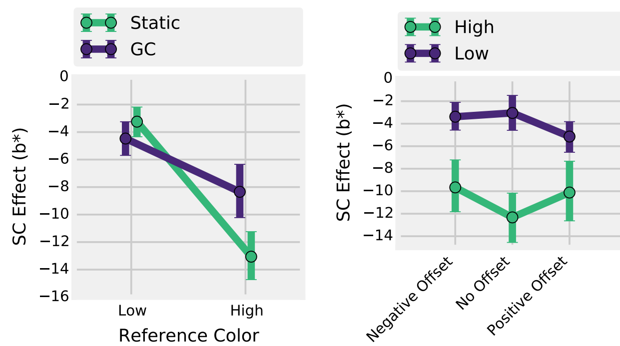

Figure 5. Plots of the interactions observed for the simultaneous contrast effect in the b* axis. $B_M \times C_C$ **(Left),** $C_C \times C_\delta$ **(right).**

Across all axes we also see a small but consistent main effect of the peripheral gaze-contingent manipulation (C_δ). Participants matched their stimulus with a small influence of peripheral color change (see Figure 6).

There are two small interactions in the b* axis that involve C_δ: the first one with C_C and the second one with B_M (Figure 6). We see that the difference between C_δ positive and negative persisted, but the no-offset condition seemed to deviate for C_C high and B_M GC. These findings show that there are exceptions to the effect of C_δ in very specific conditions.

Discussion

The strong effect sizes of the intercept for all axes indicate that Exp. 1 was able to replicate the simultaneous contrast effect and, more importantly, that gaze-contingent presentations of the stimuli cause simultaneous contrast as well (H1.1 is supported). Looking at it in terms of $\Delta_{CIE2000}$, the absolute measures indicate that SC can induce changes in color appearance in the range of 3 or 4 $\Delta_{CIE2000}$ units depending on the axis. The results also showed some small differences between gaze-contingent and static presentation, but only in the b* axis. H1.2 is consequently only partially supported; there are systematic effects that might prevent us from applying current SC models directly to GC-SC.

The results also show that SC does not take place uniformly across the CIELAB space. One might be tempted to think that since CIELAB is designed to be perceptually uniform, SC would happen uniformly across the space as well; however, our data suggest that this is not the case.

We have also learned that changing the reference color patch while in the periphery (reference patch manipulation) can also produce shifts in the matched color. Although these shifts are

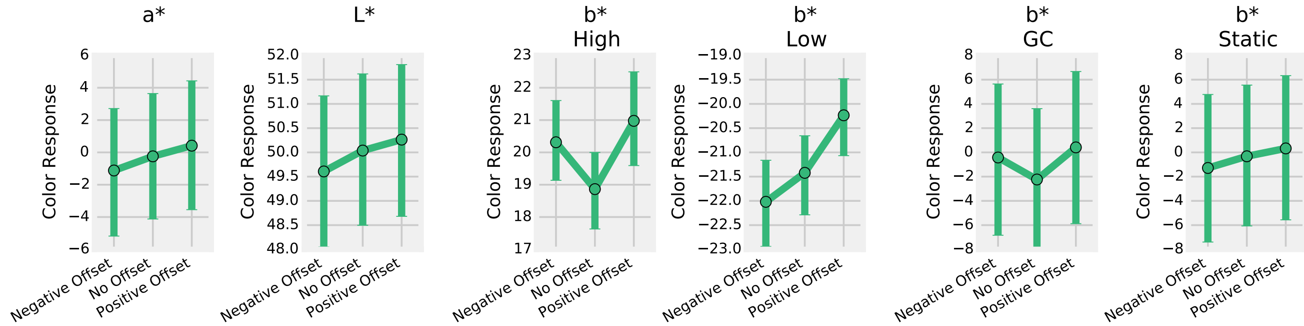

Figure 6. Plots of baseline color response modulated by C_δ. From left to right the results are for the a* axis, the L* axis, followed by the b* axis split by C_C (high and low) and then the b* column split by B_M (GC and static).

Factors	df	$\widetilde{df}$	F	p	η_p^2
*Results for L**					
$(Intercept)$	1.00	22.00	506881.52	<0.01	1.00
B_M	1.00	22.00	0.95	0.34	<0.01
C_C	1.00	22.00	5158.22	<0.01	0.98
C_δ	2.00	44.00	8.20	<0.01	0.06
$B_M \times C_C$	1.00	22.00	1.21	0.28	<0.01
$B_M \times C_\delta$	1.48	32.48	0.78	0.43	<0.01
$C_C \times C_\delta$	2.00	44.00	0.28	0.75	<0.01
$B_M \times C_C \times C_\delta$	2.00	44.00	1.05	0.36	<0.01
*Results for a**					
$(Intercept)$	1.00	22.00	1.76	0.20	0.01
B_M	1.00	22.00	0.02	0.88	<0.01
C_C	1.00	22.00	3532.09	<0.01	0.98
C_δ	2.00	44.00	6.34	<0.01	0.04
$B_M \times C_C$	1.00	22.00	1.62	0.22	<0.01
$B_M \times C_\delta$	2.00	44.00	1.43	0.25	<0.01
$C_C \times C_\delta$	1.60	35.21	0.73	0.46	<0.01
$B_M \times C_C \times C_\delta$	2.00	44.00	0.02	0.98	<0.01
*Results for b**					
$(Intercept)$	1.00	22.00	4.01	0.06	0.02
B_M	1.00	22.00	0.79	0.38	<0.01
C_C	1.00	22.00	2441.87	<0.01	0.97
C_δ	2.00	44.00	6.00	<0.01	0.03
$B_M \times C_C$	1.00	22.00	1.53	0.23	<0.01
$B_M \times C_\delta$	2.00	44.00	5.22	<0.01	0.02
$C_C \times C_\delta$	2.00	44.00	2.50	0.09	0.01
$B_M \times C_C \times C_\delta$	2.00	44.00	0.27	0.77	<0.01

Table 2. Results of the repeated measure ANOVA of absolute color appearance in Experiment 1, split by CIELAB axis.

small compared to the SC effect and are modulated by the patch's color, they deserve further exploration and open an interesting possibility of gaze-contingent manipulation which we explore further in Experiment 2.

Figure 7. Example of stimulus setup. Relatively high-contrasting L* axis colors are shown for illustrative purposes; differences between patches were much subtler in real trials.

EXPERIMENT 2 — COLOR SORTING

Exp. 2 investigates if GC techniques (simultaneous contrast and the peripheral color adjustment discussed in Exp.1) can enhance color discrimination. Although Exp. 1 showed that GC manipulations can be used to shift how a color is perceived, we now consider whether this can be leveraged to increase the differentiability of color steps perceived by viewers.

To test this we use a gradient sorting task similar to a Farnsworth-Munsell 100 hue test [11] where participants are asked to arrange a shuffled sequence of color patches in order according to their color. We hypothesize that:

H2.1: Gaze-contingent simultaneous contrast presentation of color will result in fewer errors in the ordering of the sequences.
H2.2: Peripheral manipulation of colors will result in fewer errors in the ordering of the sequences.

Stimuli & Task

The stimuli in this task consisted of eight square color patches, each covering 2°×2° visual angle. The patches were placed horizontally with a gap separation of 2° (see Figure 7) within a square background of 35°×35°. Outside of this area the display was white. The patch colors were from a gradient of similar colors (see Table 3). The leftmost and rightmost patches were fixed in position and showed the color extremes. The other patches could be re-arranged via mouse input using drag-and-drop. While dragging, a patch only showed as a black outline to prevent a participant from moving squares for comparison. After moving a patch, a small white line below the patch flashed to indicate change. This reassured participants that changes had occurred when they were working with very small color differences.

	Color Patch Gradients						Background Gradients		
	L*		a*		b*		L*	a*	b*
	low	high	low	high	low	high			
Lower	39.10	54.19	-23.84	16.16	-23.84	16.16	45.50	-5.76	-5.76
Upper	45.10	60.19	-16.16	23.84	-16.16	23.84	54.50	5.76	5.76
Δ_{CIE2000}	5.44	5.50	4.59	4.59	4.04	4.04	9.00	10.62	15.97

Table 3. Color Gradients used in Experiment 2 and Δ_{CIE2000} differences between them. Values denote upper and lower ends of the gradients along the relevant color axis in CIELAB space. Intermediate values where interpolated linearly. Color swatches provided for illustration might not correspond to the exact color displayed in the experiment, and can vary depending on viewing medium.

The task was to arrange the patches from left to right according to their color so that they formed a gradient between the fixed patches at the extremes. Accuracy was measured through an error score taken from the original Farnsworth task [11]. Each patch was assigned a number according to its actual position along the gradient. For each patch in the participant-determined order, we added the absolute difference of the patch's number with respect to the numbers of the patches on its left and right, subtract two, and then summed the sub-scores for all patches. A perfect order gives a score of zero.

At the start of the trial the patches appeared in a randomized arrangement with an error score of 21. This kept the baseline error score sufficiently high and consistent between participants, and avoided varying difficulty between trials.

Color Gradients and Backgrounds

As in the previous experiment, we sampled along each CIELAB axis. The exact gradients are described in Table 3. The gradients contained very similar colors that were hard to distinguish. If the task had been too easy the different manipulations would not show differences due to ceiling effects. Δ_{CIE2000} (a measure of perceptual differences) of the extremes of the gradient was about 5, where a value of 1 corresponds approximately to a *just noticeable difference*.

Each gradient had a corresponding background gradient (also in Table 3) for the GC-SC manipulation. To choose these, we balanced the goal of maximizing simultaneous contrast effects (according to the data that we obtained from Exp. 1) while keeping the experiment simple (by using a single background gradient for both ends of the axis). These background gradients were thus chosen to be broad but centred around the middle point of each axis.

Techniques

We tested five different color presentation techniques. These corresponded to all combinations of absent or present manipulations of the background (i.e., the simultaneous contrast manipulation) and the peripheral object color manipulation, plus an additional static technique that served as control.

Static ($S_{\mathbf{u}}$) – This was the baseline, with no manipulations. It displayed the color gradient on a background of static uniform middle grey (L*=50, a*=0, b*=0).

GC patches ($\mathbf{GC_{patch}}$) – Peripheral patches changed their color to increase contrast in relation to the currently-attended patch. We used this function to compute the colors to display:

$$\mathrm{r}(c_i) = \begin{cases} c_i & \text{for } i = i_a \\ \mathrm{interp}(c_0, \max(c_0, c_a - \Delta c), \frac{i}{i_a}), & \text{for } i < i_a \\ \mathrm{interp}(\min(c_7, c_a + \Delta c), c_7, \frac{i-i_a}{7-i_a}), & \text{for } i > i_a \end{cases}$$

where $\mathrm{r}(c_i)$ is the resulting L*/a*/b* value for the current trial, c_i is the color along the gradient at index i (c_0 is the lower end of the gradient and c_7 the upper end), i_a is the color index of the currently attended patch, interp(a,b,x) is a linear interpolation function at x (in $[0,1]$) between $(0,a)$ and $(1,b)$, and Δc is a constant value that depended on the CIELAB axis (3 for L* and 3.84 for a* and b*).

Since the visual space between patches is very small, we chose not to use continuous interpolation for gaze position between patches, but instead used a hysteresis-based approach; a patch would only be considered attended once the gaze position was measured inside of its visible area on the screen.

GC background ($\mathbf{GC_{bg}}$) – This technique changed the background based on the attended patch, i.e., it applied simultaneous contrast. The currently attended patch was determined as in $\mathrm{GC_{patch}}$.

GC background and patches ($\mathbf{GC_{bg+patch}}$) – This technique combined both $\mathrm{GC_{patch}}$ and $\mathrm{GC_{bg}}$simultaneously.

Static with Frames ($S_{\mathbf{f}}$) – This technique was similar to S_{u}, but each patch was enclosed by a 0.25° wide frame. The colors of the frames were picked from the background gradient to enhance the difference between patches through SC. This technique provided SC-enhanced color in a static form, but is somewhat artificial because it is feasible only for specific spatial arrangements, adds visual noise, and is consequently of limited utility in realistic scenarios.

Consistent with our hypotheses, we expected the three gaze-contingent techniques to reduce errors compared to the baseline. We also suspected that the static with frames technique (S_{f}) would perform well due to the additional visual information included in the frame, which could be used in addition to the patch color to inform ordering.

Experimental Design

The design was a $3 \times 2 \times 5$ (color axis $\times$ color $\times$ technique) within-subjects design with two repetitions per cell, resulting in 60 trials per participant. The presentation of trials was

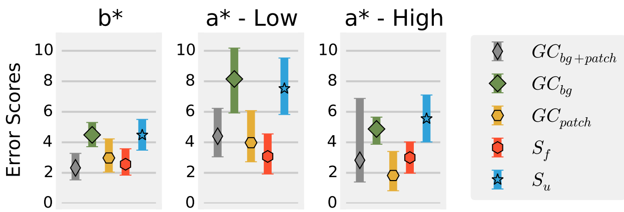

Figure 8. Error scores on the a* and b* axis for each technique.

blocked by technique, block order was balanced between participants using Latin squares.

Apparatus

The apparatus is identical to Exp. 1 except that, due to lab requirements for another experiment, the screen was replaced with an Iiyama MM904UT 19 CRT running at 1280 px × 1024 px and 85 Hz. This setup was re-calibrated using the same procedure as the previous one. The participants provided responses through a keyboard and mouse.

Participants

We tested 20 participants (14 female, aged 18 to 39, M = 23.85, SD = 6.32, all had normal or corrected-to-normal vision, 15 were right-eye dominant, 16 were right-handed). Screening of the participants proceeded as in Exp. 1. Two participants where excluded from the analysis due to severe problems with their eye tracking.

Procedure

Participants gave written consent in compliance with the local ethics regulations. We collected demographic information through a preliminary questionnaire and then performed the vision screening tests.

The participants then sat at the eye tracker, learned the task through a tutorial (four trials with easy black to white gradients), and performed a five point calibration procedure. Each trial began when the participant looking at a cross. After each block there was a short break. After each break, we checked the calibration for changes in accuracy and re-calibrated if the average error was more than 1 degree. The main part of the experiment lasted about 45 minutes.

Measures and Statistical Analysis

The main measure was the error score derived from the final configuration of the patches. The error responses were not expected to be normally distributed (skewed towards perfect performance). Although we use a parametric model for the omnibus test, the comparison analysis and the confidence intervals are non-parametric and therefore robust.

Results

Table 4 shows the results of the RM-ANOVA. We focus on the *technique* factor, which is directly related to our hypotheses. The effect sizes of Technique on the number of errors are smaller than in Exp. 1, but still sizable in all axes (η_p^2 of 0.21, 0.61 and 0.56 for L*, a* and b* respectively). This indicates that the different techniques affected accuracy and justifies further comparisons between techniques.

Unfortunately, when looking at error scores according to axis we found that performance with the L* axis was close to perfect for most participants, despite of its gradients having equivalent Δ_{CIE2000} ranges to the other axes. This ceiling effect masks the differences between techniques, making pairwise comparisons uninformative; therefore, we omit the L* axis in the following analysis. These data and analysis are still available through the supplemental material.

Factors	df	$\widetilde{df}$	F	p	η_p^2
*Results for L**					
(Intercept)	1.00	19.00	25.77	<0.01	0.21
Color	1.00	19.00	<0.01	0.97	<0.01
Technique	2.86	54.38	5.13	<0.01	0.10
Color × Technique	2.27	43.06	0.35	0.73	<0.01
*Results for a**					
(Intercept)	1.00	19.00	68.26	<0.01	0.61
Color	1.00	19.00	10.97	<0.01	0.06
Technique	4.00	76.00	15.11	<0.01	0.17
Color × Technique	4.00	76.00	1.97	0.11	0.02
*Results for b**					
(Intercept)	1.00	19.00	55.84	<0.01	0.56
Color	1.00	19.00	0.09	0.77	<0.01
Technique	4.00	76.00	7.62	<0.01	0.09
Color × Technique	4.00	76.00	0.56	0.69	<0.01

Table 4. Results of the RM-ANOVAs of error scores in Exp. 2.

	S_f		GC_{patch}		$GC_{bg+patch}$		GC_{bg}	
	M_D	d_{diff}	M_D	d_{diff}	M_D	d_{diff}	M_D	d_{diff}
a*	-3.50	-1.04	-3.64	-1.05	-2.93	-0.61	-0.03	-0.01
b*	-1.92	-0.49	-1.50	-0.42	-2.15	-0.74	0.01	0.00

Table 5. Differences in error scores of each technique compared to the baseline technique S_u.

The performance of the individual techniques in the a* and b* axes (Figure 8) reveals a clear pattern: in both axes the S_u and GC_{bg} condition had the highest error scores, while the three other techniques had low error scores. This pattern is evident for both color axes. The differences in error scores compared to the baseline S_u appear in Table 5, where we observe lower error rates for all techniques except GC_{bg}.

Effect sizes of other interactions are not large enough to be of practical relevance except for the interaction of color and technique in the a* axis, which is small but we decided to investigate nonetheless. A closer look revealed some outliers in the a*-high condition. Otherwise both a*-high as well as a*-low show the same pattern (see Figure 8). The effect of color in the a* axis indicates that one of the gradients was more difficult than the other M_D=1.8, d_{diff}=0.44.

Discussion

Exp. 2 results show that gaze-contingent techniques that manipulate peripheral patches (GC_{patch} and $GC_{bg+patch}$) improve performance in a color ordering task with respect to the uniform background S_u, which is the baseline technique (H2.2

is supported). Surprisingly, gaze-contingent manipulation of only the background (i.e., only with SC) does not seem to help with color differentiation as the GC_{bg} technique did not show a comparable advantage (H2.1 is *not* supported).

Therefore, it is likely that the advantages in the ordering task of Exp. 2 are due to peripheral color manipulation. Although this is not strictly an SC effect, it is still a valid way to take advantage of gaze-contingency.

The static technique with the SC frames is interesting and deserves further investigation. As we mentioned above, it is not feasible for full-range displays, but it might result in better color differentiability for reduced ranges if properly harnessed. This technique showed error scores comparable to the best GC-based techniques.

Overall, this experiment found that we can improve color discrimination using gaze-contingent techniques, only not through the use of simultaneous contrast induced through the change of the overall background. Perhaps a more targeted background adjustment (similar to the static individual background) that partially preserves relative background might lead to improvements, however, this kind of technique will have to be investigated in future work.

GENERAL DISCUSSION

The results from our two experiments provide insights into properties and benefits of color perception on gaze-contingent displays in general and simultaneous contrast (SC) specifically. We provide the first empirical data on gaze-contingent SC showing that SC can be induced through background manipulations of attended objects, and that SC persists even if the background changes when an object is unattended. We also provide the first empirical evaluation of a technique that uses gaze-contingent peripheral contrast enhancement to successfully increase color discrimination in a color sorting task.

Gaze-contingent SC could be used to create a new kind of High Dynamic Range (HDR) rendering technique. Since the appearance of a color can be moved along the CIELAB axes, colors at the edge of the display gamut can be pushed outside of the physical gamut of the screen, essentially increasing its perceivable gamut size. This could be used to display images with higher perceived luminance ranges (as suggested by [3, 24]), but also higher perceived chromaticity, allowing the display to render more vivid photographs or display medical images (e.g., MRI, X-ray) with more observable detail.

While we focused on SC as the main driver of changes in color appearance, in Exp. 2 we found that techniques based on changing the appearance of peripheral objects (enhancing local contrast) improved color discrimination, whereas the purely SC-based technique did not. We expected to see the gamut extended through GC-SC of Exp. 1 to have a similarly beneficial effect in the color ordering task of Exp. 2, but found otherwise. This indicates that our color matching task and color ordering tasks are affected by gaze-contingency in different ways.

The results of Exp. 2 are nevertheless useful since they suggest that GC peripheral changes can help color discrimination. This type of technique could be used to increase the number of categorical colors for encoding information in information visualisations or make the reading of color scales more precise.

Open Questions and Future Work

Our findings provide a base to further explore the application of gaze-contingent techniques for perceived gamut expansion and improved color differentiability; however, our ability to take advantage of these techniques in realistic scenarios requires further empirical and practical work. It is necessary to generalize the manipulations described in this paper to work in more complex displays that go beyond the carefully-controlled stimuli of our investigations. Application areas include GC-based gamut-enhanced photos and movies.

Two related outstanding issues are screen flicker and the noticeability of the gaze-contingent changes. We did not design our studies to detect or measure these, but these are obviously important matters for the feasibility of GC color manipulation techniques. Our own experience with our system suggests that flicker was not an issue in our experiments, but flicker and noticeability certainly need to be considered in future extensions and applications of our GC-SC based techniques.

Finally, our measurements of the effects of gaze-contingent manipulation are not exhaustive as they only cover a limited number of points on the CIELAB axes. The precise control of perceived color with gaze-contingent techniques might require a higher-density sampling of the color space, perhaps leading to a model that accounts for differences due to the gaze-contingency of the display. Our findings of differences between SC effects in GC and non-GC presentation, as well as asymmetries across different axes and values, highlight the need for more comprehensive knowledge in this area.

CONCLUSION

In this paper, we presented an empirical evaluation of gaze-contingent manipulation of colors through simultaneous contrast and peripheral object color manipulation. We conducted two experiments that provide insight into general perceptual properties and benefits of gaze-contingent color presentation.

We contribute evidence that gaze-contingent simultaneous contrast can be used to change the appearance of colors, which could be used to extend the perceived gamut of a display. We also show that changing the appearance of peripheral objects can be used to improve color differentiability. Our results can be used to inform future work on gaze-contingent color manipulations to extend the capabilities of displays or on manipulation of perceived colors to enhance the user's color discrimination ability.

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