

What predicts the strength of simultaneous color contrast?

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The perceived color of a uniform image patch depends not only on the spectral content of the light that reaches the eye but also on its context. One of the most extensively studied forms of context dependence is a simultaneous contrast display: a center-surround display containing a homogeneous target embedded in a homogenous surround. A number of models have been proposed to account for the chromatic transformations of targets induced by such surrounds, but they were typically derived in the restricted context of experiments using achromatic targets with surrounds that varied along the cardinal axes of color space. There is currently no theoretical consensus that predicts the target color that produces the largest perceived color difference for two arbitrarily chosen surround colors, or what surround would give the largest color induction for an arbitrarily chosen target. Here, we present a method for assessing simultaneous contrast that avoids some of the methodological issues that arise with nulling and matching experiments and diminishes the contribution of temporal adaption. Observers were presented with pairs of center-surround patterns and ordered them from largest to smallest in perceived dissimilarity. We find that the perceived difference for two arbitrarily chosen surrounds is largest when the target falls on the line connecting the two surrounds in color space. We also find that the magnitude of induction is larger for larger differences between chromatic targets and surrounds of the same hue. Our results are consistent with the direction law (Ekroll & Faul, 2012b), and with a generalization of Kirschmann's fourth law, even for viewing conditions that do not favor temporal adaptation.

oldest and most well-known examples is simultaneous contrast, which refers to the transformation in perceived color of a homogeneous target embedded in a homogeneous surround. An illustration of simultaneous color contrast is presented in Figure 1a. The two inner squares in the left and right displays are physically identical, but appear different because the two surround colors influence the appearance of the targets. For this particular combination of target and surrounds, the difference in perceived color of the targets is quite strong: the perceived color of the target embedded in the left surround appears similar to the surround color of the right hand display and vice versa. However, for the surround colors depicted in Figure 1b and Figure 1c, there is very little or no difference in the perceived color of the targets. The effect of surrounds on the perceived color of a target can therefore vary substantially; yet, despite over a century of work, there is currently no consensus about when the effects of surrounds on perceived color are “large” or “small.”

There are two aspects of the chromatic transformations exhibited in simultaneous contrast displays that any model must be able to explain: their *direction* and *magnitude*. The majority of studies of chromatic induction have focused on the influence of chromatic surrounds on achromatic targets. In such contexts, the direction of perceived color shift is approximately *complementary* to the inducing hue of the surround (Fechner, 1840); the color transformation is presumed to be independent of the target's color and depend only on the color of the surround. Recently, however, Ekroll and Faul (2012b) proposed that this model be replaced with a *direction law*, which asserts that the direction of color induction depends on both the color of the surround and the color of the target. In particular, the direction law states that the color of a target is displaced away from the color of the surround along the path of

Introduction

It is well known that the perceived color of a surface or target can be affected by its context. One of the

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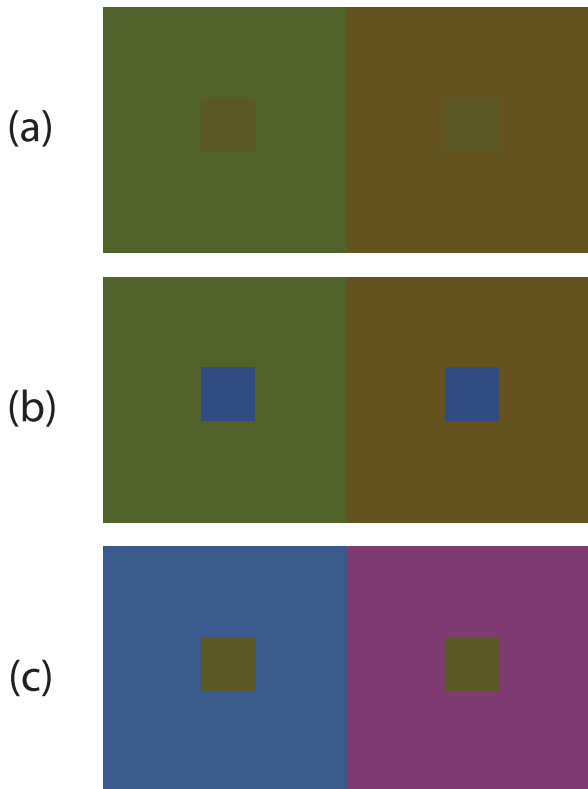


Figure 1. Three examples of chromatic simultaneous contrast displays. The central target patches are identical in each pair of surrounds. Note that the perceived difference between the targets is quite large in (a), where each target appears nearly identical to the surround of the other target. However, these surrounds have very little impact on the blue targets in (b), or when the same targets in (a) are placed on two surround colors in (c). Thus, the size of chromatic induction can vary substantially depending on the choice of surround and target colors.

the line formed between the surround color and the target color. This model assumes that there is no “neutral” surround in terms of induction: all surrounds are assumed to induce a shift along the line connecting the target and the surround, including achromatic surrounds. The direction of color induction predicted by the complementarity law and the direction law are depicted in Figure 2a and Figure 2b, respectively, for a fixed surround color and variable target colors. Note that in this figure, the magnitude of the induction is depicted as a constant displacement that is independent of the distance between the surround color and the target color. It can be seen that the two hypotheses predict different directions of induction for all targets except those located on the line segment extending from the surround through the neutral point.

The empirical evidence concerning how the magnitude of induction depends on the distance in color space between a target patch and its surround is mixed. Kirschmann’s fourth law asserts that the size of

simultaneous color contrast of a neutral (achromatic) target increases monotonically as a compressive non-linear function of surround saturation. It is not obvious how this law can be generalized to colored targets with different degrees of saturation or for surrounds with different hues, since it was articulated solely in the context of achromatic targets and surrounds of constant hue. Moreover, experiments that have attempted to assess this law in these restricted contexts have obtained conflicting results (Bosten & Mollon, 2012; Crane, 1917; De Valois, Webster, De Valois, & Lingelbach, 1986; Kinney, 1962; Köhler, 1903; Krauskopf, Zaidi, & Mandler, 1986; Shepherd, 1999; Valberg, 1974). Bosten and Mollon (2012) found that the exact relationship between the induction size and surround saturation varied substantially as function of method. Asymmetric matching data were characterized by induction curves that rose rapidly and then quickly saturated as a function of surround saturation, generating approximately constant levels of induction for high surround saturations. Similar patterns were obtained when the matching target was placed on either a gray or black surround, although the matches made using a match pattern on a black surround were more saturated than those on the gray surround. A color-nulling method generated a pattern of matches that increased linearly with surround saturation. A dichoptic-matching task generated a mixture of these two patterns, exhibiting a monotonic nonlinear compressive growth in induction, with the rate of increase decreasing as a function of surround saturation. Finally, the magnitude of induction has even been shown to *decrease* as a function of the target’s contrast with the surround when the matching target is embedded in a variegated surround containing a broad distribution of colors. Ekroll and colleagues (Ekroll & Faul, 2009; Ekroll, Faul, & Wendt, 2011) found that low contrast targets on a homogenous surround appear more saturated than the same targets on a variegated surround that had the same mean color, but this perceptual difference diminished as the saturation of the target was increased. They argued that the textured surround was the most appropriate comparison to evaluate the nontemporal aspects of simultaneous contrast (i.e., the truly “simultaneous” component) because it equated any effects of adaptation to the mean color in both the match and target images.

The conflicting empirical findings make it difficult to articulate a general model that predicts when simultaneous contrast effects will be large or small, since there is currently no model that captures how the magnitude of induction varies independently of method used. One potential problem with asymmetric matching is that it often fails to generate metameric matches; the matches obtained often represent an observer’s “least unsatisfactory” setting or some sense of “minimal difference,”

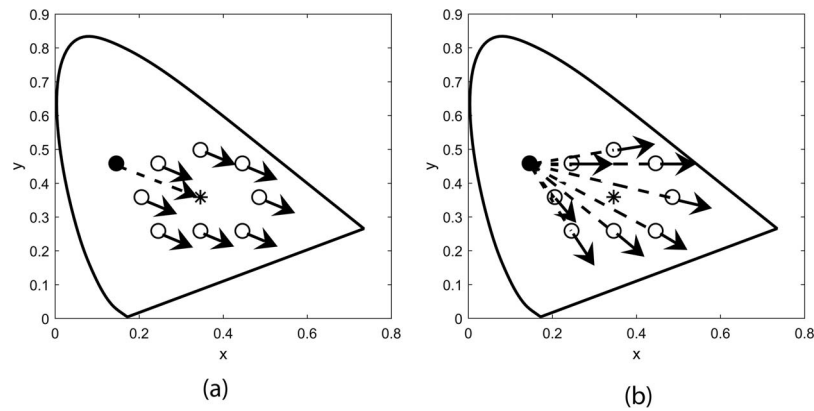


Figure 2. Two models of the direction of induction induced by an arbitrarily chosen surround color (filled circle). The asterisk depicts the neutral point. The predicted induction of the complementary law is depicted in (a). The direction of induction is presumed to be complementary to the surround hue and independent of the target hues (open circles), which is the direction from the surround color to the neutral point. The direction law is depicted in (b), which asserts that the direction of induction occurs along the extended line joining the surround to the target hue. In this schematic, the magnitude of induction is assumed to be constant (i.e., independent of the target's distance or direction from the surround hue).

rather than a true perceptual match. Related issues arise with nulling methods. Bosten and Mollon (2012) attempted to assess the magnitude of simultaneous contrast by temporally modulating the surround and target colors in antiphase to null the effects of chromatic induction. They reported that no satisfactory null point could be found (e.g., all increments on a red surround appeared reddish, and all decrements appeared greenish). They concluded that simultaneous contrast could not be reliably measured using this technique and suggested that some of the difficulty with this method might arise because it induced a sense of transparency.

More recently, Ekroll and Faul (2013) suggested that the chromatic induction exhibited in all simultaneous contrast displays might be a consequence of perceived transparency, but that the perception of transparency is strongest for lower contrast targets. The suggestion that the strongest forms of simultaneous contrast arise in conditions that induce the perception of transparency gains conceptual support from evidence showing that transparency can generate dramatic transformations in both perceived lightness and color (Anderson, 1997, 2003; Anderson & Khang, 2010; Anderson, Khang, & Kim, 2011; Anderson & Winawer, 2005, 2008; Wollschläger & Anderson, 2009). The strongest effects occur when the targets and surround contain either textures or contours. The geometric continuity of the textures and/or contours in the surround and target can induce a decomposition of the target into multiple layers, which, in turn, gives rise to dramatic transformation in the perceived color or lightness of the target. In simultaneous contrast displays, the targets and surrounds are also texturally continuous, in the sense that they are both uniform, but there are no strong geometric cues for the continuation of the surround

through the target region of the kind known to give rise to vivid percepts of transparency (such as contours or textures). It is therefore difficult to generate a prediction for when transparency should be induced in homogeneous center-surround patterns, or how the induction of transparency should modulate the chromatic appearance of a target as a function of the chromatic difference between a target and its surround.

Although it is difficult to predict *when* transparency might be induced in homogeneous center-surround displays, it is possible to predict some aspects of how the perceived color of a target should be affected if such decomposition were to occur. For targets that are decomposed into two layers, one of which is transparent, the direction of simultaneous contrast is predicted to occur along the direction of the line from the surround color to the target color, consistent with the direction law (Ekroll & Faul, 2013). The magnitude of the shift would depend on the transmittance assigned to the filter, which is unconstrained; it is unknown how the visual system might compute this property from a homogeneous center-surround pattern. Nonetheless, the transparency model predicts that the size of the effect should increase with increases in perceived transmittance, but it provides no insight into how transmittance should vary as a function of the chromatic distance between a target and its surround (cf. Ekroll & Faul, 2013). Consider, for example, an achromatic (gray) target and a set of red surrounds that vary in saturation. If the gray target is decomposed into two layers, the target must be assigned both a color and opacity. There are a host of ways the visual system could potentially perform this decomposition. One possibility is that all red surrounds induce a fixed shift in the perceived color of the target independently of the surround saturation (consistent with the constant size

hypothesis), and the increase in surround saturation causes a decrease in the perceived transmittance of the target. Another possibility is that the visual system assigns a fixed transmittance to a target, and changes in surround saturation are compensated by changes in the color of the target (i.e., the amount of induction would grow as surround saturation increases). Yet another possibility is that the perception of transmittance increases as the contrast of a target relative to the surround decreases, in which case induction should increase for low contrast targets (consistent with the inverse size hypothesis). Ekroll and Faul (2013) provided some evidence for this last possibility: observers' transmittance settings varied inversely with the saturation of the surround, and the size of induction was greatest for their high transmittance settings. It should be noted, however, they only measured the effects of *achromatic* surrounds on chromatic targets, so it is unclear how (or whether) these results generalize to chromatic surrounds. We will return to this issue in the General discussion.

In the experiments described herein, we attempt to provide new insight into color induction in simultaneous contrast displays using a method that avoids the issues with asymmetric matching and nulling methods while diminishing the contributions of temporal adaptation. Our goal is to articulate general principles that can predict when the size of induction will be large or small for arbitrarily chosen pairs of center-surround displays. Whereas almost all experimental studies of simultaneous contrast measure the impact of a colored surround on a single target, most demonstrations of simultaneous contrast present identical targets on two differently colored surrounds. The perceptual “size” of the effect is captured by the perceived dissimilarity of the targets on the two surrounds. For example, the dissimilarity of the targets in Figure 1a is immediately apparent and striking, whereas the difference in the color of the targets in Figure 1b and Figure 1c is minimal or nonexistent. Such dissimilarity judgments can be performed on very short time scales. For dissimilarity judgments, the problem of creating a large simultaneous contrast effect can be expressed as follows: What (single) target color generates the greatest perceptual difference when placed on two arbitrarily chosen surround colors? Experiment 1 attempts to answer this question.

Experiment 1: Color induction with fixed surrounds

The purpose of Experiment 1 was to determine the target color that generates the largest perceptual difference when placed on two arbitrarily chosen surround colors. We used a pairwise comparison

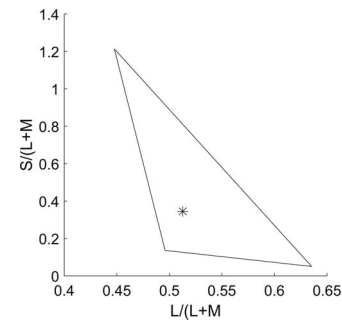


Figure 3. Gamut of the CRT monitor used to display the monitor gamut at luminance level 4.6 cd/m^2 . The asterisk indicates the equal energy white point.

method to assess the magnitude of induction in simultaneous contrast displays. The target color was varied along different directions in MacLeod and Boynton (MB) color space (MacLeod & Boynton, 1979), including along the major axes and along oblique lines. For each surround-pair condition, we presented five targets embedded in both surrounds. Each target pair contained physically identical targets arranged in a single column. Participants compared the perceived color difference of the five pairs of targets and ordered them from the most to least different. Target and surround samples were chosen so that they included a reasonable range of different color distributions to insure that any explanation generalized to arbitrarily chosen surround colors. The surround colors were chosen such that the line joining the two surrounds fell on the cardinal axes or along oblique lines in MB color space (MacLeod & Boynton, 1979). The gamut of the monitor used to display the stimuli is shown in Figure 3 at a luminance of 4.6 cd/m^2 , which is the value used in all of the experiments.

Methods

Observers

The author (SR) and 29 naïve observers participated in Experiment 1. The observers were 27 undergraduate observers who participated for course credit, and were recruited using an online system at the School of Psychology, University of Sydney, and two postgraduate students that were members of the visual perception research group at the University of Sydney. The nonstudent observer was recruited by verbal request. The observers tested color normal for Ishihara plates (Ishihara, 1967).

Apparatus and stimuli

The stimuli were presented on a LaCie Electron 22 Blue IV monitor (LaCie, Paris, France) running at a refresh rate of 75 Hz with a resolution of 1280 pixels

Target coordinates (L, S)	Surround coordinates (L, S)
Condition 1 (0.5504, 0.2859) (0.5504, 0.3011) (0.5504, 0.3318) (0.5504, 0.3471)	(0.5457, 0.3156) (0.5552, 0.3156)
Condition 2 (0.5409, 0.3156) (0.5457, 0.3156) (0.5504, 0.3156) (0.5552, 0.3156) (0.5600, 0.3156)	(0.5504, 0.3011) (0.5504, 0.3318)
Condition 3 (0.5421, 0.3236) (0.5463, 0.3201) (0.5504, 0.3156) (0.5546, 0.3129) (0.5588, 0.3093)	(0.5460, 0.3134) (0.5540, 0.3195)
Condition 4 (0.5421, 0.3093) (0.5463, 0.3129) (0.5504, 0.3156) (0.5546, 0.3201) (0.5588, 0.3236)	(0.5469, 0.3195) (0.5540, 0.3134)
Condition 5 (0.5594, 0.2859) (0.5594, 0.3011) (0.5594, 0.3156) (0.5594, 0.3318) (0.5594, 0.3471)	(0.5546, 0.3156) (0.5642, 0.3156)
Condition 6 (0.5409, 0.3292) (0.5457, 0.3292) (0.5504, 0.3292) (0.5552, 0.3292) (0.5600, 0.3292)	(0.5504, 0.3139) (0.5504, 0.3446)

Table 1. Target and surround coordinates in MB space for Experiment 1a.

wide by 1024 pixels high. The display was controlled by a Dell Precision T3610 desktop computer (Dell, Round Rock, TX) running Microsoft Windows 7 operating system (64 bits) with an Optiplex 990 graphics card (32 bits/pixel). Matlab (R2010a; MathWorks, Natick, MA) simulation software and the Psychophysics Toolbox (Brainard, 1997) were used to present the stimuli. The monitor's phosphor spectra were measured using a spectrophotometer PR670 (Photo Research, Syracuse, NY). The MB space was created using Smith and Pokorny cone sensitivity functions (DeMarco, Pokorny, & Smith, 1992) in the wavelength range of 400 nm to 700 nm sampled at 1-nm intervals. The cone sensitivity functions and the individual phosphor spectra were sampled at 1-nm intervals to obtain an accurate estimate for the transfer matrix that is used to convert the cone fundamentals to monitor primaries. The equal energy point was used as the white point of the MB space and the axes of MB space were not scaled. However, the step sizes to sample the target colors in the direction of L and S axes on the MB space were determined to evoke approximately equal perceptual difference relative to CIELUV color space. In particular, the step size in the direction of L and S axes have approximately equal Euclidean distance in CIE-LUV space.

Target colors were sampled on the line joining the two surrounds or from other portions of MB space (see below). The targets that fell along the line joining the two surrounds were subdivided into two categories: targets in between the two surrounds and targets on the extended line joining the two surrounds. Three experiments were designed (1a, 1b, and 1c) to evaluate a range of chromatic conditions. In Experiment 1a, the

targets were chosen on a line perpendicular to the line joining the two surrounds, such that one of the targets fell precisely between the two surround chromaticities. In Experiment 1b, the targets were on the extended line formed by the two surround chromaticities; for Experiment 1c, the targets were chosen such that they all fell on the line in between the two surround chromaticities. In all three experiments, one target was chosen to be located at the midpoint of the line connecting the two surrounds in MB space.

The five targets in Experiment 1a were chosen to fall on a line perpendicular to and bisecting the line joining the two surrounds. The two surrounds either straddled the achromatic point or were on the same side of the achromatic point. Six different surround conditions were evaluated in this experiment: (a) both surrounds on the L axis, (b) both surrounds on the S axis, (c) surrounds on a negative oblique line relative to the positive L axis (slope of -1.16), and (d) surrounds on a positive oblique line relative to the positive L axis (slope of 1.16). The lines joining the five targets in these conditions passed through the achromatic point (equal energy) of the MB space. Conditions 5 and 6 were created to assess whether the achromatic point is in any sense "special" in terms of its susceptibility to chromatic induction. In Condition 5, the two surround colors fell on the positive L axis. In order to obtain the color samples for this condition, the constellation formed by the target and surround was shifted to the right by 0.009 units in MB space. Condition 6 was created by shifting the constellation formed by the targets and surrounds down by 0.0127 units in MB space. Coordinates of the targets and surrounds in MB space are listed in Table 1.

Target coordinates (L, S)	Surround coordinates (L, S)
Condition 1 (0.5504, 0.2859) (0.5504, 0.3011) (0.5504, 0.3156) (0.5504, 0.3318) (0.5504, 0.3471)	(0.5504, 0.3037) (0.5504, 0.3292)
Condition 2 (0.5409, 0.3156) (0.5457, 0.3156) (0.5504, 0.3156) (0.5552, 0.3156) (0.5600, 0.3156)	(0.5481, 0.3156) (0.5528, 0.3156)
Condition 3 (0.5421, 0.3236) (0.5463, 0.3201) (0.5504, 0.3156) (0.5546, 0.3129) (0.5588, 0.3093)	(0.5469, 0.3195) (0.5540, 0.3134)
Condition 4 (0.5421, 0.3093) (0.5463, 0.3129) (0.5504, 0.3156) (0.5546, 0.3201) (0.5588, 0.3236)	(0.5469, 0.3134) (0.5540, 0.3195)
Condition 5 (0.5504, 0.2987) (0.5504, 0.3139) (0.5504, 0.3292) (0.5504, 0.3446) (0.5504, 0.3598)	(0.5504, 0.3156) (0.5504, 0.3420)
Condition 6 (0.5498, 0.3156) (0.5546, 0.3156) (0.5594, 0.3156) (0.5642, 0.3156) (0.5689, 0.3156)	(0.5570, 0.3156) (0.5618, 0.3156)

Table 2. Target and surround coordinates in MB space for Experiment 1b.

The six surround conditions evaluated in Experiment 1b were similar to the surrounding conditions used in Experiment 1a, which fell along the cardinal axes or on positive or negative oblique lines relative to the positive L axis. Five target colors were chosen that fell on the extended line joining the two surrounds, but only one target color fell between the two surround colors (at the midpoint of the two surrounds, target ID 3); the other target color fell on the extended line that joined the two surround colors. The distance between adjacent targets on either side of the extended line were equal in MB space. The coordinates of the targets and surrounds in MB space are listed in Table 2.

In Experiment 1c, all five targets fell between or on the two surround colors. The five targets were chosen on the line joining the two surrounds at equal intervals in MB space, such that two of the target locations coincided with the two surrounds and the rest fell between the two surrounds. As with Experiment 1a, six surround conditions were evaluated by choosing the surrounds along the cardinal axes or on positive and negative oblique lines relative to the positive L axis. The MB chromaticity coordinates of the targets and surrounds used in creating the six conditions are listed in Table 3.

In each of the three experiments (1a, 1b, and 1c), six different conditions were evaluated to determine how

Target coordinates (L, S)	Surround coordinates (L, S)
Condition 1 (0.5409, 0.3156) (0.5457, 0.3156) (0.5504, 0.3156) (0.5552, 0.3156) (0.5600, 0.3156)	(0.5409, 0.3156) (0.5600, 0.3156)
Condition 2 (0.5504, 0.2859) (0.5504, 0.3011) (0.5504, 0.3156) (0.5504, 0.3318) (0.5504, 0.3471)	(0.5504, 0.2859) (0.5504, 0.3471)
Condition 3 (0.5421, 0.3236) (0.5463, 0.3201) (0.5504, 0.3156) (0.5546, 0.3129) (0.5588, 0.3093)	(0.5421, 0.3236) (0.5588, 0.3093)
Condition 4 (0.5421, 0.3093) (0.5463, 0.3129) (0.5504, 0.3156) (0.5546, 0.3201) (0.5588, 0.3236)	(0.5421, 0.3093) (0.5588, 0.3236)
Condition 5 (0.5498, 0.3156) (0.5546, 0.3156) (0.5594, 0.3156) (0.5642, 0.3156) (0.5689, 0.3156)	(0.5498, 0.3156) (0.5689, 0.3156)
Condition 6 (0.5504, 0.2987) (0.5504, 0.3139) (0.5504, 0.3292) (0.5504, 0.3446) (0.5504, 0.3598)	(0.5504, 0.2987) (0.5504, 0.3598)

Table 3. Target and surround coordinates in MB space for Experiment 1c.

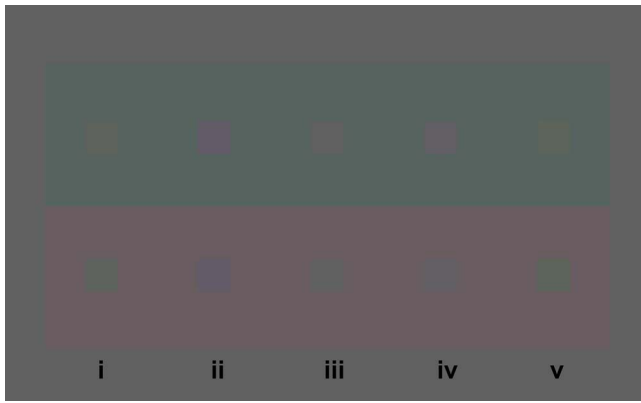


Figure 4. Example stimulus used in Experiment 1. Note that that colors do not reproduce correctly.

the magnitude of color induction varied as a function of distance from the surrounds in MB space. The five targets were labeled from 1 to 5 and the particular sequence of colors was randomly ordered when displaying the stimuli (see Figure 4). The background for the surrounds was achromatic with a mean color the same as the trichromatic values of the equal energy achromatic point of MB space. During the experiment, the only light in the room was the light emanating from the monitor that displayed the stimuli. The viewing distance was approximately 80 cm. The center target square subtended a visual angle of 0.8° and the surround subtended 6° wide by 2.5° high.

Procedure

The participants were instructed to compare the perceived color difference between the top and bottom targets in each pair of center surround displays and to order the pairs in a descending order of their perceived color difference. The target sequence was randomly changed on each trial. The observers entered the ID of the target to record their selection. They first entered the target ID that exhibited the largest perceived color difference and pressed the Return key; they then entered the ID of the target that exhibited the second largest color difference and pressed the Return key, and so on for the five target pairs. An achromatic uniform screen with the same luminance as the stimuli was displayed for a few seconds between different display sequences. In Experiment 1c, the target and the surround had identical colors in two of the center-surround displays. For these pairs, participants were instructed to compare the target color in the image where the target was visible with the surround color of the image that did not contain a visible target. The procedure was otherwise identical to that used in Experiment 1a and 1b.

Results

The results of Experiment 1a through 1c are plotted in Figures 5 through 7. The panels in the first and third columns depict the sampled points for the targets and surrounds in MB space. The panels in the second and fourth columns present the mean rank data calculated over all observers. The target pair that exhibited the largest color induction was given rank 5, the second largest target pair was given rank 4, and so on, such that the smallest difference was given rank 1. The error bars depict 95% confidence intervals calculated by bootstrapping using the built-in function in Matlab programming software (MathWorks). An asterisk between two data points indicates that the p value calculated from a Mann–Whitney U test (a nonparametric test for ordinal data) is smaller than the familywise corrected alpha value (0.0125). The correction on the alpha value was performed to account for multiple comparisons similar to a Bonferroni correction used for parametric statistics.

The results from Experiment 1a reveal that observers reported that the target that fell at the midpoint between the line joining the two surrounds in MB space exhibited the largest difference in perceived color (see Figure 5). Observers reported that targets 2 and 4 exhibited the second largest difference (i.e., the two targets closest to the midpoint), and the smallest difference was reported for targets 1 and 5 (i.e., the two targets farthest from the midpoint). Following the completion of the experiment, many observers reported difficulty choosing the bigger perceived color difference when comparing targets (2, 4) and (1, 5), which is not surprising given that they are equally distant from the two surround colors. Similar results were obtained with Experiment 1b (see Figure 6). Observers again reported the largest perceived difference occurred for the target that fell at the midpoint of the line joining the two surround colors, the second largest for targets 2 and 4 (with the exception of one data point in Condition 5), and for 9 out of 12 comparisons, the smallest for targets 1 and 5. The results of Experiment 1c are depicted in Figure 7. Observers report very little difference for any of the targets when they both lie in between the two surround colors on the line that joins the surrounds in MB space.

Discussion

The general finding of Experiment 1 is that the target that exhibits the largest perceived difference for two arbitrarily chosen surround colors falls on the line connecting the two surround colors. In Experiment 1a, the perceived difference in the target color decreased as the distance from the surround colors to the target

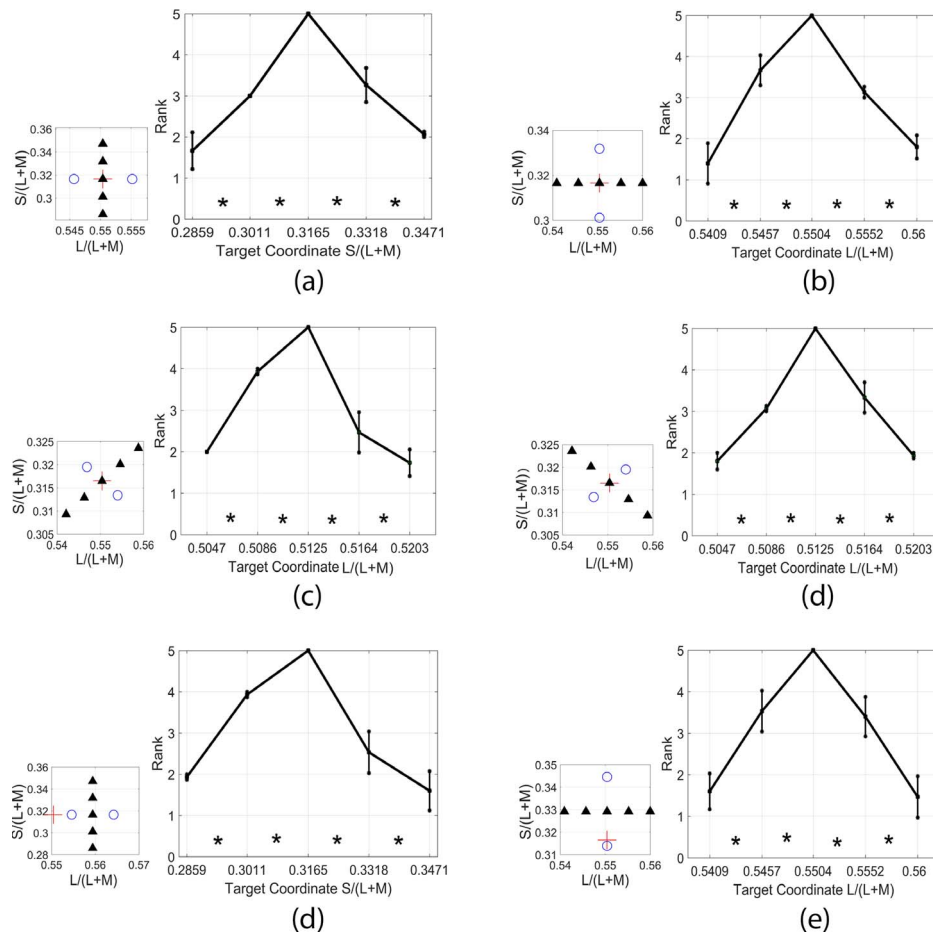


Figure 5. The results of Experiment 1a. The first and third columns depict the color coordinates of the targets (filled triangles) and surrounds (open blue circles) in MB space, and the second and fourth columns depict the mean rank data. The error bars were bootstrapped. The red cross depicts the neutral point. The asterisk between two data points indicates that the p value calculated from Mann–Whitney U test is smaller than the corrected alpha value (0.0125). The data reveal that the largest perceived difference occurs for targets that fall on the line that joins the two surround colors, and decreases for targets as a function of distance from that line and the two surrounds.

colors (which were located on a line orthogonal to the line joining the surrounds) increased. In Experiment 1b, the largest difference in color again occurred for the target that fell between the two surround colors, but decreased as the distance along the extended line joining the two surrounds increased. There were no consistent statistically reliable differences for visible targets that all fell on the line connecting the two surrounds in Experiment 1c.

What are the implications of these data for models of the direction and magnitude of induction in chromatic center-surround displays? The direction law states that a target is displaced in the direction of the vector from the surround to the target color, but it is unclear how the magnitude of induction should vary as a function of chromatic distance in MB space. In what follows, we will assume the validity of the direction law and see if it is capable of accounting for our pattern of results under different models of the magnitude of induction.

Consider first the constant size hypothesis. The direction law states that the targets that fall on the line in between the two surrounds in Experiment 1c should all be displaced in opposite directions by a constant magnitude, and hence should all appear equally different in perceived color. Moreover, the target pair where one of the targets coincides with one of the surround will only have one target that is displaced away from the surround color; hence, the perceived difference for these two conditions should be smaller. Both of these predictions are consistent with the data from Experiment 1c. The data from Experiment 1a are also consistent with the direction law and constant size hypothesis (see Figure 7). In this experiment, the target that fell between the two surround colors should be displaced in opposite directions, whereas colors that fell that did not fall on the line connecting the two surround colors will be displaced in directions that become more similar as distance from the surround is

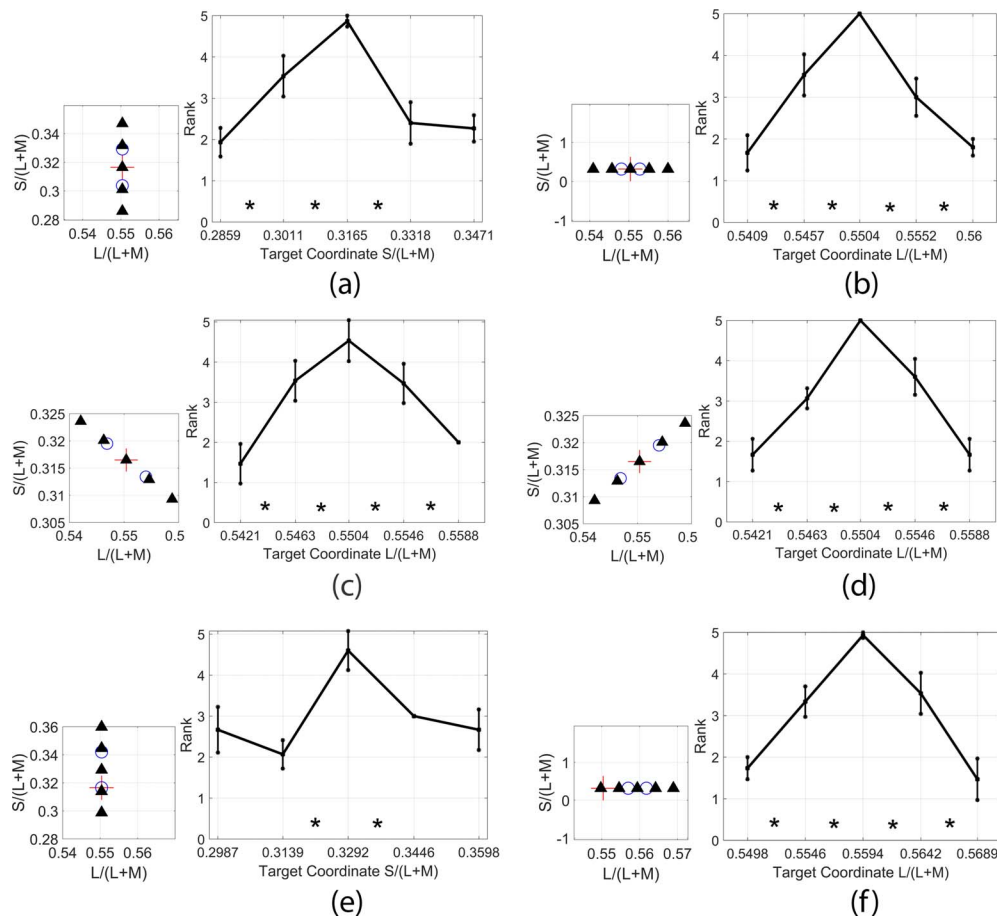


Figure 6. Results of Experiment 1b. All of the labeling conventions are identical to those in Figure 3. As in Experiment 1a, the data reveal that the largest perceived difference occurs for targets that between the two surround colors, and generally decreases for targets that fall on either side of the extended line joining the two surround colors.

increased. Thus, for targets sampled on a line perpendicular to the line joining the two surrounds, the perceived difference in color should decrease as a function of distance if the constant size hypothesis is correct, consistent with the data from Experiment 1a. However, the pattern of data obtained in Experiment 1b is not consistent with the constant size hypothesis; it predicts that the targets on either side of the extended line should be displaced by the same amount and therefore appear equally dissimilar. This is not what our data show; the difference in perceived color decreases as the distance from the two surrounds increases. Thus, if the direction law is correct, then the results of Experiment 1b do not support the constant size hypothesis.

Let us now consider our pattern of data when the direction law is combined with either the inverse size or increasing size hypotheses. It is clear from Figure 8 that the direction law and inverse size hypothesis predict the ordering of perceived color differences in Experiment 1a, since the target closest to the two surrounds is perceived as most different and the perceived difference for the other targets decreases as a function of distance

in MB space. However, if induction increases as a function of distance, the predicted pattern of results depends on the quantitative rate that induction increases relative to the decrease predicted on the basis from the direction law (see Figure 8). If induction increases rapidly and then saturates such that the increase in magnitude is less than the decrease predicted from the angular difference in the direction of induction (as predicted from the direction law), then an increasing size hypothesis could also account for the data in Experiment 1a. A similar ambiguity arises for Experiments 1b and 1c. The targets on the extended line joining the two surrounds are both predicted to be displaced in the same direction, but the inverse and increasing size hypotheses predict that the size of the induction is a function of chromatic distance to the two surrounds. If the size of induction saturates as a function of chromatic distance, then both models predict that the target that is more distant from the two surrounds should appear the least different, which is what our data show. Thus, taken as a whole, the results of Experiment 1 do not support the constant size hypothesis, but are incapable of distinguishing between

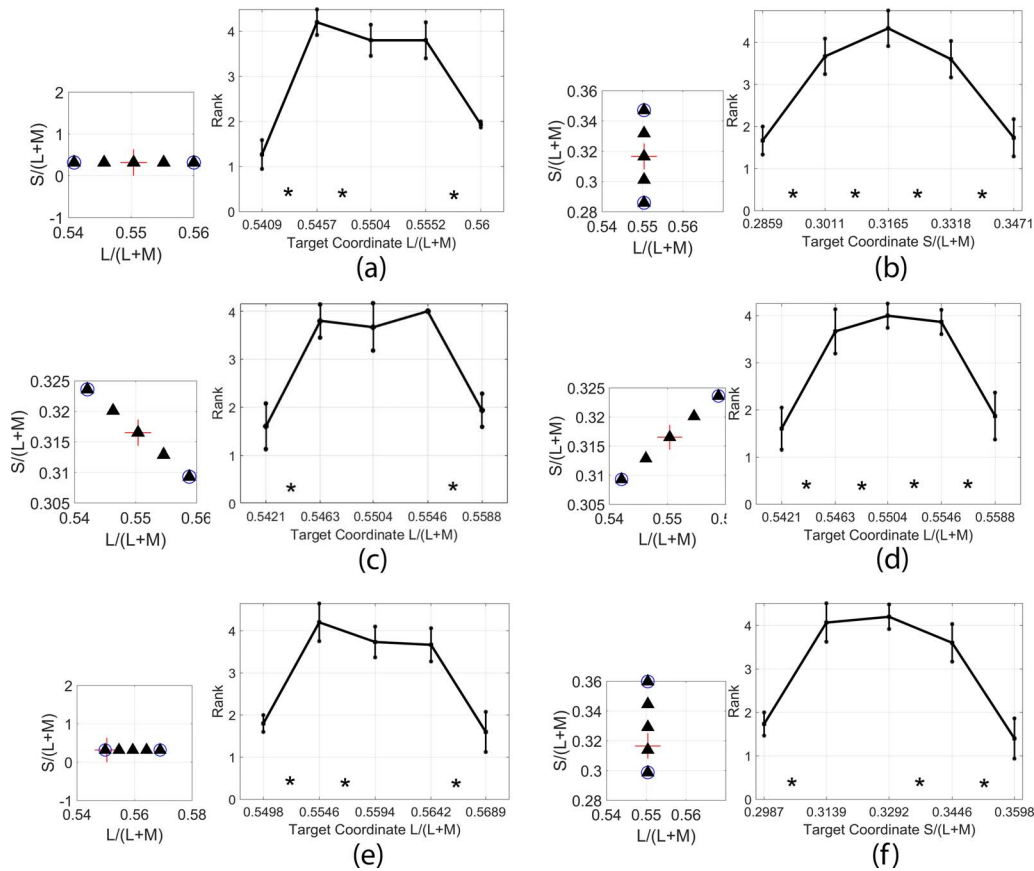


Figure 7. Results of Experiment 1c. Plotting conventions are identical to those in Figures 3 and 4. Apart from one data point in (2) and (6), there were no reliable differences in the perceived dissimilarity of targets that fall on the line connecting the two surround colors.

the inverse or increasing size hypothesis for models that exhibit compressive nonlinearities.

Experiment 2: Fixed targets with a variable surround

In Experiment 1, we attempted to understand what target color exhibits the greatest perceived difference for two arbitrarily chosen surround colors in an equiluminant plane. The goal of Experiment 2 was to attempt to determine how induction varies with chromatic distance by fixing target chromaticity and varying surround saturation. One of the surrounds was constant and achromatic to serve as a fixed reference, whereas the saturation of the other surround was varied. This allowed us to compare the effects of surround contrast on the magnitude of induction for fixed chromatic targets.

The different models of the dependence of induction on chromatic distance make different predictions for the conditions tested. The inverse size hypothesis predicts that induction should be largest when the difference between the surround and target is small,

whereas an increasing size hypothesis predicts that for a given target the induction should grow with surround saturation. The constant size hypothesis predicts no difference for targets displaced along a fixed line if the direction of induction of the two surrounds is the same.

Methods

Observers

Eight naïve participants and one of the authors (SR) participated in Experiment 2. The participants were undergraduate students, postgraduate students, and one nonstudent. The undergraduate observers participated for course credit and were recruited using an online system at the University of Sydney. The two postgraduate students were members of the visual perception research group at the University of Sydney. These two students were recruited by sending emails to individual students to volunteer for the experiment. The remaining observer participated in this experiment was recruited by verbal request. The subjects tested color normal for Ishihara plates (Ishihara, 1967).

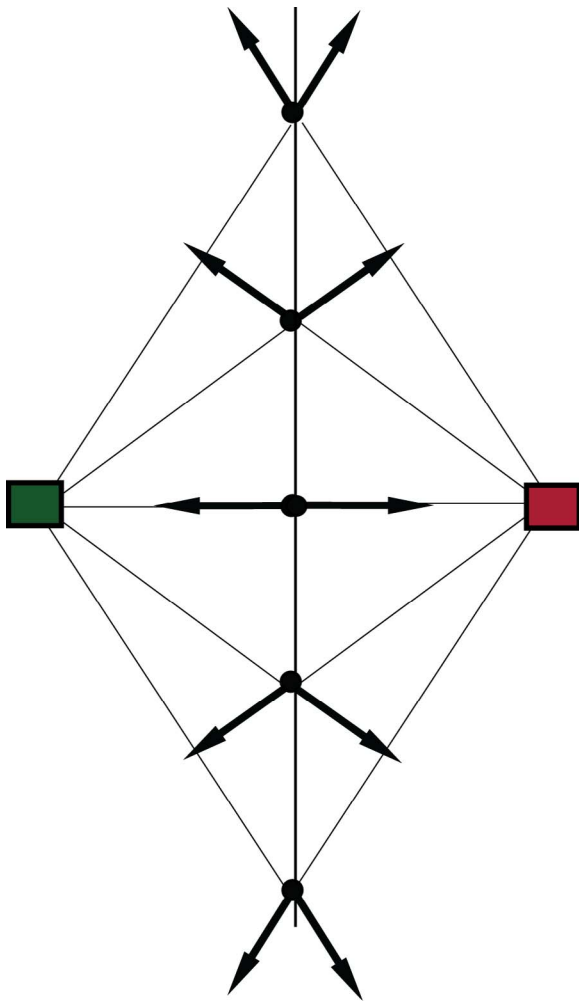


Figure 8. The predicted strength of induction for two arbitrary surround hues (red and green squares) and a series of target hues that lie perpendicular to the line connecting the two surround hues under an assumption that the magnitude of induction is constant. The length of the arrows depicts the magnitude of induction, and the perceived dissimilarity is captured by the distance between the tips of each pair of arrowheads. Note that the direction law predicts that the perceived dissimilarity should be greatest for the target that lies between the two surround colors. The same prediction would also hold if the size of induction decreased with chromatic distance between the targets and the surrounds. If the size of induction increases with chromatic distance, then the predicted pattern of results will depend on the rate that the induction increases relative to the decrease predicted by the angular separation predicted by the direction law.

Apparatus and stimuli

Experiment 2 contained six chromatic conditions. A typical stimulus used for Condition 1 is shown in Figure 9. The stimuli were created using the four surround colors depicted by the locations of the white dots and the target color depicted by the black square in Figure 9a. The targets are all physically identical,

and the surround of the bottom targets was the equal energy achromatic point of the MB space. Four pairs of center surround displays were created in each condition. The target (bottom) was fixed and embedded in an achromatic surround, whereas the target (top) was in one of the four different surround chromaticities sampled from the MB space. The positions of the targets were randomly ordered during each trial presentation and assigned an ID for each pair of center surround display. The stimuli were displayed on the same monitor as Experiment 1.

The six conditions evaluated in this experiment were chosen such that the target and surrounds were either: (a) on the positive S axis, (b) on the positive L axis, (c) on the negative S axis, (d) on S axis but on the opposite sides of the achromatic point, (e) on the negative S axis and on the positive L axis, and (f) in different quadrants of MB space and off the cardinal axes of MB space (see Figure 10). In Condition 6, the target was in the first quadrant and the surrounds were in the fourth quadrant of MB space. Coordinates of the targets and surrounds in MB space are listed in Table 4.

Procedure

The procedure was similar to that used in Experiment 1. Observers compared the color difference between the four pairs of targets and ordered these pairs in decreasing order of perceived color difference. Pilot studies revealed that some observers did not see any color difference for some of the pairs. In such cases, observers were instructed to press the Equal key and the Return key to record the observation, which was assigned a rank of 1. Participants entered the ID of the stimuli in a decreasing order of color difference, which were assigned ranks between 5 and 2, with 5 as the most different. The surrounds were randomly ordered and displayed on a screen in a dark room.

Results

The results of Experiment 2 are shown in Figure 10. The data points depict the mean rank for each target based on the subjects' data and the standard error calculated on the bootstrapped data. An asterisk between two data points indicates that the p value calculated from Mann–Whitney U test is smaller than the corrected alpha value (0.0125). The sampled locations of the target (filled triangles) and surrounds (open blue circle) are shown for each condition.

The data demonstrate that the perceived difference between the pairs of targets increases as the saturation of the surround increases for all of the surround and

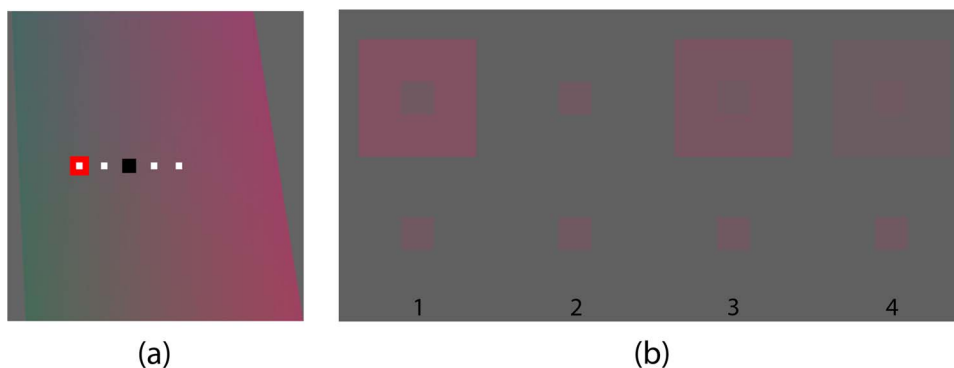


Figure 9. An example of the stimuli used in Experiment 2. The insert in (a) depicts the colors of the target (black square) and the surrounds (white dots). The open square was the neutral point and served as a constant surround for each pair of displays. An example of one of the experimental stimuli is presented in (b). In this example, the greatest perceived difference appears in column 1. Note also that the perceived color difference in column 1 is larger than the perceived color difference of the third and second most saturated surround depicted at the top of columns 3 and 4, respectively.

target combinations tested. The target color was chosen to lie in the middle of the four surround colors in Conditions 1-3, and the surrounds varied along the positive S axis, positive L axis, and negative S axis, respectively. In all of these conditions, the direction law predicts that induction should be strongest for the two most saturated surrounds, since the other surround was fixed and achromatic. The inverse size hypothesis

predicts that the induction should be stronger for the second most saturated surround in our stimuli, but this is not what we observed: the strongest difference occurred with the most saturated surround. The same pattern of data was obtained when the target colors were chosen from locations that did not lie along the axis that the surround saturation was varied. The general finding from Experiment 2 is that color

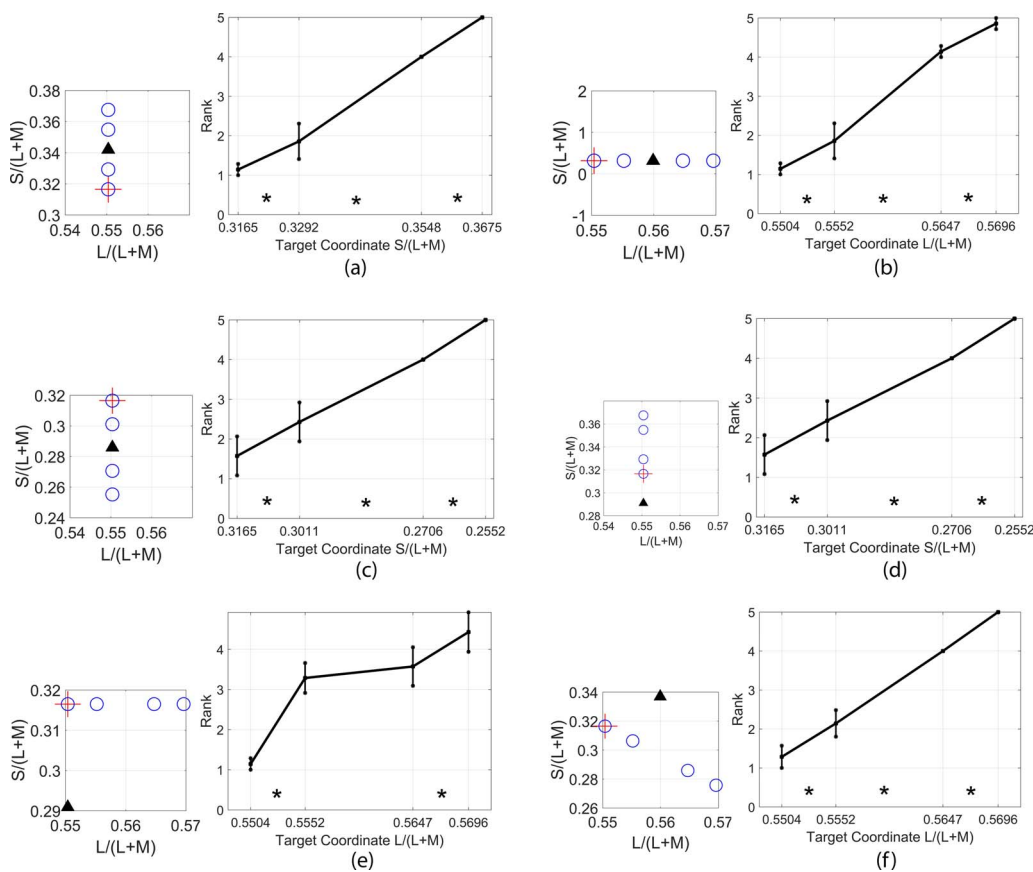


Figure 10. Results of Experiment 2. Plotting conventions are the same as those used in Experiment 1a through 1c. The perceived difference increases as a function of surround saturation for all variations in surround saturation and choice of target colors.

Condition	Target coordinates (L, S)	Surround coordinates (L, S)
1	(0.5504, 0.3420)	(0.5504, 0.3156) (0.5504, 0.3292) (0.5504, 0.3548) (0.5504, 0.3675)
2	(0.5599, 0.3156)	(0.5504, 0.3156) (0.5552, 0.3156) (0.5647, 0.3156) (0.5696, 0.3156)
3	(0.5504, 0.2859)	(0.5504, 0.3156) (0.5504, 0.3011) (0.5504, 0.2706) (0.5504, 0.2552)
4	(0.5504, 0.2909)	(0.5504, 0.3156) (0.5504, 0.3292) (0.5504, 0.3548) (0.5504, 0.3675)
5	(0.5504, 0.2909)	(0.5504, 0.3156) (0.5552, 0.3156) (0.5647, 0.3156) (0.5696, 0.3156)
6	(0.5599, 0.4356)	(0.5504, 0.3156) (0.5552, 0.3063) (0.5647, 0.2859) (0.5696, 0.2757)

Table 4. Target and surround coordinates in MB space for Experiment 2.

induction in center-surround displays increases with surround saturation whether the hue of the target and the surround are the same or different. These results suggest that Kirschmann's fourth law can be generalized: color induction increases with saturation of the surround in a homogeneous center-surround display for targets of any hue.

General discussion

The goal of the preceding experiments was to understand the factors that modulate the magnitude of color induction in simultaneous contrast displays. Previous work has led to conflicting results; the magnitude of induction has been found to depend on both the method used and the properties of the matching surround. One significant issue with both asymmetric matching and nulling methods is the time that it takes to achieve an adequate match, which increases the influence of temporal adaptation. We attempted to minimize the contribution of temporal adaptation by using a difference-scaling method, in which observers ordered pairs of simultaneous contrast displays from the most to least different. This task can be performed within a few seconds. We also informally found that the same pattern of results can be obtained by comparing any two pairs of displays, a judgment that is immediately apparent. The readers can verify this for themselves by comparing the two most saturated surrounds in Figure 9: the target on the most saturated surround appears less red than the target on the second most saturated surround. Taken together, the results of Experiments 1 and 2 suggest that the largest induction (perceived difference) in a pair of homogeneous center-surround displays occurs when the two surrounds have the largest saturation difference obtainable, and when the target falls between the two surround chromaticities.

Our results are generally consistent with the predictions of the direction law, which states that a central target is displaced along the extended line connecting the target and the surround color. The results of Experiments 1 and 2 also provide insights into how the magnitude of induction varies as a function of

surround–target contrast. Both experiments are inconsistent with the constant size hypothesis, which states that the magnitude of induction is independent of chromatic distance between the target and the surround. The results of Experiment 2 are also inconsistent with the inverse size hypothesis, which states that the strongest induction should be observed with targets that have the smallest contrast relative to the surround and decreases as chromatic contrast is increased. We found that the size of induction increases as a function of surround saturation, although our paired comparison method provides no insight into the rate of this increase or whether it saturates for higher levels of contrast and/or saturation. Indeed, it should be noted that the equiluminant contrasts used in our experiments were not highly saturated, so it is possible that the magnitude of induction saturates with higher contrasts or even decreases for higher levels of contrast than those tested herein.

Some recent work supports the view that the size of induction may vary nonmonotonically as a function of the hue difference between targets and their surrounds. Klauke and Wachtler (2015) used an equiluminant circular cone-contrast space where the distance from the center corresponded to the chroma (saturation) and the azimuth angle corresponds to the hue. They used an asymmetric matching task in which observers adjusted the hue of each target on an achromatic surround to match the perceived hue of a target on each chromatic surround (the saturation of each available hue in the match pattern was fixed). They found that the chromatic induction initially increased for hue angles between approximately 0° and approximately 60° to 90° , but declined thereafter (Figure 11). This suggests that the magnitude of induction may vary nonmonotonically as a function of hue difference. It is worth noting, however, that Klauke and Wachtler's (2015) data can be derived from the direction law. Figure 11b depicts the predicted induction of the targets used in their experiment by the direction law. The black arrows indicate the predicted direction of induction, and their (fixed) length depicts a constant size induction (for simplicity of graphing). The angular difference between the adjacent dashed lines of the same color depict the predicted size that hue is expected to

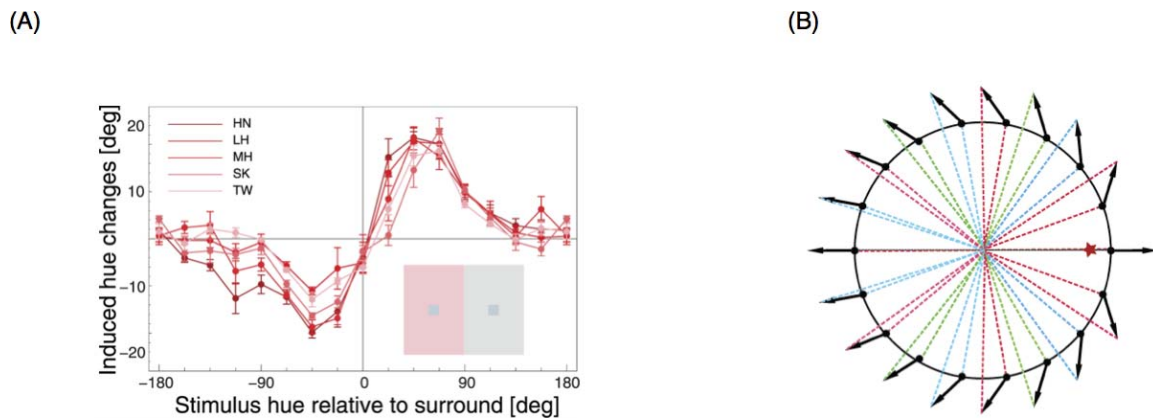


Figure 11. (a) Data for one of the surround surrounds from Klauke and Wachtler (2015). The effect of the surround was measured as an angular difference between the target color and the matched hue on the asymmetric surround. Observers could only vary the hue of the match, and the saturation was fixed. (b) The predictions of the direction law in a circular cone contrast space. For simplicity, the magnitude of induction is assumed to be constant and given by the length of the black arrows. The surround color is represented by the red star, and the hues of the tested targets are represented by the black dots. The angular separation of the colored dashed lines connecting each target color and the corresponding arrow tip depicts the predicted change in perceived hue (the colors of the lines are solely to facilitate the ease of seeing how the size of induction varies as the hue of the targets is varied; the angle between adjacent dashed lines of the same color is the predicted hue shift). The direction law and constant size hypotheses predict that induction should initially increase, reach a maximum and then decrease as the angular difference between the surround hue and target hue increases for either positive or negative directions of angular difference relative to the surround hue. This is consistent with the pattern of data that Klauke and Wachtler (2015) obtained.

change. Note that the predicted change exhibits the same general pattern as the one observed by Klauke and Wachtler (2015; see Figure 11a): Induction initially increases and then declines thereafter, with no induction for hues separated by 180° . This same general pattern of data would also be expected from an inverse size hypothesis or if the magnitude of induction exhibited a monotonically increasing nonlinearity that saturates for large chromatic distances; the precise form of the nonlinearity would simply shift the location of the predicted peak of induction and the rate that inducing increases and declines as a function of hue angle. Thus, the nonmonotonicities exhibited in Klauke and Wachtler's (2015) data can be derived from the direction law and any of the monotonic hypotheses about how the magnitude of induction varies as a function of chromatic distance. Further experiments are needed to resolve how the magnitude of induction varies as a function of hue differences, and for surrounds that are more saturated than the targets.

The main source of empirical support for the inverse size hypothesis comes from a series of papers by Faul, Ekroll, and colleagues (Ekroll & Faul, 2012b; Faul, Ekroll, & Wendt, 2008). Faul, Ekroll, and Wendt (2008) observed that low contrast targets appear more saturated on homogenous surrounds than on unstructured variegated surrounds, but this difference decreases as the saturation of the target increases. A similar effect occurs if the targets are surrounded by

black rings or embedded in surrounds that differ strongly in luminance. The interpretation favored by Ekroll and Faul (2012b) is that “unstructured variegated surrounds of sufficiently high color variance are assumed to be neutral (with respect to simultaneous contrast, but not with respect to temporal adaptation)” (p. 111). In other words, they assume that the perceived color of the targets on a sufficiently variegated surround reflects the target's “true” color (i.e., free of effects of induction), apart from any induction that arises from temporal adaptation. It should be noted, however, that their data only provides evidence that there is a *difference* in the perceived saturation of targets embedded in a variegated surround compared to those embedded in a homogeneous surround; the cause of this difference is unclear. An alternative explanation for the perceived difference between these two types of displays is that the chromatic variance of the variegated surround—or contrast of *any* kind between the target and the surround—*suppresses* the perceived chromaticity of the target. This explanation implies that the gamut expansion effect, which motivates the inverse size hypothesis, would be misnomer; in this account, the observed color difference between the homogenous and variegated surrounds arises from a suppression of the perceived color of the target on the variegated surround, not an expansion of the perceived gamut of the targets on the homogeneous surround. Indeed, we recently showed that the magnitude of gamut expansion depends on the particular distribution

of chromatic variance present in the surround, not just its mean chromaticity (Ratnasingam & Anderson, 2015). Specifically, we showed that textured surrounds that contain variance along the same color axis as a target induced a larger decrease in its perceived saturation than variance along an axis orthogonal to a target's color. This suggests that chromatically variegated surrounds are not neutral in terms of their influence on the appearance of targets. It is therefore unclear whether the gamut expansion effect arises from a genuine expansion of the color gamut of low contrast targets on homogeneous surrounds, or whether it represents a contraction of the color gamut of targets on variegated surrounds (as the original authors of this paper duly noted; see Brown & MacLeod, 1997). These two explanations need not be mutually exclusive; both phenomena could contribute to the observed differences.

Ekroll and Faul (2009, 2012a, 2012b) have suggested that the effects observed in simultaneous contrast displays can be understood as the consequence of two distinct mechanisms: a temporal adaptation mechanism such as von Kries scaling, and a purely spatial mechanism, for which the term simultaneous contrast is most naturally reserved. They argued that this spatial component can be captured by a “crispness” parameter, which is strongest for low contrasts and decreases with increasing contrast. They further suggested that Kirschmann's fourth law should be most evident in conditions that favor adaptation, such as strict fixation and prolonged viewing. Although it is impossible to eliminate the contributions of adaptation in simultaneous contrast displays, the method used herein attempted to diminish the contribution of such processes. Fixation was not controlled, and the stimuli were only viewed for a few seconds. We also informally observed that all of the statistically reliable differences we obtained could also be observed in effectively “simultaneous” pairwise comparisons. The readers can verify this for themselves by comparing the stimuli we used in Experiment 2 (see Figure 9). The perceived color difference in column 1 is larger than the perceived color difference in column 3. These differences are immediately apparent. This does not preclude the possibility that adaptation contributes to these effects, but if so, this adaptation must occur very rapidly (see e.g., Rinner & Gegenfurtner, 2000). It would therefore seem appropriate to consider both proposed mechanisms as forming the basis of the simultaneous component of simultaneous contrast displays if adaptation does play a role.

Finally, it should also be noted that although some of our comparisons involved target-surround combinations in which some targets can appear as both an increment and decrement relative to the two surrounds,

which would induce differences in both hue and saturation (e.g., red and green). Such pairs may be rated as more dissimilar than two targets of the same hue (e.g., red and redder), but it could be argued that this does not imply that the size of simultaneous contrast is larger in these conditions. However, it should be noted that such conditions are only a small subset of those tested herein. Our general finding suggests that the largest induction will be observed with targets that fall between any two chosen surround colors, whether they are of the same or different hue, and that the effect of a surround on a fixed target is larger for more saturated surrounds.

Conclusions

Our data suggest that the perceived difference of a target will be greatest when the target falls on the line in color space joining a pair of arbitrarily chosen surrounds in color space. Our data also support a generalization of Kirschmann's fourth law for chromatic targets: A more saturated surround produces a larger induction than a less saturated surround for all of the target colors tested. The results of both of our experiments are consistent with the direction law proposed by Ekroll and Faul (2012a, 2012b, 2013), but our overall pattern of data do not support either the constant size hypothesis or inverse size hypothesis. Our results suggest that Kirschmann's fourth law cannot be attributed solely to the effects of temporal adaptation, or if so, such adaptation processes must occur on very short time scales.

Keywords: color induction, simultaneous color contrast, color perception

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