The role of scission in the perception of color and opacity

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Recent work has shown that the decomposition of textures into a layered representation can induce striking percepts of inhomogeneous transparency and modulate the perceived lightness of achromatic textures (B. L. Anderson & J. Winawer, 2005, 2008). It was argued that two photo-geometric principles of perceptual organization were responsible for the percepts that arise in these images: a polarity constraint that determines the relative lightness of the two layers and a transmittance anchoring principle, which is responsible for determining portions of the scene that are in plain view. Here, we show that similar principles of perceptual organization underlie the decomposition of textures that vary only in chromaticity. We show that the chromatic contrast relationships along contours play a critical role in determining when chromatic scission occurs and in determining the perceived color and opacity of the layers that emerge when such conditions prevail. These findings provide evidence that a similar set of computational principles is used to decompose images into layers along both chromatic and achromatic axes of color space.

Keywords: color vision, color appearance/constancy, lightness/brightness perception


Introduction

The chromatic content of the light that reaches the eye depends on the spectral content of the light source, the reflectance properties of surfaces, and the absorption and reflectance properties of intervening media. To recover surface color, the visual system must implicitly or explicitly disentangle the contributions of the illuminant and atmospheric media from the intrinsic reflectance properties of surfaces. A fundamental goal of color science is to understand how the visual system exploits contextual relationships between a target and its visual context to recover the causes of chromatic variation in a scene.

The role of context in color appearance has been investigated in a variety of ways. One approach involves placing a target with a fixed chromatic content in different surrounds (e.g., Barnes, Wei, & Shevell, 1999; Brown & MacLeod, 1997; Jameson & Hurvich, 1972; Mausfeld & Andres, 2002; Shevell, 1982; Walraven, 1976; Zaidi, Yoshimi, Flanagan, & Canova, 1992). In experiments of this kind, the general goal is to determine how the perceived color of the target is affected by its surround colors, a dependency that has been termed color induction. Another method for studying color appearance evaluates the effects of placing target surfaces with a fixed spectral reflectance function in different illumination environments (e.g., Arend & Reeves, 1986; Brainard & Wandell, 1992; Land & McCann, 1971). Studies of this kind hold the distal surfaces constant, allowing the spectral content of the target and its surrounding context to vary in the image (the proximal stimulus). In such paradigms, the primary goal is to assess the extent to which perceived surface color remains constant across spectrally varying illumination fields that jointly affect a target and its surrounding context. Despite their differences, a common goal of both approaches is to understand how perceived color is modulated by chromatic context and to deduce the nature of the computations and/or mechanisms that underlie such dependencies.

One common assumption that shapes both the experimental methodology and modeling of color induction phenomena is the belief that the effect of context can be modeled as a shift in the trivariate coordinates of the target patch, i.e., a shift in a target’s position in color space. This assumption is implicit in both asymmetric matching paradigms (where the target on one surround is putatively matched to a target on a surround with a different chromaticity; Arend & Reeves, 1986; Ekroll, Faul, & Niederée, 2004) and in chromatic “nulling” paradigms, where observers adjust a target on a colored surround to appear chromatically neutral (gray; e.g., Chichilnisky & Wandell, 1996; Delahunt & Brainard, 2004; Fairchild, 1990; Helson & Michels, 1948; Werner & Walraven, 1982). Recently, however, a number of authors have suggested that some forms of color induction arise from the decomposition (or scission) of a target into a layered image representation (Anderson, 1997; Ekroll et al., 2004; Ekroll, Faul, Niederée, & Richter, 2002; Wollschläger & Anderson, 2009). The multi-layered quality of a target cannot be adequately captured by a single set of trivariate coordinates, and hence, models that restrict themselves to such representations would be incapable of capturing the full dimensionality of color experience with stimuli that evoke such representations.
Recent work from our laboratory (Wollschläger & Anderson, 2009) directly demonstrated the role of scission in color induction (Figure 1). The target regions in these images were constructed using a random array of colored lines or dots, selected to maintain a neutral (achromatic) mean chromaticity. The full 2D space of colors available within the monitor was used for the target regions. A chromatic bias was introduced into the surround by blending the target’s color distribution with one of a pair of opponent colors (in Figure 1, “green” and “magenta”). To enhance the percept of layers, the (chromatically unbiased) target region was translated relative to the surround, and the noise was dynamically changed in each frame. For appropriately chosen combinations of surround chromaticity and chromatic variance, this manipulation induces a percept of a magenta target on the green surround, and a greenish target on a magenta surround, visible through an array of dynamic noise. In order to assess whether the color induction observed in these displays depends on a particular perceived depth ordering, the target was placed stereoscopically in front, behind, or in the same plane as the noise pattern. Wollschläger and Anderson (2009) found that the amount of induction in these displays was independent of relative depth, suggesting that the transformation in color appearance experienced in these images depends only on the decomposition into layers, not the particular depth assignment of the constituent layers.

Although this work reveals that scission can induce large changes in the chromatic appearance of a target, there is currently no general theory that specifies the chromatic and geometric conditions that support color scission. Despite a number of noteworthy exceptions (cf. Chen & D’Zmura, 1998; D’Zmura, Colantoni, Knoblauch, & Laget, 1997; Faul & Ekroll, 2002; Khang & Zaidi, 2002), the vast majority of research into perceived transparency has used achromatic stimuli and focused on conditions that support “balanced” transparency (i.e., conditions in which the transparent surface has a uniform transmittance and color). However, our laboratory introduced a class of achromatic displays that evoke percepts in which the transparent layer appears to vary continuously in opacity (Anderson, 1999, 2003; Anderson & Winawer, 2005, 2008; see Figure 2). The displays were constructed from noise patterns with an amplitude spectrum of $1/f^2$. The separate frequency components were summed with random phases and orientations, producing a texture with a cloud-like appearance (Figure 2). A number of constraints were found to be critical in predicting when scission occurred with targets formed by these textures, and how lightness and opacity was assigned to the resulting layers. First, for a coherent percept of scission to occur, the contrast polarity separating the target and its surround must have a constant sign. This polarity constraint is critical in eliciting both balanced (e.g., Adelson & Anandan, 1990; Anderson, 1997; Metelli, 1974) and unbalanced transparencies (Anderson, 1999, 2003; Anderson & Winawer, 2005, 2008). The direction of the contrast change determines how lightness is partitioned between the two layers: if the surround is darker than the target region, the target appears light; if the surround is lighter than the target, the target appears dark. The second critical constraint involves how opacity and lightness are assigned to the multiple layers in conditions where the

![Figure 1](image1.png)

Figure 1. Color induction using textured random-noise stimuli (from Wollschläger & Anderson, 2009). The central target colors are identical in the top and bottom of the random-line image (left column) and the random-dot image (right column). The chromatic distributions of the surrounds in the top and bottom have been shifted along the magenta–green opponent axes in color space, causing the central targets to take on an opponent color.

![Figure 2](image2.png)

Figure 2. The “cloud” texture introduced by Anderson and Winawer (2005). The central target disks are identical but appear to be very different in lightness due to the different surrounds on which they are placed.
polarity constraint is satisfied. It was shown that the perceived transmittance of the cloud is determined by how the strength of the edge (i.e., its contrast) varies along the target–surround boundary (Anderson, 1999; Anderson & Winawer, 2005, 2008). The transparent surface appears most dense in the regions along the target–surround boundary that generates the lowest contrast (i.e., the weakest edge strength). In the limit where the contrast of the target–surround border goes to zero, the near surface appears opaque. At the other end of the opacity scale, it was found that the highest contrast contour segment along the target–surround boundary appears in plain view, i.e., unobscured by any transparent or opaque surface. This constraint was observed for all values of contrast tested and, hence, appears as a general “anchor point” for perceived opacity. For this reason, this constraint was dubbed a *transmittance anchoring principle* (TAP), which states that the visual system treats the highest contrast regions along continuous contours as “anchor” points in scaling the transmittance of a transparent layer (by assigning a transmittance value of 1 to these regions, causing the underlying surface to appear in plain view). It should be noted that this anchor point is in no way mandated by the physics of transparency. Rather, it expresses a bias of the visual system to only postulate the existence of a transparent layer when there is some reduction in contrast magnitude of same polarity edges that is best “explained” by the presence of transparent media.

The main goal of the present paper is to determine whether the principles of organization that constrain the appearance of achromatic cloud patterns generalize to purely chromatic (equiluminant) versions of these displays. More specifically, it is currently unknown whether concepts such as the TAP will generalize to the chromatic domain, or whether there is a chromatic analogue of the polarity constraint that underlies the conditions for scission and perceived color of surfaces in images that evoke percepts of inhomogeneous transparency. It has been suggested that chromatic variations are more likely to be interpreted as variations in surface color, whereas luminance variations can arise from changes in surface reflectance, illumination changes, and/or intervening media (Kingdom, 2008), so it is not clear a priori whether color variations will be treated in the same manner as achromatic variations in these displays. Moreover, it is unknown whether (or under what conditions) chromatic variations will induce percepts of inhomogeneous transparency wherein the transparent layer appears to vary in perceived density (or “thickness”) while appearing uniform in perceived color. Whereas achromatic stimuli can only vary along one dimension, (equiluminant) chromatic stimuli can vary in two dimensions, corresponding to the “hue” and “saturation” (or “purity”) of a color. The purpose of the experiments and demonstrations reported below is to determine whether similar forms of decomposition can arise from purely chromatic stimuli, and if so, how surface color and opacity is assigned to the layers that arise from this decomposition.

**Experiments 1 and 2**

We began by constructing chromatic variants of the cloud pattern developed previously with achromatic stimuli (Anderson & Winawer, 2005, 2008). In the lightness variants of the cloud pattern, the luminance variations within the texture were constrained to lie on a straight, 1D path through color space. In the experiments reported below, we constructed two types of color analogues of these displays. In Experiment 1 (the “saturation” conditions), the color within the stimulus was constrained to lie on a 1D path connecting opponent colors through the chromatic neutral point (see Figure 3A). In Experiment 2 (the “hue” conditions), the color varied between two of the most saturated values on the perimeter of the color “circle” separated by 90 degrees, connected by a straight, 1D path (and, hence, does not go through the neutral point; see Figure 3B). In both of these conditions, clear percepts of color scission are experienced. The experiments below were designed to measure the perceived color of the circular targets for a broad range of saturation and hue conditions.

**Methods**

**Observers**

Five observers with normal or corrected-to-normal visual acuity and normal color vision participated in the experiments. Author BK was aware of the nature and purpose of the experiments. The other four observers were not informed of the experiment’s purpose until the conclusion of both experiments.

**Stimuli**

The stimuli used in these experiments were chromatic variants of those used previously by Anderson and Winawer (2005, 2008). The textures were generated by specifying a noise power spectrum that varied as 1/f². A 2D noise texture was then generated by summing the different frequency components with random orientations and phases. Texture intensity values were normalized and replaced with chromaticities. Two circular regions in the left and right halves of the display were taken as test and match (Figure 3, top). Chromaticity values of test and surrounding regions in the left half were varied across experimental conditions. The white noise in the surround of the match pattern was achromatic.
All chromaticity values were taken from MacLeod and Boynton’s (1979) equiluminant color diagram that is a transform of Smith and Pokorny’s (1975) cone fundamentals. In this space, the chromatic content of a stimulus is described by a vector with two components that specifies the relative cone excitations of the L, M, and S cones: the long wavelength sensitive cone excitations, $L / (L + M)$; and the short wavelength sensitive cone excitations, $S / (L + M)$. The normalization constant $(L + M)$ represents the luminance channel and specifies a plane of equiluminance. The CIE daylight D (D65; Wyszecki & Stile, 1982) was taken as the origin of this space, whose

Figure 3. The stimuli used for the (A) saturation and (B) hue modulation conditions. The central target disks varied in hue in both conditions, but the surround varied (A) in saturation in Experiment 1 and (B) in hue in Experiment 2. (C) Pairs of bars show the range of 6 chromatic modulation depths for the test (the lines crossing the horizontal axis) and a fixed depth for the surround (the lines below the horizontal axis). The values along the horizontal axis indicate the four modulation depths of the target, and the vertical axis represents the magnitude of modulation depth. The colors of bars indicate the colors used for red–bluish-green test and red–gray surround (A), and those for the same test but violet–red hue modulation surround (B). The four test patch modulations are shown in (D) on a “gray–red” surround.
MacLeod and Boynton’s (1979) chromaticity (L / (L + M), S / (L + M)) was (0.6551, 0.0169) at the test luminance of 30.0 cd/m². On this color space, the saturation of a color is represented as the distance from the origin (“gray”), whereas the hue is described as the angular distance from a reference axis (the positive L / (L + M) in the present study).

Highly saturated values of “red” (the L / (L + M) axis) and “violet” (the S / (L + M) axis), chosen suitably considering the gamut of the display, were used for references to compute chromaticity distance and contrast, whose chromaticities were (0.7000, 0.0169) and (0.6551, 0.0314), respectively. All chromaticities used in the present study were normalized by these two colors: the chromaticity of the origin (D65) was first subtracted from these colors, and then divided by the two difference components, respectively, between the reference and the origin on each axis. In other words, the most saturated colors used in our experiment were assigned values of 1, and all other values where scaled relative to these values. We will, henceforth, refer to the magnitude of the chromatic contrast modulation as “contrast depth,” which is analogous to the amplitude of a sine wave in our stimuli. Thus, smaller values of contrast depth denote less saturated colors; larger values denote more saturated colors.

For our two experiments, the test and its surrounding regions were varied in both saturation and hue. Let \( C(u, v) \) be the chromaticity coordinate of a color on the diagram at a position \( x, y \), where \( u = u(x, y) \) and \( v = v(x, y) \) are chromaticity components on the two axes L / (L + M) and S / (L + M), respectively, at position \( (x, y) \) in the image. A test chromaticity, \( C_t(u, v) \), can then be described as

\[
C_t(u, v) = \alpha C(u, v) + \beta,
\]

where \( \alpha \) and \( \beta \) are multiplicative and additive scalars, respectively.

**Experiment 1: Saturation variations**

Eight pairs of complementary colors were used for the saturation modulation within the test regions. These pairs included (red, bluish green), (magenta, green), (violet, greenish yellow), (cyan, yellow), (bluish green, red), (green, magenta), (greenish yellow, violet), and (yellow, cyan), chosen by moving around the hue circle in 45° increments. For a given pair, the test chromaticity was modulated along the line connecting chromaticities of the two complementary colors, passing through the origin (gray), while the surrounding chromaticity was modulated along a half-line from gray to one of the two most saturated colors (the first of any given pair). The chromaticity modulation of any given test patch was also varied in 4 depths with respect to the origin: 0, ±0.50, ±0.75, ±1.00 (see Figures 3C and 3D). The surround modulation was fixed from 0.0 to +1.0 (gray to the first end).

The last 0.0 test modulation depth was included as a control condition that generated a flat, uniform, gray color (the origin). This provides a measure of the amount of opponent color induction generated by the surround for conditions in which color scission is not likely to occur.

**Experiment 2: Hue variations**

For the hue variations, the test varied in the same manner as those in the saturation condition in terms of the chromaticity pairs chosen and their modulation depth. In other words, the target region always varied between two opponent colors in saturation. However, the surround was varied between 8 hue pairs of two highly saturated colors taken from the hue circle separated by 90° in hue angle (for example, red–violet in Figure 3B). Eight hue pairs were used that differed 45° in hue angle (for instance, red–violet vs. magenta–cyan pairs). For a given test direction, say the red–bluish green test, the surround modulation varied along a red–violet hue line (i.e., a straight line connecting the red–violet hues).

The matching pattern that observers adjusted was uniform in color, placed on an achromatic random-dot background with the same mean luminance as the chromatic test displays (and matching pattern). The chromaticity of the match pattern was adjusted by means of a computer mouse, which allowed observers to search the entire 2D color space for a suitable match.

**Procedure**

On each trial, both the test and the match pattern moved along an elliptical orbit in their respective surrounds (i.e., the left and right halves of the display). Observers were instructed to move the mouse to adjust the color of the matching disk to the perceived color of the test disk on the left half of the display. The color of the match was linked to the 2D color circle used to create the stimuli by the position of the mouse; the motion of the test patch was included to simply make it easier for observers to keep track of where their adjustment was located (in angle) around the color circle. There were 64 different tests combining 2 conditions of saturation and hue, 8 chromaticity directions, and 6 modulation depths. Five sessions were run for each observer, each taking approximately 45 min.

**Results**

The observers’ settings for saturation and hue conditions were averaged separately and drawn in Figures 4 and 6, respectively. The data in the circular graphs (top two rows) are identical to corresponding bar graphs on the bottom two rows; they merely present the data in two
Figure 4. The matching chromaticities obtained from 5 observers in Experiment 1 (saturation surround modulation). The top and bottom halves of the figure present the same data in two different formats. The horizontal and vertical axes in the top two rows indicate chromaticity contrasts along the L/(L+M) and S/(L+M) axes of MacLeod and Boynton’s equiluminant diagram, respectively. The three large dotted circles indicate equidistance from the origin (D65), which are colored according to the chromaticity of the color space. The symbol “+” indicates the maximum chromaticity in the surround regions (top half of the figure), and the text along the horizontal axis indicates the verbal labels that describe the maximum and minimum chromaticities within the test. Observers’ settings are drawn as “o’s” in both the top and bottom figures for the four modulation depths of the test. In the bottom half of the figure, the pairs of bars in each inset show the 4 chromatic modulation depths used for the test (those crossing the middle horizontal axis) and the fixed modulation depth of the surround (i.e., the lines below the horizontal line). The symbol “x” is an estimated point of the induction from uniform center–surround stimulus by fitting a curve to the data by using a Least Squares method.
different formats. In the bottom bar graphs, the horizontal axis represents the chromaticity of the settings in the L / (L + M) cone responses, whereas the vertical axis represents the chromaticity of the settings in the S / (L + M) cone responses (normalized as described in the Methods section). The vertical bars in the bottom two rows represent the most saturated color physically present within the target test patch, and the four circles in these figures correspond to observers’ settings for each contrast depth of the target (i.e., for each amplitude of chromatic variation within the target). The same data are represented in the circular (MacLeod & Boynton) graphs on the top two rows. In these figures, the colors of the 4 open circles in each figure correspond to the colors of the observers’ settings, and the 3 large circles represent the most saturated color within the target for each of the 3 contrast depths tested. The symbol “+” marks the maximum chromaticities in the surrounds. Note that all of the observers’ matches are located on the opposite (complementary) side of the surround chromaticity, and that observers’ matches become increasingly desaturated as modulation depth of the test is decreased. For instance, when the surround’s chromaticities spanned the range from a saturated red to gray (the top left inset), and the test elements were between red and bluish green, matching colors were bluish green. This pattern holds for all 8 saturation conditions shown in Figure 4.

As the chromatic modulation depth of the test decreases, observers’ complementary matches also decrease in saturation. However, as the bottom half of Figure 4 shows, as the contrast modulation within the target decreases, the matching chromaticity chosen by observers deviate more substantially from the maximum saturation of the hue within the test region for all of the 8 conditions observed. The matching data for the test patterns with zero-contrast modulation (homogeneous gray) are all close to the origin, which suggests that the effect of color induction from the surround for the untextured target was minimal and, hence, cannot explain the deviations observed in the low contrast modulations.

In each column in this figure, the target chromaticities are identical, but the surround chromaticities are rotated 180° in hue angle (for both the two top and two bottom rows). For example, in the top two (or bottom two) insets of the first column, the surround modulation was on the opposite sides of the chromaticity diagram: red to gray for the top inset; bluish green to gray for the bottom. Although the test patches were identical, the matching chromaticities were those of the maximally saturated colors present in the target (or, at low target contrast, even more highly saturated colors) that were complementary to the chromaticity of the surround. This is a clear indication that, although two target regions are identical in chromaticity and geometry, the different patterns of chromaticity in the surrounds cause the circular targets to take on extremely different colors. This can be seen directly in the demonstrations in Figure 5.

The pattern of data with the hue modulation surrounds is similar to that observed with that of the saturation modulated surround. In all eight hue conditions, the test chromaticity was modulated along the saturation line passing through the origin, but the surround chromaticity was from one highly saturated point within the test region, to a second highly saturated point separated by 45 degrees from this color (indicated by the two “+” symbols in each inset in Figure 5, top half). The chromatic variation between these two colors varied along a straight line between these two colors in the chromaticity diagram. As with the saturation condition, the chromatic content of the target is identical for each column of Figure 6; only the surround chromaticity varies within a column. Thus, the very different settings observed in each pair of rows within a given column indicate that very different settings are being made for a target with an identical chromaticity content.

In general, the data are consistent with the idea that observers’ matches are determined by regions within the target that appear in plain view. These regions are those that generate the highest chromatic contrast border with the surround, i.e., are the least similar to the target along the target–surround boundary. For instance, consider the test that was modulated from red to bluish green, and a surround that was modulated from red to violet (the left column insets in Figure 6, and the left half of Figure 7). In this condition, the reddish elements within the target are similar to the reddish elements in the surround, which means the contrast of the boundary between the test and surround is low in these regions. In contradistinction, the bluish green elements within the target formed a high
Figure 6. The matching chromaticities in hue conditions obtained from 5 observers. Data are presented in the same format as Figure 4. (Top). The two "+" symbols indicate the two endpoints of the chromaticity modulation within the surround, and the text along the horizontal axis indicates the verbal labels that describe the maximum and minimum chromaticities within the test. Observers’ settings are drawn as "o"s" in both the top and bottom figures for the four modulation depths of the test. (Bottom). The pairs of bars in each inset show the 4 chromatic modulation depths used for the test (those crossing the middle horizontal axis) and the fixed modulation depth of the surround (i.e., the lines below the horizontal line). Color variations within the bars are the ones used in the stimuli. Observers’ settings are drawn as "o", according to the height of the vertical axis.
contrast boundary with the surround, which appears in plain view, i.e., devoid of any transparent media. All 8 conditions are consistent with this pattern (see Figure 6). Matching chromaticities also differed with test modulation depth. As the contrast depth of the test modulation decreases, perceived saturation of the test pattern also decreases. Interestingly, as was observed for the saturation conditions, when the depth modulation of the test decreases, the saturation of the matches exceeds the most saturated chromaticity within the target. Here, again, the magnitude of this overestimation grows with decreasing modulation depth, except for the singular zero-contrast test (i.e., the uniform gray test).

Although the hue and saturation matches are quite similar, there is one subtle difference in the pattern of matches that can be observed in Figures 4 and 6. The hue modulations in the surround were chosen so that one of the endpoints of the hue modulation intersected the chromaticity line of the saturation modulation within the target. For example, if the target varied from red to bluish green (the horizontal L–M axis), the hue modulation was varied from one of four hue combinations: red to violet; red to yellowish green; bluish green to yellowish green; or bluish green to violet. However, observers’ matches for these four conditions do not fall precisely on the horizontal L–M axis. Rather, observers’ settings are slightly rotated in the opposite direction to the rotation used to create the hue modulations in the surround, consistent with a small opponent color induction.

As in the saturation condition, the top and bottom inset conditions of each column in Figure 6 have the same test chromaticity distribution but different distributions of surround chromaticities. Given that the same general pattern of results was obtained for the hue and saturation conditions, it suggests that there is nothing privileged about opponent axes in inducing the color transformation observed in the targets in these displays. Rather, all that seems to be required is the presence of a consistent difference in the strength of chromatic contrast between the colors within the test and the colors within the surround, i.e., a variation in the similarity between the surround and one end of the chromatic modulation within the target. To see this, consider a test region that varies between red and bluish green (an opponent axis), which is embedded in either a surround that varies from red to violet, or in a surround that varies from bluish green to yellowish green (Figure 7). In the red to violet surround, the target appears bluish green; for the bluish green to yellow surround, the target appears red. Note that in the red to violet surround, the border between the red regions within the disk and the surround are low contrast, which allows the red components within the target to group with the red components within the surround. In contradistinction, the bluish-green regions within the target region produce a very strong contrast between the target region and the surround and appear as portions of the disk in plain view. These percepts can be experienced directly in Figure 7 and are most compelling when animated (as in our experiments). The fact that the same general perceptual organization occurs for both the hue and saturation modulations suggests that these percepts depend only on the chromatic distance (contrast) between the colors within the test and surround, and not on the particular axis chosen for the surround colors.

**Discussion**

The data from both experiments are consistent with a general principle of perceptual organization in which the color within the target that is most dissimilar from the surround—i.e., generates the largest chromatic contrast with the surround—determines the perceived color of the target. This is consistent with what has been observed with achromatic versions of these displays. It has been hypothesized (Anderson, 1999, 2003) that the visual system uses the highest contrast contour segments in displays like these as “transmittance anchors,” which are seen in plain view (i.e., assigned a transmittance of 1). This predicts that the color (or lightness) of a surface should match the perceived color of the surface in plain view (as assessed with a matching paradigm such as that employed herein). Although this principle provides a good account of the perceived color of the target disk, there are two issues that arise in considering its applicability to the displays presented herein, as well as to those presented previously (Anderson & Winawer, 2005, 2008). First, the TAP only predicts the perceived color of the target region when the
A target appears behind the transparent layer. Although this is one of the possible organizations that can be experienced with these patterns, it is not the only one possible, particularly as the contrast of the target region is varied. Indeed, if the contrast of the target region is sufficiently lower than the surround, the target region will eventually appear in front as a transparent disk (see Figure 8). Second, there is a smaller but statistically reliable deviation in observers’ matches from the maximal saturation value within the target region (i.e., the matches predicted by the TAP), which is most pronounced when the contrast modulation within the target becomes small relative to the surround. This does not appear to be something that can be attributed to the adaptation level induced by the surround, since the zero-contrast target exhibited very little or no induction. The failure to observe an induction effect with the zero-contrast target would also appear to rule out a “gamut expansion” explanation. It has been suggested that the visual system expands the range of perceived chromatic contrasts in conditions of low chromatic variance (Brown & MacLeod, 1997). The zero-contrast target display had the smallest range of chromatic variability of all of our displays tested (zero) but exhibited very little chromatic induction relative to the low contrast displays that evoked percepts of transparency. Thus, it seems that the relative enhancement of the saturation of the target (relative to that of the most saturated color within the target region) cannot be understood as a form of gamut expansion. Rather, the overestimation of the target’s saturation is linked to conditions in which the target undergoes scission and increases as the target region’s contrast decreases (relative to the fixed contrast in the surround). In the next section, we consider how this pattern of overestimation may be related to the particular way in which the target’s decomposition varies as a function of contrast.

**Figure 8.** When the contrast of the target region is significantly lower than the contrast within the surround, the central target appears in front of the cloud texture as a transparent disk. This occurs for both (top) achromatic textures and (bottom) chromatic textures.

### Relative depth, scission, and perceived color

In order to understand the pattern of overestimation of the target’s saturation, we need to consider the TAP, which underlies the prediction that the most saturated color that forms a high contrast boundary with the surround should appear in plain view. The initial formulation of this principle was developed in the context of stereoscopic variants of these textures embedded in homogeneous surrounds (Anderson, 1999, 2003). In these conditions, all of the relevant contrast variations occurred along the boundary separating the target from the surround. However, by introducing texture into the surrounds, we created generalized non-reversing X-junctions (i.e., X-junctions that preserve contrast polarity along both contours). In these stimuli, only one sharp contour was present; the other “contour” was generated by the luminance gradients within the cloud pattern (and defines the sense in which it is a “generalized” X-junction; Anderson, 1999, 2003). Non-reversing X-junctions have an ambiguous depth order, which can either alternate successively over time or can cause both components to appear transparent simultaneously. Theoretically, this ambiguity should be maximal when the contrast variations in both directions are approximately balanced. This makes intuitive sense: in the limit where one contour undergoes a very large change in contrast such that one segment of the X-junction approaches zero contrast, the stimulus approximates a T-junction, which provides geometric evidence for an occlusion relationship. Such conditions should be the least ambiguous. When both “contours” forming the X-junction undergo equal amounts of contrast change, either of the two lower contrast segments is consistent with a transparent overlay, and hence, both surfaces can be decomposed into layers.

In our cloud patterns, the ambiguity of X-junctions predicts that the target region should appear unambiguously behind for high contrast depth targets, have an
ambiguous ordering (and opacity) for intermediate values of target contrast depth, and eventually appear predominantly in front of the surround (as a transparent disk) for low values of target contrast depth. In other words, as the contrast within the target disk decreases, the likelihood of the target disk appearing transparent increases. If the target region appears as a uniform transparent layer, then no regions within the disk would appear in plain view. Rather, even the most saturated opponent color would be decomposed into a combination of two layers. Consider the low contrast version of our saturation stimulus (see Figure 8). If the target disk was scissed into a transparent layer overlying the surround colors, the saturation of the target should be increased in the opposite direction to the chromaticity in the surround. This predicts that observers should select matches that are more saturated than the most saturated complementary color present in the stimulus, which is consistent with the pattern of matches we obtained.

A similar analysis can explain the pattern of responses obtained with the hue variations of our stimuli. In this experiment, observers chose matches that were more saturated than the strongest complementary color within the target (relative to the surround) and exhibited an opponent repulsion from the most dissimilar surround hue. Note that the data do not fall along the lines radiating from the achromatic center through the colors present in the target. Rather, the data are rotated away from the direction of the hue modulations within the surround. Thus, the data exhibit an opponent induction to both endpoints of the chromatic variance within the surround. The fact that essentially no such induction was observed for the homogeneous target suggests that this is not simply a consequence of some low-level adaptation mechanisms. However, if the target disk is decomposed into a transparent layer overlying the surround colors, the saturation of the target should be increased in the opposite direction of the chromatic variance within the surround. For these hue variations, this predicts that observers should select matches that are shifted in the complementary directions of the chromatic variations within the surround, which is consistent with the pattern of matches we obtained.

**Hue–hue variations**

For the experiments reported above, the target regions were identical in both the hue and the saturation variants of the cloud display. The “hue” manipulation performed in Experiment 2 was restricted to the surround. However, strong forms of color scission can be experienced in images in which both the center and surround vary between two hues. Demonstrations of these effects are presented in Figure 9. In Figure 9A, two hues that are separated by 90 degrees in color space were chosen. The target region’s chromaticity spanned the full 90 degrees, and intermediate hues fell along a straight line between these two extreme values in the MB color space. The hue variations within the surround were restricted to one of the two halves along this line in color space. In these conditions, vivid percepts of chromatic scission are experienced. Interestingly, however, no percept of coherent scission is observed if the targets are allowed to span the full hue circle along its perimeter, and the surrounds are restricted to just one half of the hue perimeter (Figure 9C). The significance of this failure to observe scission in these conditions is discussed below.

**Chromatic polarity constraints and transmittance anchoring**

There have been two main constraints that have been hypothesized to determine the appearance of our achromatic cloud images: a polarity constraint and transmittance anchoring. The polarity constraint arises from the fact that transparent surfaces cannot reverse the polarity of contours that they overlie. Transmittance anchoring is needed to specify surfaces perceived in plain view and to serve as a normalizing constant to scale the opacity of any inferred transparent surface. One of our main goals of the present work is to determine whether analogous constraints underlie the decomposition of the cloud patterns generated by purely chromatic textures. Anderson and Winawer (2008) showed that the perception of transparency is abolished in achromatic displays if thin gray rings are placed along the target/surround contour. It was argued that these rings destroyed the percept of transparency because they introduce polarity reversals along the contour separating the target and the surround. This argument was supported with demonstrations showing that the percept of layers was maintained as long as the targets were surrounded by rings that preserved the direction of contrast between the target and the surround.

If similar constraints are critical in determining the conditions for scission along chromatic axes in color space, the percept of layers should be disrupted with thin rings that have a chromaticity that falls between the colors within the target region. Such rings would introduce the equivalence of a polarity change along a chromatic axis. For example, if the target varied in saturation between “red” and “green” (i.e., along the L–M axis in the MacLeod–Boynton color space), then a mid-gray ring would introduce chromatic polarity reversals between the target and the two surrounds (the gray–green surround or the gray–red surrounds). As can be seen in Figure 10 (targets initially on the right half of each panel), the percept of layers is disrupted by this manipulation. In contrast, if a red ring is placed around the target on the red surround, or a green ring is placed around the target on the green surround, a clear sense of scission occurs: the colored ring now simply appears as part of the target (Figure 10, targets initially on the left half of each panel). A similar result occurs for the 1D hue variants of the cloud pattern (i.e., the patterns formed by varying the colors within the target along a straight line between two colors on the perimeter of the color circle). Here, again, if
the ring is given a color that falls between the maximal hues used as the endpoints of the target, the percept of layers is disrupted (Figure 11, targets initially on the right half of each panel). However, if the rings are colored so that the chromatic variance between the target and surround has the same direction (i.e., the same “sign”), then a clear percept of layers is obtained (Figure 11, targets initially on the left half of each panel).

The second key constraint that has been hypothesized to determine how and when transparency occurs in achromatic displays is the TAP. It was originally discussed in the context of displays that were generalized stereoscopic T-junctions (i.e., the termination of a gradient into a Figure 9).

Figure 10. Demonstration of the importance of chromatic contrast polarity on the clarity of scission. For the two targets that appear initially on the right side of each panel, the target disks are surrounded by thin gray rings, which cause chromatic polarity reversals to occur along the target–ring boundaries. This disrupts the perception of scission. When rings are chosen such that they preserve the chromatic contrast relationships between the targets and their surrounds (the targets that appear initially on the left in the two panels), clear scission is experienced, and the rings merely appear as portions of the target (green rings surrounding a magenta disk on the left, and a magenta ring surrounding a green disk on the right.)
contour). It was subsequently applied to the achromatic variants of the cloud pattern presented herein (Anderson & Winawer, 2005, 2008), which produce generalized X-junctions. However, the cloud pattern generates non-reversing X-junctions, which are ambiguous and/or bistable in terms of depth ordering and transparency. We begin by considering the case in which the chromatic contrast within the target is unambiguously higher than the surround, and then turn to the condition where the target is lower contrast than the surround.

For the conditions in which the chromatic contrast within the target region is high, and the surround is restricted to lie on one side of the chromatic variance within the target along a 1D (straight) path through color space (which includes one of the extreme values within the target), the region within the target that formed the highest contrast with the surround appears in plain view and (largely) determines the perceived color of the opaque, underlying disk (apart from the small deviations in chromatic matches noted above). In these conditions, the chromatic variance with the transparent “clouds” overlying the target appear to arise from a variation in opacity, not in color, similar to what is observed in the achromatic domain. This is true for both the saturation and hue variants of the display (Figures 5 and 7, respectively). For example, in the green–red target on the green–gray surround, the disk appears red overlaid by saturated green clouds that vary in opacity; the clouds do not appear as a mixture of desaturated red, gray, and green. In these images, the targets appear to be decomposed into two saturated colors (here, red and green); the values in between these two extremes are experienced as a weighted combination of these two colors, mixed in different proportions, and arising from different layers. The “mixing” is not in terms of a variation in saturation (or in hue), but rather, the proportion to which the two saturated colored layers contribute to the chromaticity at a given image point. This observation holds true for any straight trajectory that we have tested in color space, and it not restricted to opponent or cardinal axes.

Interestingly, no similar decomposition occurs with these patterns if the hue of the target spans the full 2D hue space and the surround is restricted to half of the space (Figure 9C). In these conditions, it is not possible to decompose the texture into just two chromatic components, one of which varies in opacity, which appears to be critical for eliciting scission in these types of textures. Thus, although it is possible to generate chromatic analogues of the lightness effects we observed in achromatic cloud patterns, such analogues only arise when the chromatic variations within the textures is restricted to a linear 1D path through color space, similar to the 1D variation present in the achromatic versions of these displays. In these conditions, the chromatic variations within the cloud texture can be decomposed into two (saturated) components, which is not possible if more than two saturated hues are used to define the target texture. For example, if the colors within the target and surround are chosen to follow the perimeter of the hue circle, but are restricted to some subspace (say, 180 and 90 degrees for the target and surround, respectively), a layered percept may still occur, but the transparent layer will appear to vary in chromaticity, not just transmittance (Figure 9B).

Relationship to previous work

There have been a variety of experiments and theoretical studies into the perception of chromatic transparency, although their application to the present work is not straightforward. For example, D’Zmura et al. (1997) proposed a convergence model of chromatic transparency. In this model, D’Zmura et al. argued that chromatic transparency only arose when the chromatic variance within a surround “converged” toward a common point. The intuition shaping this model is that the color of a transparent filter should shift all colors it overlies toward the color of the filter. In the limit where the filter is nearly opaque, all overlaid colors will be very close to the filter color. Note, however, that in the displays considered in this model, the chromatic variance within the target must be less than or equal to (in the limiting case of translations) the
chromatic variance of the surround. In our cloud displays, our “target” region was not synonymous with the region of transparency; the transparent clouds experienced in these displays extend over both our “targets” and our “surrounds.” Indeed, for our high contrast depth targets, the contrast within the target substantially exceeds that of the surround, forming a region of divergence, not a region of convergence. It is unclear how to apply the convergence model to images in which the transparent region does not form a closed boundary that defines the target region. In our images, the transparent layer extends over both the “target” and the “surround.” Nonetheless, it should be noted that the convergence model implicitly assumes an anchoring rule, just as Metelli’s (and all subsequent models) have assumed in lightness. This anchoring rule is needed to define a region in plain view, from which tests of “convergence” can be assessed.

There have also been a number of studies that have attempted to quantitatively distinguish different models of chromatic transparency. Probably the most extensive attempt to assess different models of chromatic transparency was presented by Faul and Ekroll (2002), who proposed a “scaling” model of perceived transparency. The scaling model can be considered a simplified version of a filter (or “subtractive”) model of transparency, rather than the additive model proposed by chromatic generalizations of Metelli’s episcotister model (such as D’Zmura’s convergence model). Faul and Ekroll (2002) provided compelling evidence in favor of their scaling (or “subtractive”) model of chromatic transparency. The data and phenomena that we report do not provide the basis for discriminating between the models investigated in these papers. However, as with D’Zmura’s model, the scaling model proposed by Faul and Ekroll (2002) also embodies an implicit anchoring rule, although none of their data directly address its role in the perception of chromatic transparency.

Finally, it should be noted that all of the experiments described herein utilized moving images to assess the perception of chromatic transparency. Gerardin, Roud, Süsstrunk, and Knoblauch (2006) recently showed that motion can cause otherwise non-transparent surfaces to appear transparent, which suggests that the use of motion in our displays could have introduced a confound in assessing the conditions of perceiving transparency in static displays. However, as can be seen directly by viewing both the static and moving versions of our displays, motion never caused a non-transparent display to appear transparent in our stimuli; it merely facilitated the judgment of the color of the target disk. We therefore do not believe that the motion per se introduced any significant artifact into the data we presented.

## Summary and conclusions

In this paper, we presented experiments and demonstrations that explore whether there are common principles that predict when scission occurs in chromatic and achromatic textures, and how surface properties are assigned to the different layers when scission occurs. Our key findings can be summarized as follows.

First, we found that no clear percept of scission occurs in cloud textures when the full 2D color space is used to construct the target. This contrasts with previous work from our laboratory (Wollschläger & Anderson, 2009) that employed uncorrelated noise textures. The spatial correlations of the chromatic variations within the cloud texture appear to increase the likelihood that the visual system treats them as intrinsic surface color changes. One plausible explanation of the failure of such patterns to induce scission involves the pattern of chromatic contrast along the target–surround border. When the full 2D space of colors is used for the target, there are a large number of high contrast contour segments along the target boundary that vary in their chromaticity. Thus, it is not possible to discern a single “highest contrast” contour segment to which the TAP would apply. However, vivid scission is experienced when the chromatic variations with the target and surround are restricted to a “straight” 1D path through color space. In these conditions, the contrast segments along the target boundary all have the same chromatic direction. One of two possible percepts can arise in these conditions. When the chromatic contrast within the target region is significantly lower than the surround, the target can appear as a transparent disk in front of a cloudy texture. For targets that contain high chromatic contrast relative to the surround, the target disk appears as a homogeneous disk behind clouds that vary in transmittance, and the chromatic variations in the target were experienced as a combination of the two most saturated colors within the target.

Second, we found further evidence that similar sign or “polarity” constraints must be satisfied for scission to occur in both chromatic and achromatic variants of these phenomena. The percept of scission is disrupted by surrounding the targets with rings that have an intermediate chromaticity to the colors within the target. Rings that preserved the direction of contrast between the targets and their surrounds did not disrupt scission. This suggests that the same type of polarity constraints underlie the decomposition of both achromatic and chromatic transparencies.

Third, we found that the perceived transmittance of the transparent layers is anchored by the highest contrast present along the target–surround boundary. When the target region is high contrast, the region along the target–surround border with the highest contrast appears in plain view and defines the color of the target (as well as the surround, although this was not measured). Regions of lower chromatic contrast appear multi-layered. The opacity of the transparent surface is determined by the amount of contrast change: large reductions in contrast correspond to a large decrease in the transmittance of the transparent layer (i.e., the cloud appears “thickest” when the contrast with
the surround is lowest). When the target region is low
contrast, it can appear in front of the textured surround and
background as a uniformly colored transparent disk. In
such contexts, the TAP now applies to the surround, which
is predicted to be in plain view.

Fourth, we found that when the chromatic contents of
the target and surround were restricted to a 1D path in color
space, and the conditions for scission were met, the
chromatic variance within the target was experienced as
two highly saturated colors that varied in density, not
saturation or hue.

In conclusion, we have shown that similar principles of
image decomposition give rise to the transformations in
perceived lightness and color observed with both the
achromatic and chromatic variants of our “cloud” displays.
The scission observed in these displays requires a consis-
tent contrast polarity relationship (in either luminance or
chromaticity direction) between the target region and the
surround. When such conditions hold, the highest contrast
contour segment appears in plain view and the reductions
in contrast appear as variations in the opacity of the
overlying transparent layer.

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