Perception of Color Change

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Abstract: This article reviews recent work on the perception of color in cases where color change leads to scission, or a perceived layering in depth of the visual field into chromatic processes. A model is proposed that predicts under what circumstances a layering in depth is perceived. The model takes into account shift in color and change in contrast; it helps to describe the colors and lightnesses of surfaces seen through a transparent filter or through fog. © 2000 John Wiley & Sons, Inc. Col Res Appl, 26, S186–S191, 2001

Key words: color; lightness; constancy; transparency; fog; scission

INTRODUCTION

Change in the conditions under which object surfaces are viewed leads to change in surface-color appearance. Yet color typically changes less than what one would expect on purely colorimetric grounds. This stability of surface-color appearance is called color constancy and has most frequently been studied in one physical situation, namely that in which the chromatic properties of a light source are changed. Yet there are many ways in which viewing conditions may be changed. This article concerns itself with those that lead to *scission*. The term scission refers to a perceived layering in depth of the visual field into chromatic processes. The layers generally include opaque surfaces, which are seen to lie farther away from the viewer, and intervening chromatic processes like illumination, transparency, and fog, which are seen to lie closer.[1,2]

Perhaps the clearest case of scission involves the perception of a transparent filter that lies atop a set of surfaces. The conditions under which one perceives such a filter have been studied by Metelli,[3] Beck,[4] and Gerbino and colleagues[5] in the case of achromatic stimuli. Metelli devised a model based on a physical device called an episcotister to account for his observations. His model involves mixing the luminance properties of overlying and underlying layers. Da Pos[6] extended Metelli's model to the three dimensions of color, substituting tristimulus values for luminances. More recently, Faul[7] and our group have tested and extended this model.

This article reviews work on the perception of color change in cases of transparency and fog. We discuss first the changes in color that lead one to perceive transparency and present a model, called the *convergence model*, that fits observational data.[8] Results of experiments that use a simple display with four colored regions verify predictions of the convergence model concerning which color combinations appear transparent.[9] We then turn to the results of asymmetric color-matching experiments on the appearance of surfaces seen to lie behind a transparent filter. The results show that the color appearance of such surfaces is described by the convergence model.[10] That the convergence model describes the color appearance of surfaces in cases of scission, more generally, is argued in the last section, wherein are described results of experiments with fog.[11]

CONVERGENCE MODEL

A photograph of a dark yellow transparent filter that lies atop colored pieces of paper is shown in Fig. 1 at the left. The filter occupies a rectangular area near the center of the image. Light from a surface that lies along the edge of the filter, like the red surface at left center, changes as the surface passes from plain view to under the filter. If the lights from all the surfaces along the edge of the filter underwent random change, then it is unlikely that a transparent filter would be perceived. Transparency perception relies on a *coherent* color change that transforms all surfaces along a filter's edge in a similar fashion. In the case of the filter shown in Fig. 1, lights from surfaces become

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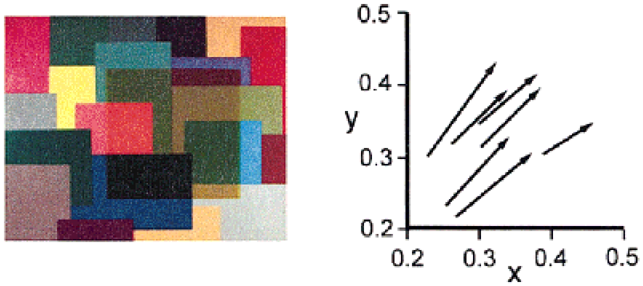

FIG. 1. Chromatic shift or translation. The seven surfaces along the border of a dark yellow transparent filter (left) are each represented by a vector in the CIE 1931 (x,y) chromaticity plane (right). The vector field describes the effect of the filter on the surfaces. The base of each vector corresponds to the chromaticity of the light from the surface when seen in plain view, while the head of each vector corresponds to the chromaticity when the surface is viewed through the filter. The vectors are approximately parallel and of the same length. This diagram of the vector field in the chromaticity plane omits important luminance information. Better would be a plot that shows simultaneously the three dimensions of chromatic change in a space of tristimulus values.

darker and yellower as the surfaces pass under the edge of the filter.

We can represent the color change undergone by a surface using a vector in color space. For instance, the chromaticity of the red surface when seen in plain view can be represented by the base of a vector, while its chromaticity when seen through the filter can be represented by the arrowhead of the vector. Figure 1 shows on the right the vector field in the chromaticity plane that represents the color change caused by the filter. To a good approximation, all the vectors point in the same direction and have the same length; the vector field is approximated well by a simple shift or translation.

Shifts in color space can evidently describe coherent color changes of the sort required for transparency perception. Change in contrast also works. Figure 2 shows a color display with a central square region that appears cloudy yet transparent. The vector field at the right shows that the filter causes lights to converge toward a central gray. The amount of convergence, which represents a reduction in contrast toward the central gray, determines filter cloudiness. We also investigated rotations and shears in color space.[8] When

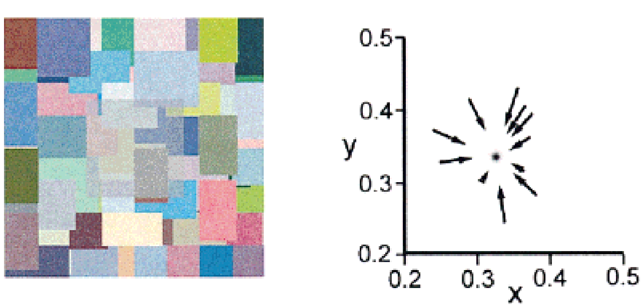

FIG. 2. Change in contrast can lead to transparency perception.

FIG. 3. Transparency with a red, equiluminant color shift.

vector fields that describe rotations or shears are used to define the chromatic transformation of a filter, no coherent percept of a transparent filter is obtained.

A convergence model accounts for these observations. The model incorporates chromatic shift and change in contrast. The model follows on the work of Da Pos[6] and extends Metelli's[3] model to the three dimensions of color. Suppose that the chromatic properties of the light from an unobscured surface are represented by a three-dimensional vector of tristimulus values **a**, and that the target of convergence is represented by a vector **s**. Then the light from the surface is shifted from **a** to **s** by some amount α to give the vector of tristimulus values **b** of the light from the surface when seen through a transparent overlay:

$$\mathbf{b} = (1 - \alpha)\mathbf{a} + \alpha\mathbf{s}. \tag{1a}$$

The parameter α determines the extent to which contrast is reduced toward the target of convergence **s**. If the target of convergence is located at an infinite distance, then the convergence degenerates to a simple, parallel shift. In an equivalent formulation, one can set the parameter β equal to $1-\alpha$ and create the translation **t** from the product $\alpha\mathbf{s}$:

$$\mathbf{b} = \beta\mathbf{a} + \mathbf{t}. \tag{1b}$$

This model differs from earlier models of transparency in that it is specified in terms of the chromatic stimulus, rather than in terms of a particular physical implementation of transparency, like a physically translucent filter or an episcotister. The convergence model predicts that transparency can be perceived in certain situations that cannot be realized by the earlier, physical implementations. In particular, it is impossible for a physically translucent filter, which subtracts light, or for an episcotister, which subtracts and adds light in a surface-independent fashion, to generate identical equiluminant color shifts for a variety of underlying surfaces. There is no natural way in which equiluminant color shifts can be generated. Yet the present model predicts that an equiluminant color shift can lead to transparency perception.

We tested whether equiluminant color shifts, like that pictured in Fig. 3, lead to transparency perception.[8] Observers matched the saliency of transparency perception for

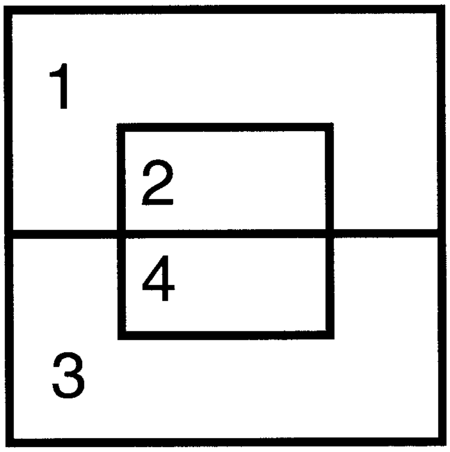

FIG. 4. Stimulus spatial configuration. The chromatic properties of areas 1, 2, and 3 were set by the experimenter. The task of the observers was to set the color of area 4 so that the central square formed of areas 2 and 4 appeared transparent.

equiluminant color shifts to the saliency of transparency perception for standard achromatic shifts, like those found with neutral density filters. The comparison of transparency perception with equiluminant stimuli and with standard achromatic filters showed clearly that equiluminant color shifts lead to transparency perception. Evidently, the study of transparency perception must be based on results concerning perception, rather than on physical implementations of transparency.

LOCI OF TRANSPARENCY

In a second study, we performed experiments to see how well the convergence model describes loci of transparency in color space.[9] The model predicts that, if one is to perceive transparency in a simple display with four colored regions, then the chromatic properties of a fourth region must be chosen from a locus in color space that is determined by the colors of the other three regions. Experimental results bear out the prediction.

We used a display like that shown in Fig. 4. The chromatic properties of the areas marked 1, 2, and 3 were set by the experimenter. The observer's task was to adjust the chromatic properties of area 4 so that the central square would appear transparent. The convergence model predicts that transparency settings lie along a line segment in color space that joins two points, which depend on the chromatic properties of areas 1, 2, and 3. As depicted in Fig. 5, the two points represent filters that are completely opaque [$\beta = 0$ in Eq. (1b)] and filters that are completely clear or unclouded ($\beta = 1$), respectively.

Three observers made ten settings for each of 24 conditions, each of which was determined by a choice of chromatic properties for areas 1, 2, and 3. Eight conditions apiece were chosen from the plane spanned by the LM and S axes, by the plane spanned by the A and LM axes, and by the plane spanned by the A and S axes.

Results show that observers' settings lie pleasingly along the predicted loci.[9] The results showed several further features. First, deviations of observers' settings from the predicted loci quite understandably depend on color discriminability in the region of the predicted locus; Faul[7] has investigated these issues in some detail. Second, observers avoided settings, along the predicted loci, that would grant to the top and bottom halves of the central square (areas 3 and 4) complementary hues, a finding that is related to a result first reported by Da Pos.[6] Finally, observers avoided certain settings that caused the display to take on a three-dimensional folded-card appearance, with the central edge projecting either towards or away from the viewer.

TRANSPARENCY AND COLOR APPEARANCE

We turned next to the question of whether the convergence model can be used to describe the colors and lightnesses of surfaces seen through transparent filters.[10] Does the visual system interpret the chromatic effects of a transparent filter in terms of a convergence in color space?

To answer this question, we employed an asymmetric color-matching paradigm.[12] In computer-graphic simulation, observers adjusted the color of a surface seen behind a transparent filter in order to match the color of a surface seen in plain view. As shown in Fig. 6, a transparent filter was placed atop a 7×7 array of colored squares. The central square, under the filter, served as the test square. The square located two squares above the central square served as the reference square. The task of the observers was to match the color of the reference square by adjusting test square color.

Three observers made asymmetric matches for each of 24 different filters with targets of convergence in the equiluminant plane. For each filter, observers made asymmetric matches to 17 equiluminant reference colors. Two observers made further matches for filters and reference colors that

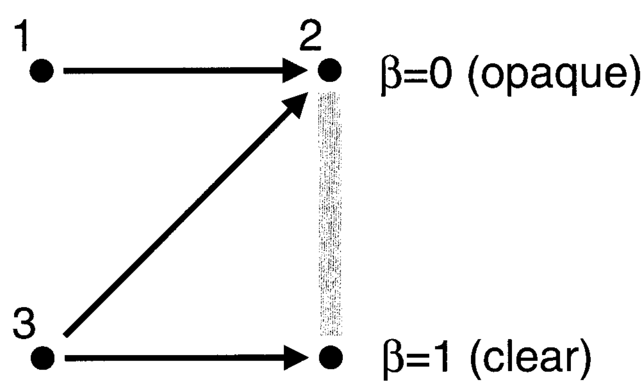

FIG. 5. Prediction of the convergence model: transparency settings lie along a line segment in color space that joins opaque and clear extremes. The chromatic properties of areas 1, 2, and 3 are indicated by points in color space. The predicted locus of transparency is shown by the gray line segment, which runs between (opaque) point 2 and (clear) a point that corresponds to a parallel translation.

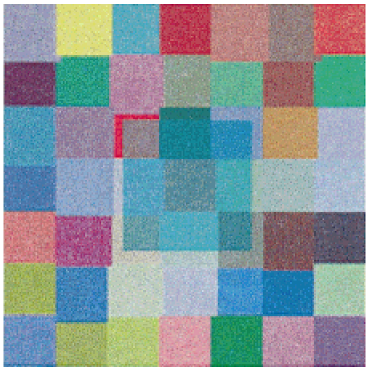

FIG. 6. Stimulus used in transparency experiments with an asymmetric matching paradigm. The simulated filter drifted from left to right and back again at constant speed with a 1-Hz rate of oscillation. The central square in the 7 × 7 array of squares was of size 2.3 × 2.3 square degrees, on average, and served as the test square. Observers adjusted the color of the test square to match that of the reference square, located two squares above in the central column and in the second row. The central test square was always covered by the filter.

varied in both lightness and color; 15 reference colors were matched for each of 18 different filters.

Sample results are shown in Fig. 7. The reference colors are shown by the filled circles and are arrayed about the central gray point of the equiluminant plane. Color matches for a single observer are shown by the open circles. These settings are in one-to-one correspondence with the reference colors. The settings are located in the blue-green half of the equiluminant plane, just like the blue-green target of convergence of the filter used in this experimental condition, marked by the ×. There is some irregularity associated with the settings; single settings are shown, not average settings found from repeated trials. Nevertheless, it should be clear that one can fit the data well by, first, reducing the contrast of the reference colors, so that they are shrunk toward the central gray point, and second, shifting the resulting colors an appropriate distance in the −LM (blue-green) direction.

We fit five models to the data from the 42 conditions, including affine, convergence, linear, translation, and von Kries[14] scaling models. The affine model is described by the equation

$$\mathbf{b} = \mathbf{M}\mathbf{a} + \mathbf{t}, \tag{2}$$

in which $\mathbf{a}$ is a vector of reference color coordinates, $\mathbf{M}$ is a 3 × 3 matrix that describes a linear transformation, $\mathbf{t}$ is a translation vector, and $\mathbf{b}$ is a predicted vector of test color coordinates. When fitting the model to data, one finds the entries of the matrix $\mathbf{M}$ and of the vector $\mathbf{t}$ that minimize the root-mean-squared error between model predictions and actual settings.

The convergence model [Eq. (1b)] is a special case of the affine model and has only four parameters. The linear model is also a special case of the affine model and is formulated by removing the translation $\mathbf{t}$ from Eq. (2). Likewise, the translation model is a special case and removes the linear transformation $\mathbf{M}$ from Eq. (2), but retains the translation $\mathbf{t}$. The von Kries scaling model, finally, can be expressed by the equation

$$\mathbf{b}' = \mathbf{D}\mathbf{a}', \tag{3}$$

in which $\mathbf{a}'$ is a vector of reference color L-, M-, and S-cone excitations, and $\mathbf{D}$ is a diagonal matrix that scales the cone excitations to produce the model predictions $\mathbf{b}'$.

Model fits show that the convergence model fits the data nearly as well as the affine model, despite the fact that the affine model has 12 parameters and the convergence model has only four. The linear, translation, and scaling models performed significantly less well, especially in experimental conditions where a cloudy filter was used. Both the contrast reduction parameter β and the color shift $\mathbf{t}$ in Eq. (1b) are required to fit matching data found with transparent filters.

The fits provided by the convergence model offer a way to estimate the degree of color constancy exhibited by observers in these tasks. We correlated the contrast reduction parameters β found by fitting data to the actual, physical, contrast reduction parameters associated with the filters used in the experiments. The correlation coefficients were

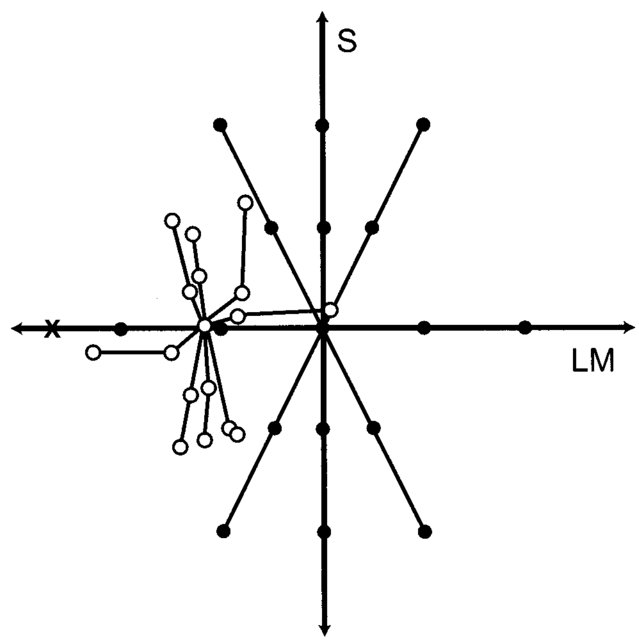

FIG. 7. Single asymmetric color-matching settings (open symbols) shown for a single observer in the equiluminant plane. The blue-green filter shown in Fig. 6 was used, with parameter $\alpha = 0.5$ and target of convergence shown by the ×. 17 reference colors are indicated by the filled circles. The central point in the equiluminant plane corresponds to a neutral gray. Lights along the LM axis[13] vary in L- and M-cone excitation,[14] but neither in luminance nor in S-cone excitation. The positive, right end of the LM axis corresponds to "red"; the other end corresponds to "blue-green." Lights along the S axis vary in S-cone excitation, but neither in L- nor in M-cone excitation. The positive, upper end of the S axis corresponds to "yellow-green"; the other end corresponds to "purple." One can fit the settings by reducing the contrast of the reference colors and then shifting them in the −LM (blue-green) direction.

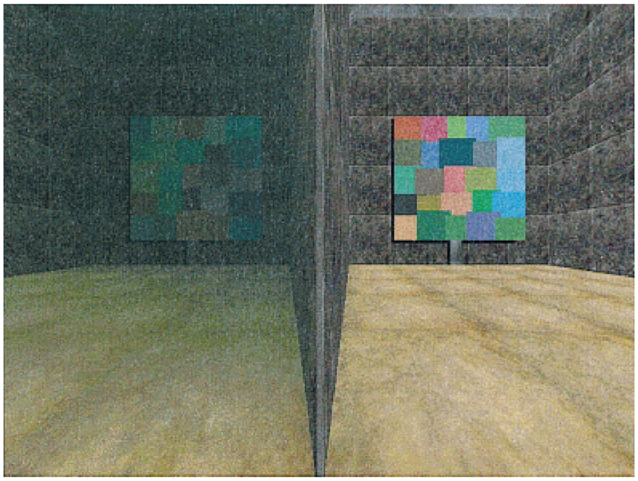

FIG. 8. Sample stimulus used in asymmetric matching study of the colors of surfaces seen through fog. The fog target of convergence lies along the positive, "yellow-green" end of the S axis in this figure. Observers adjust the chromatic properties of the test square in the center of the 5 × 5 array of colored squares on the left (yellow-green fog) so that it appears to have the same surface color as that of the reference square, located in the center of the array on the right (no fog).

uniformly high. The slopes of the best-fit lines ranged from 0.44–0.69. These figures suggest that observers discount filter contrast reduction, but underestimate true contrast reduction by a factor of nearly two. That humans discount contrast reduction when judging surface color was first pointed out by Brown and MacLeod.[16]

We also correlated the lengths of the translation vectors found by fitting data with the convergence model to the actual translations associated with the filters used. The correlations were significant, with one exception, and the slopes of the best-fit lines ranged from 0.38–0.56. Just as is the case for contrast reduction, observers underestimate filter color shift by a factor of about two.

FOG

The chromatic changes caused by fog are similar formally to those caused by the interposition of a transparent filter. In the case of fog, light reflected from a surface is added to light scattered by intervening particles, and the combination is described by the convergence model of Eq. (1).[11]

The spatial properties of fog differ from those of a transparent filter; there need be no sharp edges (see Fig. 8). Rather, the effects of fog on light from a surface increase smoothly as a function of the length of the path through the fog from the viewer to the surface. The question thus arises: can human observers discount the effects of spatially smooth chromatic processes? Because scission between surfaces and fog is readily perceived, one guesses that, yes, one can discount fog properties when estimating surface color properties.

Experimental results show that this guess is correct.[11] In computer graphic simulation, we varied fog color, fog intensity, and test placard position in depth. Five fog colors (gray, red, blue-green, purple, yellow-green), two levels of fog intensity (half and full), and two levels of placard position (near and far) were varied factorially to provide a total of 20 conditions. The placard in the fogless reference condition was placed in the far position, as shown in Fig. 8.

The data in the fog experiments strongly resemble those in the transparency experiments (e.g., Fig. 7). We found, again, that the convergence model fit the data nearly as well as the more complex affine model, and that both of these fit the data substantially better than linear translation or von Kries scaling models. Comparing results found with different amounts of fog (e.g., there is less fog when the test placard is in the near position or when the fog is at half intensity) shows clearly that contrast reduction plays an important role in fitting experimental data. Correlating convergence model parameters found by fitting observers' data to the physical properties of the simulated fog shows, finally, that observers are strikingly good at discounting contrast reduction associated with fog. The majority of observers in these experiments discounted fully 100% of the contrast reduction associated with fog.

CONCLUSIONS

Color constancy operates in many situations other than change of illumination. Appropriate change in color across space can give rise to scission or layering of color processes in depth. When scission is apparent, we can discount both shift in color and change in contrast caused by an intervening color process. Experimental results show that the convergence model, which takes into account shifts in color and changes in contrast, describes color constancy in cases where color processes are perceived to be layered in depth.

Our ability to perceive transparency when equiluminant color shifts are used, alluded to earlier, shows that one must not be misled by physical models of chromatic change when studying color perception. The study of color constancy, in particular, has long been conducted under the shadow of a single physical model—change in the spectral properties of illumination. Yet a physical model cannot provide a strong and direct basis for fundamental research on visual perception. We argue that the perceived scission of the visual field into various chromatic processes is far more important to understanding surface color perception. Scission underlies our ability to perceive coloration in light sources, to perceive transparent filters, and to see surfaces through fog. Our understanding of color vision will benefit by focusing on perceptual phenomena, like scission, in addition to physical models.

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