

Accuracy of color scission for spectral transparencies

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When surfaces are overlaid by a transparent filter, color scission refers to the perceptual separation of the colors of the image into the colors of the underlying surface and the color of the overlaying layer. We used filter matching to measure the accuracy of color scission for simulated physical filters and materials. Standard filters were placed on various sets of chromatic materials and match filters on achromatic materials. In the majority of cases, filter matching was close to veridical. The spectral effects of filters are complex, but with respect to the visual system, they can be closely approximated by 3-D affine transformations of cone absorptions or chromaticities. Veridical filter matches can be predicted by neural strategies that match ratios of mean cone absorptions or match mean chromatic contrasts between filtered and exposed regions. However, when the shape of a filter transmittance differed significantly from the shapes of background reflectances, the overlaid region had lower saturation than the surround, and filter matches had broader transmittance spectra than veridical.

Keywords: color scission, color transparency, color constancy

Introduction

When a transparent filter is moved in front of a variegated surface, observers can see not only the surface through the transparent layer but also the layer itself. Perceptual separation of the stimulus into the underlying surface and the overlaying layer is termed color scission (Heider, 1932; Metelli, 1974). Implicit is the notion that scission leads to transparent layer constancy and surface color constancy (Gerbino, Stultiens, Troost, & de Weert, 1990). Consider a red filter situated in front of a set of green-yellow materials and the same red filter in front of a set of achromatic materials (Figure 1). The appearance of the local colors of the two overlaid regions is different. The question is whether observers can extract transparent layer properties common to the two overlaid regions, and tell whether the two filters are identical. Here we used filter matching to examine the accuracy of color scission for transparencies across different sets of colored background materials.

Perceptual scission can occur in scenes where surfaces are partially overlaid by a transparent layer, spotlight, shadow, or fog. The color signal coming from each point of the overlaid image is a composite function of surface, illuminant, and intervening medium, and does not in itself contain separable information about the characteristics of the components. However, because of the physical characteristics of the transparent layers, images contain geometrical and color cues that promote scission. For example, the continuation of objects from exposed to overlaid regions creates X-junctions in the image (Kersten, 1991), and the filtering effects of spectrally homogenous transparencies can be succinctly

described by 3-D affine transformations in chromatic space (Westland & Ripamonti, 2000; Khang & Zaidi, 2002a). How accurately the visual system disentangles the composite image into overlay and background components is an empirical question that we tested by placing transparent layers on chromatically different sets of background materials.

Only a few studies have tested whether transparent layers or surface colors are perceived as invariant under different conditions. Gerbino et al. (1990) treated transparency perception of neutral density filters as a constancy problem. By superimposing transparent layers on two different sets of achromatic backgrounds, they tested whether the opacities of two layers could be matched. Observers adjusted the luminance of overlaid regions of one background set to match the perceived overlay superimposed on the other set. The transparency and background components, derived from the data, corresponded well with Metelli's (1974) episcotister model of scission. Khang and Zaidi (2002a) have examined the effects of perceptual scission and image junctions on identification of colored transparent layers across different illuminants. Their results showed that, despite differences in the appearance of overlaid regions under two different illuminants, observers could identify transparent layers across illuminants almost as well as they could discriminate within illuminants. They suggested that whether transparency cues such as X-junctions were present or not, the primary cues for color identification were systematic color shifts across illuminants. D'Zmura, Rinner, and Gegenfurtner (2000) and Hagedorn and D'Zmura (2000) have examined the other side of scission (i.e., constancy of the color of a surface seen through a transparent layer or a fog). In an asymmetric color-

matching task, observers adjusted the color of a surface seen to lie behind a transparent layer or fog to match the color of the same surface seen in plain view. Matching results were described well by a convergence model that took into account both color shifts and changes in contrast.

Here we have tried to learn more about transparency by simulating physical materials and filters. We examine the color information available about the transparent material in physically realistic situations, and in what form and under what conditions is the information used by the visual system. We ask whether the information available is sufficient to extract accurate (i.e., unbiased and precise) estimates of the spectral properties of the transparencies, and whether such estimates are actually extracted by the visual system. We examine conditions where scission is easily perceived, and ask whether the color aspect of scission is accurate enough to identify filters across backgrounds. Given that we simulate physical filters, we use *veridical scission* to define the case where filters of identical transmittance match in extracted appearance across backgrounds. This enables us to go beyond previous studies on the accuracy of color scission. This work supplements the [Khang and Zaidi \(2002a\)](#) study in two ways: by measuring filter appearances instead of identification, and by using backgrounds from different quadrants of chromatic space instead of spectral variations between natural illuminants. In the everyday world, colors of backgrounds and terrains show a much larger variability than the changes created by illumination differences ([Webster, 2001](#)). It is, therefore, important to study color constancy across changes of background colors.

Filter-Matching Experiment

Using spectrally selective materials and filters, we examined how accurately two filters overlaid on different sets of colored background materials can be matched. We presented one filter on chromatic materials and another filter on luminance-matched gray materials ([Figure 1](#)). Observers adjusted the transmittance of the filter on the gray materials to match the appearance of the filter on chromatic materials.

Methods

Stimuli

The stimuli were simulations of materials representing a wide variety of spectral reflectances, spectrally selective filters, and Equal Energy light. Background surfaces were chosen from a collection of 4,824 reflectance functions that consisted of flowers, leaves, and fruits measured by [Chittka, Shmida, Troje, and Menzel \(1994\)](#), natural and man-made objects measured by [Vrhel, Gershon, and Iwan \(1994\)](#), Munsell

color chips measured by [Hiltunen \(1996\)](#), and animals skin measured by [Marshall \(2000\)](#). Five sets of 40 colored materials and one set of gray materials were used. [Figure 2a](#) shows MacLeod-Boynton chromaticities ([MacLeod & Boynton, 1979](#)) (L/L+M, S/L+M) of the six sets of materials under Equal Energy light, while [Figure 2b](#) shows the reflectance spectra. The first four sets of materials (color coded circles) were selected from single quadrants of MacLeod-Boynton color space, whereas the fifth set (crosses) was equally balanced across the four quadrants. The sixth set consisted of 40 achromatic materials (square in center of chromaticity diagram), each of whose reflectances were equal to the mean of one of the 40 material reflectances of the balanced set.

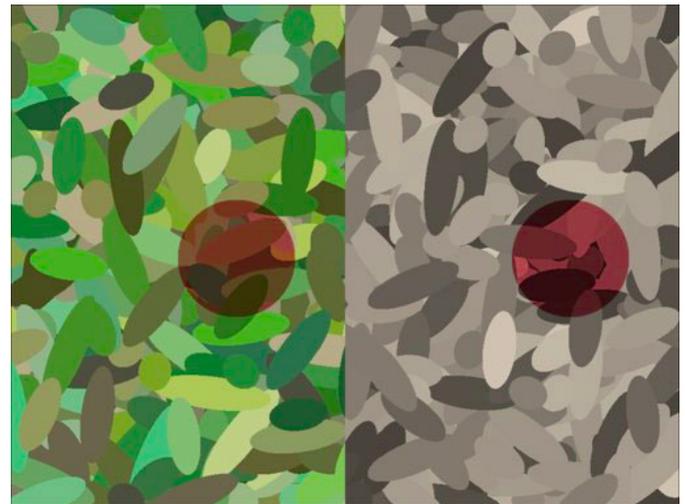


Figure 1. Red filter on chromatic materials (left) and the same red filter on achromatic materials (right). Both filter and materials are under equal energy light. To see them moving, click on the figure.

The transmittance spectra of seven filters, six [Kodak CC30 color filters](#) (red, green, blue, yellow, magenta, and cyan) and one Neutral Density (ND) filter with 70% transmittance were used to simulate the transmittance of transparent overlays. [Figure 3](#) shows the transmittance spectra of the seven filters. We simulated filters with zero reflectance. Glass filters have been measured to reflect less than 5% of the illuminant multiplied by the double-pass transmittance plus 1.0 ([Nakauchi, Silfsten, Parkkinen, & Usui, 1999](#)).

Materials were simulated as randomly sized, oriented, and overlapping ellipses ([Figure 1](#)). The length of the major axis ranged from 2.20° to 6.59° and the length of the minor axis was 1.83° . Seven different spatial layouts were drawn in image memory, and a different layout was randomly chosen as the background on each trial. There were 576 ellipses per layout, some ellipses were partially or completely occluded by others. Materials were randomly assigned to ellipses on each trial. Filters were simulated on the left and right halves of the screen. Each filter was simulated as overlaying a circular region with a

diameter of 6.6° and moving along a circle with a circumference of diameter of 6.6° . The advantages of simulating a moving filter are twofold: a moving filter can overlay a larger sample background of materials than a static filter of the same size, and the movement of filters greatly enhances the percept of a transparent layer (D'Zmura et al., 2000).

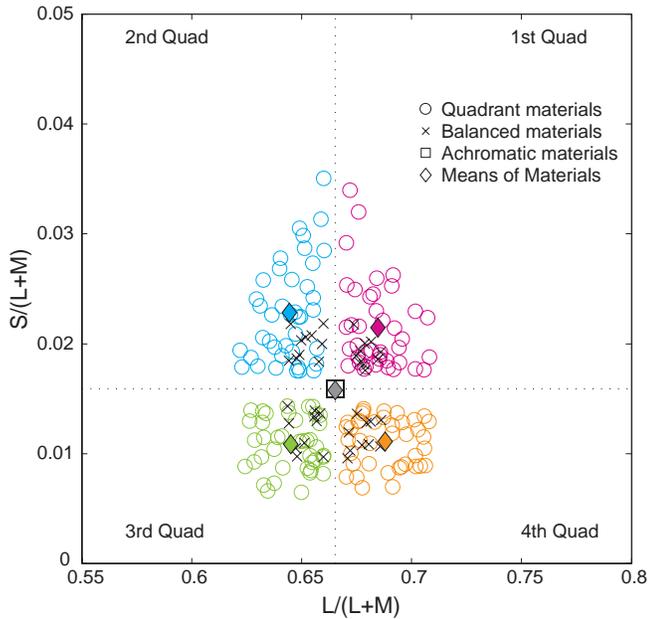


Figure 2a. MacLeod-Boynton chromaticities of the 240 materials used, which consist of 6 sets of 40 materials, 4 sets of chromatic materials from each quadrant, one set of balanced chromatic materials, one set of achromatic materials. Colored diamonds indicate mean of each quadrant materials, while gray diamond on the center of the horizontal and vertical dotted lines (Equal Energy light) represents mean of balanced chromatic materials, which is identical to that of achromatic materials.

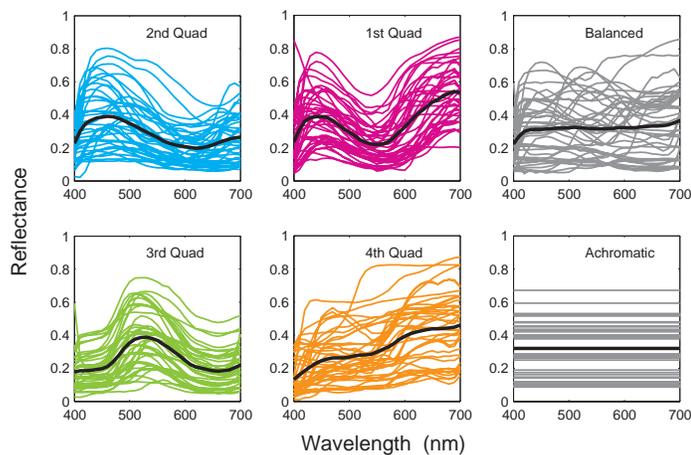


Figure 2b. Reflectance spectra of material sets. Dark lines represent mean reflectance of 40 materials in each set.

A material with reflectance $R_i(\lambda)$ seen under an Equal-Energy illuminant with spectrum $E_i(\lambda)$ was rendered by first calculating cone absorptions L_{ij} , M_{ij} , and S_{ij} , for the long-, middle-, and short-wavelength sensitive cones (Smith & Pokorny, 1975):

$$L_{ij} = \sum L(\lambda) * R_i(\lambda) * E_j(\lambda)$$

$$M_{ij} = \sum M(\lambda) * R_i(\lambda) * E_j(\lambda)$$

$$S_{ij} = \sum S(\lambda) * R_i(\lambda) * E_j(\lambda)$$
(1)

where $\lambda = 400 \dots 700$ nm and "*" represents wavelength-by-wavelength multiplication. The cone absorptions for materials overlaid by a filter with transmittance $F_k(\lambda)$ and zero reflectance were calculated by:

$$L_{ijk} = \sum L(\lambda) * R_i(\lambda) * E_j(\lambda) * F_k^2(\lambda)$$

$$M_{ijk} = \sum M(\lambda) * R_i(\lambda) * E_j(\lambda) * F_k^2(\lambda)$$

$$S_{ijk} = \sum S(\lambda) * R_i(\lambda) * E_j(\lambda) * F_k^2(\lambda)$$
(2)

For the six sets of materials, in exposed and filtered conditions under Equal Energy light, means and standard deviations of MacLeod-Boynton chromaticity coordinates ($L/(L+M)$, $S/(L+M)$), and of $L+M+S$ [representing brightness] are shown in Table 1. This table shows that spectrally selective filters simply reduce the mean and standard deviation of the brightness of the overlaid region, but the chromatic effects are more complex: filters shift the chromatic means and can increase or decrease the standard deviations.

Procedure

On each trial, one of the five sets of the chromatic materials was simulated as the background on the left half of the screen and the achromatic set was simulated as the

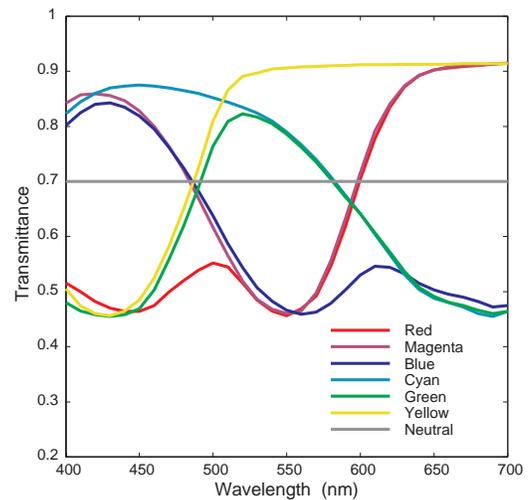


Figure 3. Transmittances of 7 filters used as standard filters.

Table 1. Means and Standard Deviations of Chromaticities (L/(L+M), S/(L+M), and L+M+S) of the 6 Sets of Materials Under Equal Energy Light Filtered by 7 Filters or No Filter.

L/(L+M)						
	1 st Quad	2 nd Quad	3 rd Quad	4 th Quad	Balanced	Achromatic
Red	0.750 (0.013)	0.694 (0.017)	0.687 (0.017)	0.747 (0.015)	0.719 (0.020)	0.720 (0.000)
Magenta	0.733 (0.013)	0.677 (0.015)	0.678 (0.017)	0.737 (0.015)	0.706 (0.020)	0.707 (0.000)
Blue	0.667 (0.012)	0.627 (0.010)	0.634 (0.012)	0.679 (0.013)	0.653 (0.015)	0.653 (0.000)
Cyan	0.644 (0.009)	0.616 (0.007)	0.622 (0.009)	0.653 (0.010)	0.634 (0.011)	0.634 (0.000)
Green	0.656 (0.009)	0.627 (0.008)	0.628 (0.009)	0.661 (0.010)	0.643 (0.011)	0.643 (0.000)
Yellow	0.697 (0.011)	0.655 (0.011)	0.651 (0.011)	0.696 (0.013)	0.674 (0.015)	0.674 (0.000)
Neutral	0.685 (0.011)	0.644 (0.010)	0.645 (0.011)	0.688 (0.013)	0.665 (0.014)	0.665 (0.000)
No Filter	0.685 (0.011)	0.644 (0.010)	0.645 (0.011)	0.688 (0.013)	0.665 (0.014)	0.665 (0.000)
S/(L+M)						
	1 st Quad	2 nd Quad	3 rd Quad	4 th Quad	Balanced	Achromatic
Red	0.013 (0.003)	0.017 (0.003)	0.009 (0.002)	0.007 (0.001)	0.011 (0.003)	0.011 (0.000)
Magenta	0.034 (0.007)	0.041 (0.007)	0.020 (0.004)	0.018 (0.004)	0.028 (0.007)	0.028 (0.000)
Blue	0.048 (0.008)	0.050 (0.009)	0.025 (0.005)	0.026 (0.005)	0.036 (0.009)	0.037 (0.000)
Cyan	0.030 (0.005)	0.029 (0.006)	0.014 (0.003)	0.016 (0.003)	0.021 (0.006)	0.021 (0.000)
Green	0.012 (0.002)	0.012 (0.002)	0.006 (0.001)	0.006 (0.001)	0.008 (0.002)	0.008 (0.000)
Yellow	0.008 (0.001)	0.009 (0.002)	0.004 (0.001)	0.004 (0.001)	0.006 (0.001)	0.006 (0.000)
Neutral	0.021 (0.004)	0.023 (0.005)	0.011 (0.002)	0.011 (0.002)	0.016 (0.004)	0.016 (0.000)
No Filter	0.021 (0.004)	0.023 (0.005)	0.011 (0.002)	0.011 (0.002)	0.016 (0.004)	0.016 (0.000)
L+M+S						
	1 st Quad	2 nd Quad	3 rd Quad	4 th Quad	Balanced	Achromatic
Red	4.747 (2.199)	3.785 (1.842)	4.423 (2.076)	5.337 (2.603)	4.933 (2.612)	4.893 (2.473)
Magenta	5.265 (2.411)	4.302 (2.074)	4.800 (2.258)	5.736 (2.809)	5.409 (2.841)	5.375 (2.717)
Blue	3.719 (1.715)	3.489 (1.686)	3.931 (1.813)	4.067 (2.072)	4.099 (2.145)	4.088 (2.066)
Cyan	6.924 (3.274)	6.987 (3.440)	8.408 (3.816)	7.997 (4.184)	8.222 (4.361)	8.207 (4.148)
Green	6.283 (3.015)	6.295 (3.134)	7.878 (3.562)	7.505 (3.921)	7.607 (4.068)	7.586 (3.834)
Yellow	9.844 (4.708)	9.045 (4.494)	11.282 (5.146)	11.706 (5.954)	11.399 (6.088)	11.352 (5.738)
Neutral	6.254 (2.957)	5.822 (2.867)	7.040 (3.217)	7.254 (3.698)	7.159 (3.799)	7.135 (3.607)
No Filter	12.759 (6.033)	11.878 (5.849)	14.362 (6.564)	14.800 (7.546)	14.606 (7.750)	14.557 (7.358)

background on the right half. Two filters, the Standard and Match filters, were simulated as overlaying circular regions on each of the two halves of the screen. The Standard filter overlaid on the chromatic materials was one of the seven filters in Figure 3, and the Match filter, placed on the achromatic materials, could be varied in spectral transmittance by the observer. Observers were told to look at the Standard filter on the chromatic background, to imagine how it would look if it were placed on the achromatic background and to adjust the transmittance of the Match filter to match the two filters by using two toggle switches. The switches varied the transmittance of the Match filter $F_m(\lambda)$ inside the convex hull formed by the linear combination of the Standard filter $F_s(\lambda)$, the Neural Density filter $F_n(\lambda)$, and the two filters $F_1(\lambda)$ and $F_2(\lambda)$ with spectra closest to the Standard filter (e.g., magenta and yellow for the red Standard filter):

$$F_m(\lambda) = \Delta_n \{ F_t(\lambda)[1 - \Delta_c] + \Delta_c F_1(\lambda) \} + [1 - \Delta_n] F_n(\lambda) \quad \text{for } 0 \leq \Delta_c \leq 1, \tag{3}$$

$$F_m(\lambda) = \Delta_n \{ F_t(\lambda)[1 + \Delta_c] - \Delta_c F_2(\lambda) \} + [1 - \Delta_n] F_n(\lambda) \quad \text{for } -1 \leq \Delta_c \leq 0, \tag{4}$$

The first switch varied the shape of the transmittance of the Match filter as a linear combination of the Standard filter and the two filters $F_1(\lambda)$ and $F_2(\lambda)$ by changing Δ_c from -1 to 1. With Δ_c equal to 1, the spectral transmittance of the Match filter was that of $F_1(\lambda)$, with -1 to that of $F_2(\lambda)$, and with 0 to that of the Standard filter. Perceptually, this adjustment varied the hue of the Match filter. The second switch varied Δ_n thus changing the bandwidth of the Match filter. As the value of Δ_n increased from 0 to 1, the spectral transmittance of the

Match filter changed from the uniform spectrum of the Neutral Density filter to that of a linear combination of the spectrally selective filters. Values of Δ_n greater than 1 were allowed up to the point where all of the overlaid achromatic materials remained within the gamut of the CRT. Perceptually, this adjustment varied the saturation of the Match filter. Δ_c and Δ_n were initially assigned random values on each trial.

There were 35 material and Standard filter combinations (five sets of background materials and seven Standard filters). Each trial consisted of a filter match for a randomly chosen Standard filter on one of the five sets of the chromatic materials. Fifteen observations were made for each condition per observer. There were eight sessions per observer. Stimuli on each trial were presented continuously until the observer had finished the adjustment of the match filter. A single session lasted about 35 min.

Observers

Four observers participated in Experiment 1, all of whom had normal or corrected-to-normal visual acuity and normal color vision. Observer B.K., the first author, was aware of the nature and purpose of the experiment, but the other observers were not informed until after the conclusion of both experiments.

Equipment

All stimulus presentations and data collection were computer controlled. Stimuli were displayed on the $36^\circ \times 27^\circ$ screen (1024 \times 768 pixels) of a Nokia Multigraph 445Xpro color monitor with a refresh rate of 70 frames/s at a viewing distance of 60 cm. Images were generated by using a Cambridge Research Systems Visual Stimulus Generator (CRS VSG2/3) running in a 400-MHz Pentium II-based system. Through the use of 12-bit digital-analog converters, after gamma correction, the VSG2/3 was able to generate 2861 linear levels for each gun. Any 256 combinations of the three guns could be displayed during a single frame. By cycling through precomputed lookup tables, we were able to update the entire display each frame. A Spectra-Scan PR-704 photospectroradiometer was used to measure complete spectra for the three phosphors. Phosphor CIE (x,y) chromaticities and maximum luminances were (0.60, 0.34) and 11.6 cd/m² for the R-gun (0.28, 0.60), 34.2 cd/m² for the G-gun (0.15, 0.07), and 4.8 cd/m² for the B-gun. Cone absorptions were calculated for the phosphors, and then by standard methods, cone absorptions for filtered and unfiltered materials were transformed to gun values and displayed on the screen.

Results

Using Equations 3 and 4 and the values of Δ_c and Δ_n set by the observer, each match can be converted into a spectrum for the Match filter, and compared with the

spectrum of the Standard filter. Figure 4 shows the average transmittances of Match filters for each of the seven Standard filters (indicated within each panel), shown as separate colored lines for each of the five chromatic backgrounds. Each average is taken over 15 observations and 4 observers. The average Match transmittances for each set of background materials are colored according to the same code as Figure 2b. The transmittances of the Standard filters are shown as dotted black lines. The most notable result is that the transmittances of the Match filters have shapes that are similar to those of the corresponding Standard filter. If all Match transmittances were identical to corresponding Standard transmittances, we could conclude that all matches were veridical and that color scission was exact and accurate. Notice that matches to the Neutral Density filter are almost exactly veridical for all backgrounds. For the spectrally selective filters, the most noticeable deviations from veridicality are Match transmittances that are shallower (i.e., broader-band) than Standard transmittances (e.g., the green curve representing Quadrant 3 in the magenta filter panel and the orange curve representing Quadrant 4 in the cyan filter panel). It is clear that these broader bands represent mixtures of the Neutral Density filter with a transmittance very similar to the Standard filter. Since the Match filter overlays achromatic surfaces, any spectrum that is metameric to it will also provide a good match to the Standard filter. However, two physically distinct filters that are metameric on the achromatic surfaces are almost certainly not going to be metameric on the chromatic background. This reflects the fact that observers do not have access to spectra and have conscious access only to functions of cone absorptions that are related to color appearance.

There is no extant method of accurately representing color appearances, so as an approximation, we have used MacLeod-Boynton chromaticity coordinates ($L/(L+M)$, $S/(L+M)$) to provide a better description of the pattern of results and similarities between observers, and to provide tests of specific hypotheses. We have calculated the mean MacLeod-Boynton chromaticities of each set of background materials when overlaid by each of the Standard and mean Match filters. The Standard filter was always presented on the chromatic background and the Match filter on the achromatic background. A veridical match would result in the mean chromaticity of the overlaid Match region being equal to the calculated mean chromaticity of the achromatic background overlaid by the Standard filter.

In Figure 5, each panel represents mean data (15 observations each) for one of the 4 observers. Each cross (X) represents the mean chromaticity of the achromatic materials overlaid by the Standard filter (i.e., Match filter transmittance set equal to Standard filter transmittance, the expected value for a veridical match, and perfectly accurate color scission). Clustered near each cross are filled disks (o) representing the mean chromaticities of

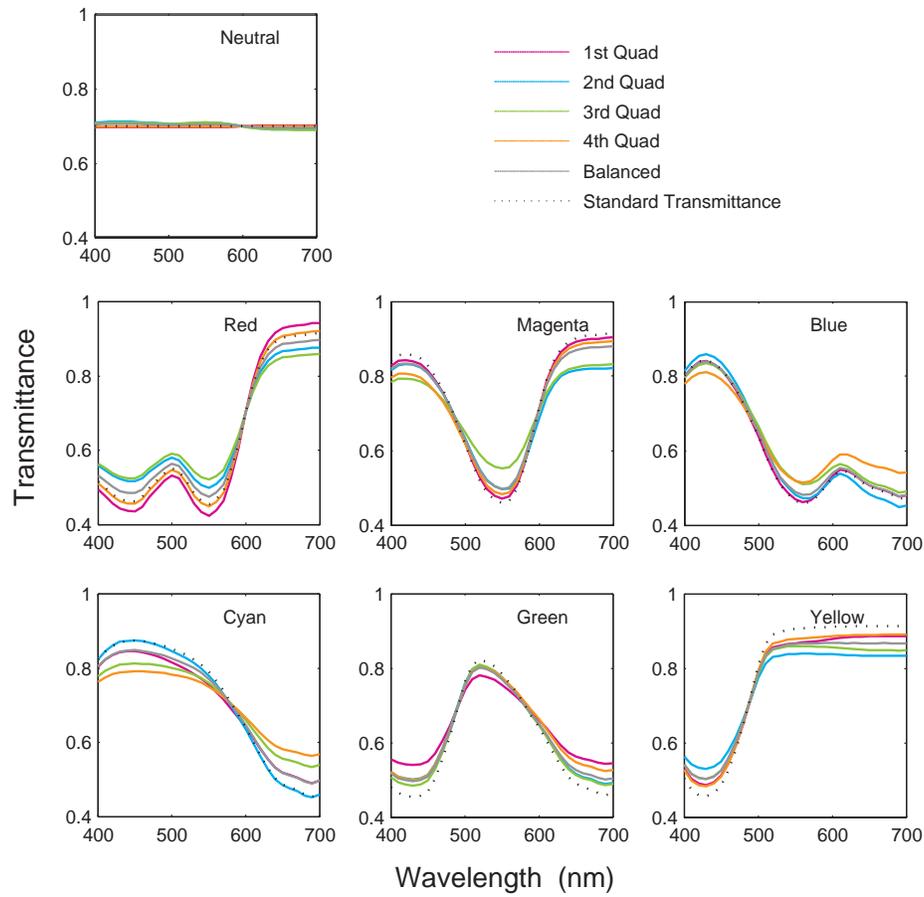


Figure 4. Mean transmittances of Match filters averaged over 4 observers. Colors of the lines indicate chromatic background conditions, Gray=Balanced, Purple=1st Quadrant, Cyan=2nd Quadrant, Green=3rd Quadrant, Orange=4th Quadrant.

the achromatic materials overlaid by the mean Match filters. The colors of the disks represent the chromatic materials on which the referenced Standard filter was situated.

The patterns of discrepancies between the crosses and circles shown in Figure 5 are systematic and similar for the 4 observers. First, filter matches for the Neutral Density Standard filter show overlap between the circles and the crosses for all 4 observers, indicating almost perfect accuracy of scission, whereas matches for colored Standard filters indicate some systematic departures from veridicality. Second, matching tended to be more veridical when the balanced set of the chromatic materials was used as background for the Standard filter than when quadrant sets were used as background. Third, deviations of the Matched filter from the Standard tended to occur along the line connecting the crosses for the Standard and Neutral Density filters, which indicates that departures from veridical filter matches occurred in terms of saturation rather than hue.

Since the patterns formed by the colored disks in Figure 5 are similar for all 4 observers, for the purposes of hypothesis testing, we calculated means over all 4 observers. In Figure 6, the averages of the mean chromaticities of the achromatic background under the

mean Match filters are shown as pluses (+) separately for the five chromatic Standard backgrounds, and enclosed by rectangles that indicate ± 1 SD on the two chromaticity coordinates. Symbols are color coded according to the Standard filter. The crosses represent the chromaticity of the achromatic background under the Standard filter, and are at identical values in all five panels and Figure 5. The pluses thus represent empirical matches while the crosses (x) represent veridical matches or perfect scission. Lines join each mean empirical match to the corresponding veridical match. The diamonds represent the mean chromaticity of the chromatic materials overlaid by the Standard filter; this value would have been obtained for the chromaticity of the Matched overlay region if observers had matched mean color appearances of the two sides. The diamonds thus indicate predictions for matches in the absence of color scission of the transparent layer from the background. In most cases, the pluses are close to the crosses, indicating reasonably accurate color scission. There are, however, systematic departures from veridicality. Note that for the balanced background, the diamonds overlap the crosses, indicating that unbalanced chromatic backgrounds are necessary for testing the hypothesis of veridical scission versus no-scission.

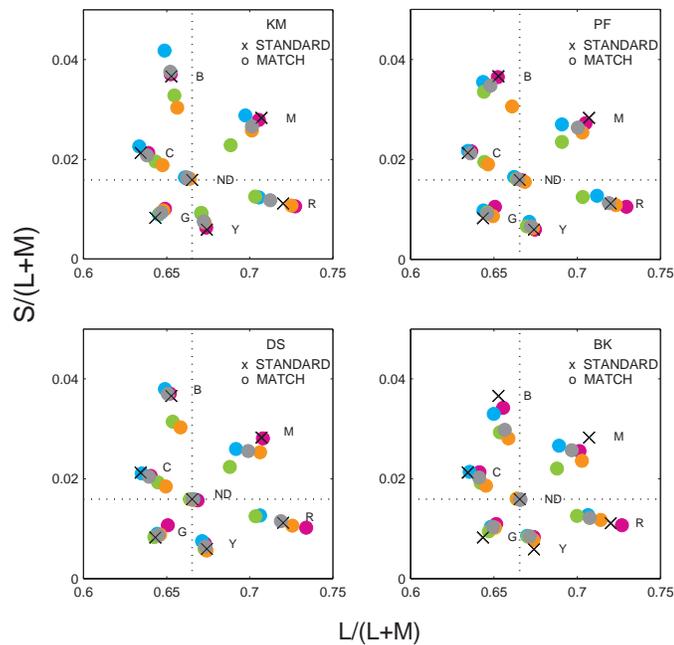


Figure 5. Mean chromaticities of achromatic materials under the Standard (x) (R,M,B,C,G,Y,ND) and Match filters (o) for each of four observers. Colors of the circles indicate chromatic background conditions, Gray=Balanced, Purple=1st Quadrant, Cyan=2nd Quadrant, Green=3rd Quadrant, Orange=4th Quadrant.

The largest departures from accurate scission occur when the Standard filter overlays a set of chromatic materials whose reflectance spectra are most dissimilar in shape to the transmittance spectrum of the Standard filter (e.g., green filter on the 1st quadrant [red-blue] materials, red on the 2nd quadrant [green-blue], magenta

on the 3rd quadrant [green-yellow] materials, and cyan on 4th quadrant [red-yellow]). The common feature of these cases is that the diamonds indicating the chromaticity of the chromatic region overlaid by the Standard filter are close to the achromatic point in the chromaticity diagram. In all of these cases, the mean chromaticity of the overlaid region on the Match side tended to be less saturated than what would have been expected from the veridical matches (Figure 5 and Figure 6). In fact, for these cases, the mean chromaticities of the Matched overlaid region are relatively closer to no-scission chromaticities (Figure 6). In terms of filter transmittances, these are the cases in which Match filter transmittances were broader than corresponding Standard filter transmittances. It seems that when the overlaid chromatic region is lower in mean saturation than the exposed chromatic region, observers attribute the decrease in saturation to the filter layer rather than to filter-background color combination.

Appearance-Matching Experiment

We also tested whether induced color contrast or different adaptation to the chromatic and achromatic surrounds could have biased observers' judgments in the discrepant cases. In a second experiment, we asked observers to match the color appearance of the filtered region on the chromatic side to the appearance of the same filtered region with an achromatic surround.

This experiment was different from the filter-matching experiment in two aspects. First, as shown in Figure 7, a circular patch of the chromatic materials

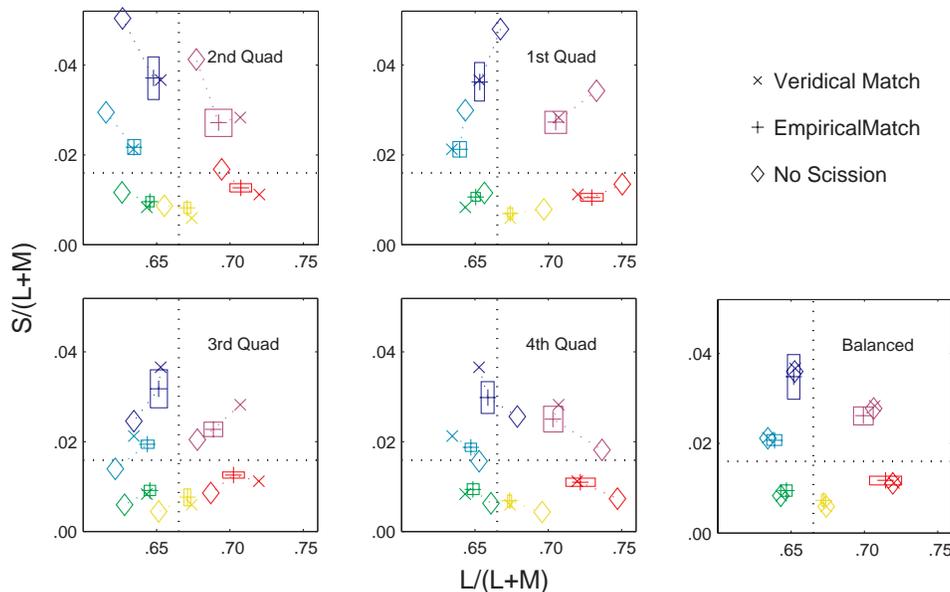


Figure 6. Mean chromaticities of the achromatic materials under the Standard filters (x) and under the Match filters (+). Diamonds represent mean chromaticities of the chromatic materials under the Standard filters. Rectangles enclosing pluses indicate $\pm 1SD$ along the two chromatic axes.

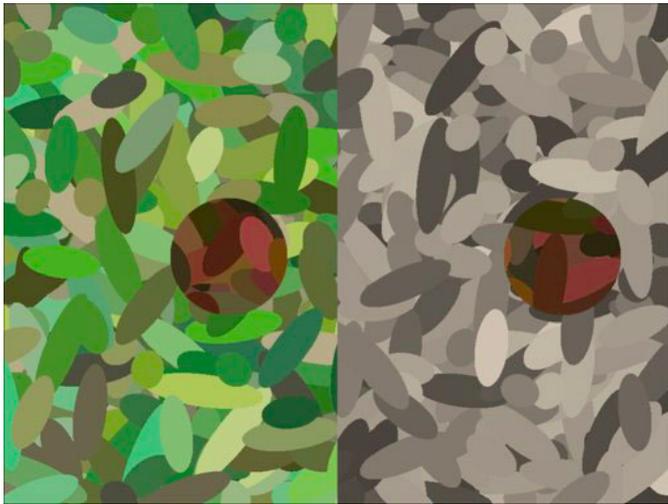


Figure 7. Green-yellow material patches overlaid by red filter on chromatic (left) and achromatic (right) sides. To see them moving, click on the figure.

overlaid by a Standard filter was simulated on the chromatic side (Standard patch), and another circular patch of the chromatic materials overlaid by a Match filter was simulated simultaneously on the achromatic side (Match patch). The Standard and Match patches were moved across the background materials in the same manner as in the filter-matching experiment. However, in this case, the image contained a number of T-junctions on the boundaries of the circular regions, which elicited a sense of opaqueness rather than transparency. The chromatic and spatial statistics of the filtered and background regions on the chromatic side remained identical to those of the filter-matching experiment. Second, observers were asked to adjust the color of the Match patch so that it looked like it was cut

from the same material as the Standard patch. While the apparent effects of the switch manipulations by the observers were changes in the hue and saturation of the Match patch, in physical terms, the observers were adjusting the Match filter overlaid on an unchanging background in a manner identical to the filter-matching experiment (i.e., the Match filter was defined by Equations 3 and 4). Hence, the results of the two experiments can be directly compared.

Except for the stimulus and the instructions for observers, all details of the appearance-matching experiment were identical to those of the filter-matching experiment. The 4 observers who participated in the filter-matching experiment also participated in the appearance-matching experiment. Eight observations per match were obtained from each of the 4 observers.

Results

The transmittances of the Match filters obtained from 8 observations for each of the 35 conditions were averaged separately for 4 observers. The MacLeod-Boynton chromaticity coordinates ($L/(L+M)$, $S/(L+M)$) of the 40 chromatic materials overlaid by the Standard and Match filters under Equal Energy light were calculated. In Figure 8, each diamond represents the mean chromaticity of the chromatic materials overlaid by the Standard filter. These values are identical to the no-scission diamonds in Figure 6. The circles represent mean chromaticities of the chromatic materials overlaid by the mean Match filters. The colors of the circles are coded according to the Standard filters. For each diamond, there are four circles representing the data of separate observers. If there were no effect of the surrounding background on the appearance of the overlaid Standard patch, then the

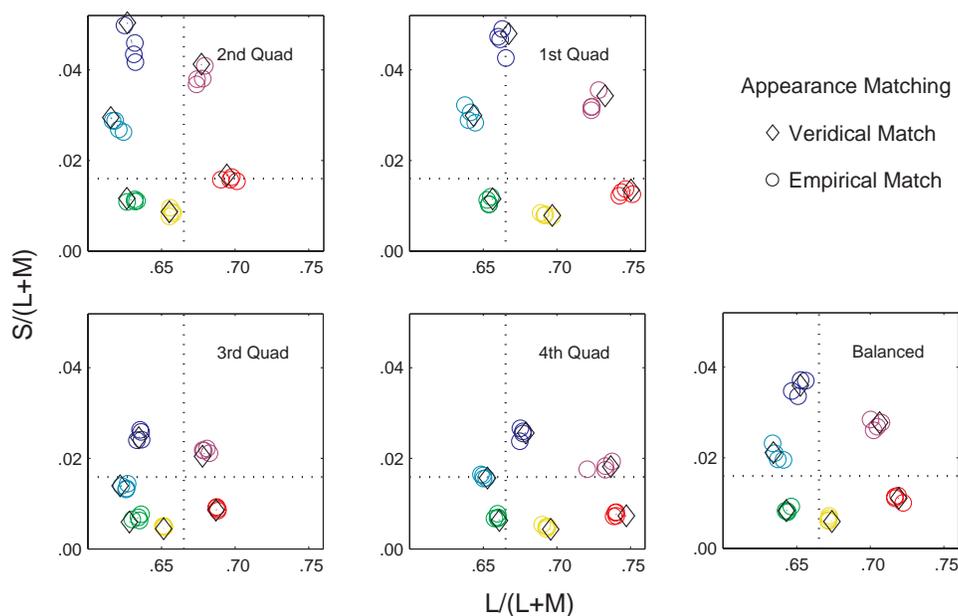


Figure 8. Mean chromaticities of the chromatic materials under the Standard filters (diamonds) and under the Match filters (circles).

Match filters should be identical to the Standard filter and the mean chromaticities under the Match filters should fall on top of the corresponding diamonds. Figure 8 shows that this is approximately the case for all conditions. In other words, induction or adaptation from the surround does not alter the appearance of the Standard patches, and the no-scission values in Figure 6 can be assumed to represent the appearance of the Standard overlaid region. In the filter-matching experiment, the separation of the observers' settings from these values indicates that observers were matching the appearance of extracted filters, not that of the overlaid region. Even though the different quadrant backgrounds have different mean chromaticities, the absence of a discernable induction effect is consistent with the result that the presence of high spatial frequency chromatic changes in the surround will drastically reduce the induced effects of low chromatic spatial frequency components of the surround such as the mean chromaticity (Zaidi, Yoshimi, Flanigan, & Canova, 1992). Informal observations indicated that a substantial induced effect existed if overlay and background regions were made spatially uniform and set equal to the mean chromaticities.

Invariances Available for Filter Matching

In the filter-matching experiment, Standard filters were placed on chromatically variegated backgrounds, whereas Match filters were placed on luminance-matched variegated achromatic backgrounds. The appearances of the two overlaid regions were thus too different for point-by-point color matching to function as an effective filter-matching strategy. In this section, we use transmittance spectra of filters, reflectance spectra of materials, absorption spectra of human cone photoreceptors, and early neural combination rules to examine the information that is available to the human visual cortex in solving the filter-matching problem. In the next section, we will examine whether the visual system actually uses this information.

On a wavelength basis, spectrally selective filters modify the light reaching the eye from materials with spectrally selective reflectances, but it is difficult to discern simple systematic rules. At the level of the cone absorptions, however, Westland and Ripamonti (2000) and Khang and Zaidi (2002a) have shown that L, M, and S cone absorptions from sets of materials seen through spectrally broad-band transparent layers are highly correlated with absorptions from the same materials seen directly. For the materials and filters used in this study, correlation coefficients for all pairs of Standard filters and background sets ranged from 0.9941 to 0.9999. Due to space limitations, we illustrate just a few cases below.

On the three panels of the first row of Figure 9, L, M, and S cone absorptions of the 40 materials in the red-blue quadrant placed under the magenta filter are plotted as circles versus those of the same materials seen directly. L, M and S cone absorptions from the achromatic side under the same filter are plotted as plusses against the absorptions from the directly viewed materials. In each of the panels, almost all of the circles and plusses fall on or close to the best-fitting regression lines, and the two regression lines have intercepts of zero, and slopes that are very similar and less than 1.0. On the three panels of the second row of Figure 9, L, M, and S cone absorptions of the 40 materials in the green-yellow quadrant placed under the magenta filter are plotted versus absorptions from the same materials in direct view as squares. The plusses again represent achromatic materials, and are identical to the top row. Even in the cases where the transmittance spectra of a filter are not similar in shape to the reflectance spectra of the materials, the three cone absorptions reveal high correlations. Considering that the Standard filters and material sets are quite complicated stimuli in multi-dimensional wavelength space, it is remarkable that orderly relations between the filtered and exposed materials already exist at the cone excitation level, the earliest stage of visual processing (Zaidi, 2001).

The regression lines have zero intercepts because the filters simulated in the present study have zero reflectance, and thus will not add light to overlays placed over materials of zero reflectance. Since the intercepts of the regression lines are zero, cone absorptions of the filtered materials (L_F , M_F and S_F) can be expressed in terms of cone absorptions of the exposed materials (L_E , M_E and S_E) as follows:

$$\begin{bmatrix} L_F \\ M_F \\ S_F \end{bmatrix} = \begin{bmatrix} t_l & 0 & 0 \\ 0 & t_m & 0 \\ 0 & 0 & t_s \end{bmatrix} \begin{bmatrix} L_E \\ M_E \\ S_E \end{bmatrix} \quad (5)$$

where t_L , t_M and t_S are the ratios of the means of the cone absorptions. Since we simulated light-absorbing filters, the ratios are always less than 1. These ratios represent transmittance parameters in cone space because they specify the multiplicative changes in absorption for different cone types caused by a filter. Notice that the multiplicative parameters for a filter are different for different cone classes. Equation 5 shows that even though the spectral effects of filters are complex, at the cone absorption level, the effects can be adequately described by a 3-D affine transformation; in fact, a diagonal transformation suffices in the case of filters of zero reflectance. The high correlations within cone classes indicate that the off-diagonal interaction terms would contribute little and can be left out. Equation 5 can be conceived of as a 3-D generalization of Metelli's (1974) episcotister model (Da Pos, 1989; Brill, 1994; D'Zmura et al., 1997; Faul, 1997).

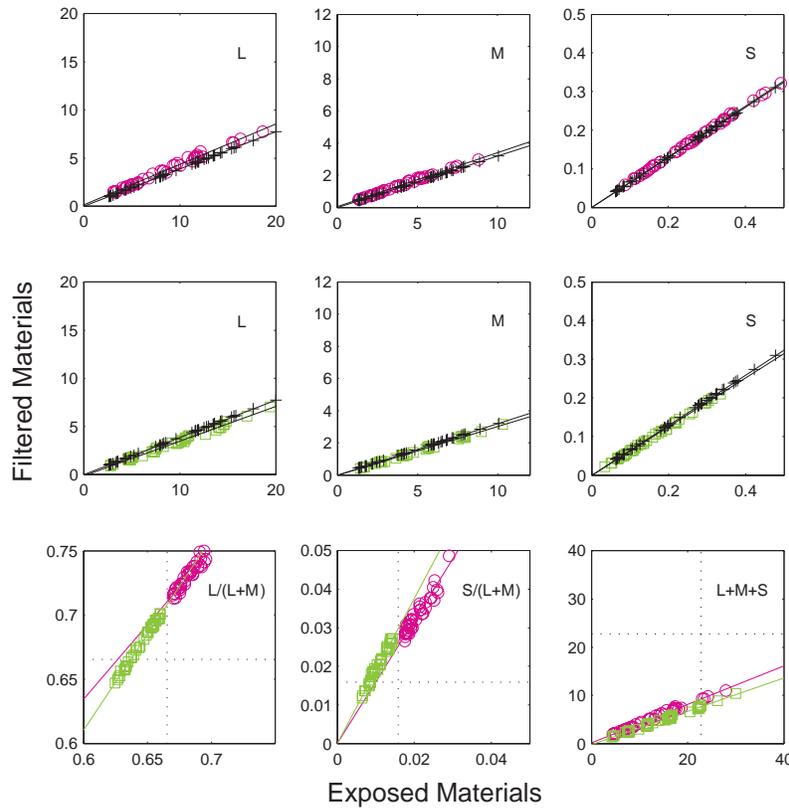


Figure 9. (top row) Cone absorptions of the 1st Quadrant (red-blue) materials under Magenta filter versus cone absorptions of the same exposed materials shown as circles. Cone absorptions for achromatic materials shown as pluses. (Middle row) Cone absorptions of the 3rd Quadrant (green-yellow) materials under Magenta filter versus those of the same exposed materials drawn as circles. Cone absorptions for achromatic materials drawn as pluses. (bottom row) Chromaticities of the 1st and the 3rd Quadrant materials under Magenta filter versus those of the same exposed materials. Lines represent regression of chromaticities of 40 materials under Magenta filter to those of the same materials without filter.

In the retina, cone signals are combined into opponent-color mechanisms whose maximal sensitivities are well described by the axes $L/(L+M)$ and $S/(L+M)$ (Derrington, Krauskopf, & Lennie, 1984). On the third row of Figure 9 are shown the $L/(L+M)$, $S/(L+M)$, and $L+M+S$ chromaticity values of the red-green (circles) and green-yellow (squares) materials overlaid by the magenta filter versus those of the same exposed materials. Most of the chromaticity values fall on or near the best-fitting regression line (correlation coefficients are 0.99, 0.97, 0.99 for green-yellow materials, and 0.93, 0.97, 0.99 for red-blue materials). To examine the effects of filters on the chromaticities of background materials, we fit linear equations to all pairs of filters and backgrounds in graphs similar to the bottom panel of Figure 9. We found that r^2 ranged from 0.86 to 0.99, indicating excellent fits of regression lines. Using RG, YV, and LD as mnemonics for $L/(L+M)$, $S/(L+M)$, $L+M+S$, respectively, we found that the chromatic effects of filters could be adequately described by:

$$\begin{bmatrix} RG_F \\ YV_F \\ LD_F \end{bmatrix} = \begin{bmatrix} m_{RG} & 0 & 0 \\ 0 & m_{YV} & 0 \\ 0 & 0 & m_{LD} \end{bmatrix} \begin{bmatrix} RG_E \\ YV_E \\ LD_E \end{bmatrix} + \begin{bmatrix} a_{RG} \\ 0 \\ 0 \end{bmatrix} \quad (6)$$

Equation 6 is a 3-D affine transformation with no interaction terms, and with an additive term only for the RG chromaticity. These calculations thus show that the color information arriving at the visual cortex, from physical transparencies, has a systematic and simple form. Zaidi (2001) shows the algebraic reasons to expect the additive term for the RG coordinate but not the YV coordinate.

Strategies for Filter Matching

Given that systematic and simple information is available from the stimuli about the color effects of filters, a number of simple neural strategies can be hypothesized for filter matching. In this section, we explore three such strategies in terms of their efficacy in leading to veridical matches and their ability to predict empirical matches (i.e., first, whether these strategies incorporate the critical information and, second, whether observers use these strategies).

The use of the exposed portions of the background is crucial for the accuracy of color scission. In a study to be published, we have studied color scission for spectrally filtered spotlights. In this case, the exposed backgrounds

were set to 0 or 20% of the luminance of the present study, but all other details were identical. Empirical spotlight matches plotted on a diagram like Figure 6 were closer to the no-scission predictions than the veridical match predictions.

Ratios of the Means of Cone Absorptions

Given that filter effects on the chromatic and achromatic sides can be described by similar multiplicative terms at the cone absorption level, the first strategy we tested involves filter matching by equating the ratios of filtered to exposed mean cone absorptions on the achromatic side to the ratios on the chromatic side:

$$\begin{aligned}
 L_{ma}/L_a &= L_{tc}/L_c \\
 M_{ma}/M_a &= M_{tc}/M_c \\
 S_{ma}/S_a &= S_{tc}/S_c,
 \end{aligned}
 \tag{7}$$

where the subscripts *tc* and *c*, respectively, indicate the means of cone absorptions of the chromatic materials under the Standard filter and those of the exposed chromatic materials, whereas the subscripts *ma* and *a*, respectively, represent the means of cone absorptions of the achromatic materials under the Match filter and those of the exposed achromatic materials.

As the values for the mean of the filtered chromatic materials, the mean of the exposed chromatic materials and the mean of the exposed achromatic materials are set in the stimuli; the means of the filtered achromatic

materials (i.e., observers' settings) can be predicted from the three equations as follows:

$$\begin{aligned}
 L_{ma} &= L_a L_{tc}/L_c \\
 M_{ma} &= M_a M_{tc}/M_c \\
 S_{ma} &= S_a S_{tc}/S_c.
 \end{aligned}
 \tag{8}$$

Predicted values of L_{ma} , M_{ma} , and S_{ma} for the 35 cases were transformed to MacLeod-Boynton chromaticities and depicted by up-triangles in Figure 10. The pluses and crosses represent empirical and veridical matches, respectively, and the ± 1 SD rectangles are identical to Figure 6. In general, the up-triangles are close to the crosses, indicating that if an observer followed this strategy, he/she could achieve close to veridical matches without extracting the spectra of the filters. Since the majority of empirical matches were close to veridical, this strategy can be said to provide a good fit to the observers' strategy for the majority of the conditions. However, in cases where empirical filter matches were less saturated than veridical, this strategy does not provide good predictions (e.g., green filter on 1st quadrant, magenta filter on 3rd quadrant).

Differences of Mean Chromaticity

The bottom row of Figure 9 illustrates that the effects of filters on materials can also be described in terms of correlated changes in chromaticity of overlaid regions as compared to exposed regions. As an alternative to matching cone-ratios, filter matching can also be

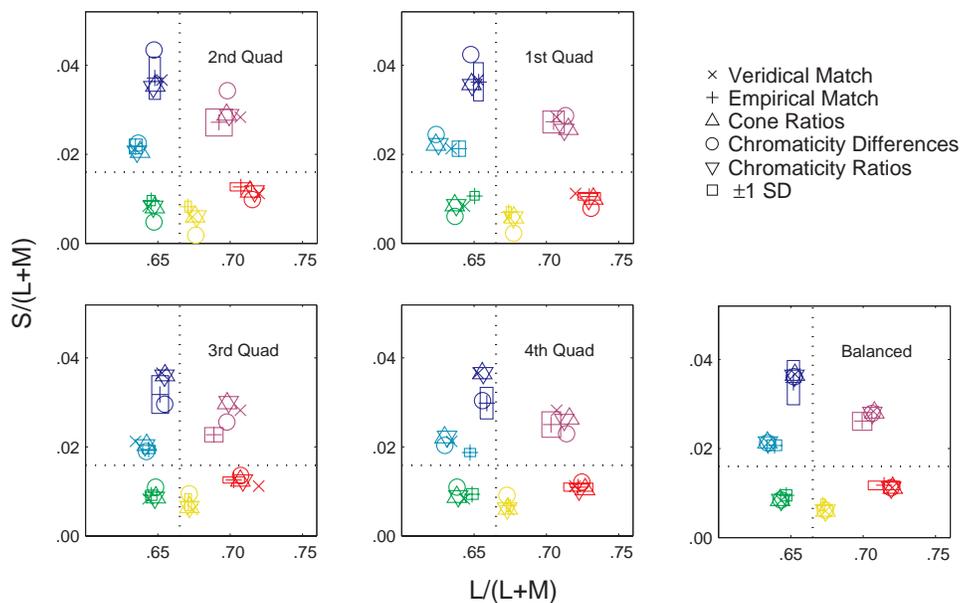


Figure 10. Mean chromaticities of the achromatic materials under the Test filters (x) and under the Match filters (+). Up-triangles, circles and down-triangles represent chromaticities of the achromatic materials overlaid by the Test filters, which are predicted by equating cone ratios, chromaticity differences and chromaticity ratios, respectively. Rectangles enclosing pluses indicate ± 1 SD in the two chromatic axes.

considered as an operation of comparing the changes in chromaticity on the Match side with those on the Standard side. In other words, the components attributable to the background must be subtracted from the composite of the filter and background on both sides, and the resultant components must be equated. Since there is no possibility of equating any chromatic statistics higher than the mean (on the achromatic side SD and higher chromatic statistics are all equal to zero), a simple hypothesis is that observers take the difference of the mean chromaticities of the filtered and unfiltered regions on the chromatic side and adjust the mean chromaticity of the overlaid region on the achromatic side to equate the mean differences from the backgrounds. Using the same subscripts as Equation 8, this hypothesis can be stated as follows:

$$\begin{aligned} RG_{ma} - RG_a &= RG_{tc} - RG_c \\ YV_{ma} - YV_a &= YV_{tc} - YV_c \end{aligned} \quad (9)$$

From these equations, the mean chromaticity of the achromatic materials overlaid by the Match filter can be predicted by

$$\begin{aligned} RG_{ma} &= RG_{tc} - RG_c + RG_a \\ YV_{ma} &= YV_{tc} - YV_c + YV_a \end{aligned} \quad (10)$$

Predicted values of RG_{ma} and YV_{ma} are depicted as circles in Figure 10. Except for the balanced background set, the circles in general do not predict veridical or empirical matches. This suggests that equating mean chromatic differences is neither a good strategy to achieve veridical filter matches nor does it seem to be a general strategy followed by our observers.

Mean Chromatic Contrasts

It is well established that perceived chromatic differences, as measured by thresholds, vary systematically as a function of adaptation level (e.g., Krauskopf & Gegenfurtner, 1992; Zaidi, Shapiro, & Hood, 1992). In the absence of explicit measurements of adaptation-based threshold levels, we tested the efficacy of a strategy that equates mean chromaticity differences between overlaid and exposed regions on Standard and Match sides, after the chromaticity differences are normalized by the sum of the mean chromaticities representing the adaptation level:

$$\begin{aligned} \frac{RG_{tc} - RG_c}{RG_{tc} + RG_c} &= \frac{RG_{ma} - RG_a}{RG_{ma} + RG_a} \\ \frac{YV_{tc} - YV_c}{YV_{tc} + YV_c} &= \frac{YV_{ma} - YV_a}{YV_{ma} + YV_a} \end{aligned} \quad (11)$$

From these equations, the predicted values of RG_{ma} and YV_{ma} are derived as follows:

$$\begin{aligned} RG_{ma} &= RG_a RG_{tc} / RG_c \\ YV_{ma} &= YV_a YV_{tc} / YV_c \end{aligned} \quad (12)$$

and depicted as downward triangles in Figure 10. The downward pointing triangles often overlap the upward pointing triangles or are close to them. Equation 11 indicates that this strategy could also be conceived of as equating mean chromatic contrasts on the Standard and Match sides. Given that in our experiment, chromaticity changes were a more powerful adjustment cue than luminance changes, it is not surprising that a 2-D chromatic contrast-matching strategy is as good as a 3-D cone-ratio strategy for predicting veridical and empirical matches. Equation 12 indicates that this strategy also equates ratios of mean chromaticities on the two sides.

Discrepant Matches

Empirical matches that are discrepant from veridical do not follow the cone-ratio or chromatic contrast-matching strategies, which would lead to veridical matches in these cases. These are cases where the shapes of the transmittance spectra of the Standard filters are most dissimilar to the shapes of the reflectance spectra of the background chromatic materials, and include green Standard filter on red-blue materials (1st quadrant), yellow filter on blue-green materials (2nd quadrant), magenta filter on green-yellow materials (3rd quadrant), and cyan filter on red-yellow materials (4th quadrant). For instance, the 4th quadrant (red-yellow) materials are more reflective in the medium- and long-wavelengths than in the short-wavelengths (Figure 2b), whereas the cyan filter transmits more in the short-wavelengths (Figure 3). As a result, the filtered regions consist of desaturated and dark colors. Results showed that the Match filters in these cases were generally combinations of the Standard and Neutral Density filters (Figure 4). As a consequence, the mean chromaticity of the achromatic materials overlaid by the Match filters tended to be less saturated than what would have been expected from veridical matches (Figures 5 and 6).

Phenomenal observations suggest that the overlaid region looked appreciably darker than the surround, the range of colors inside the overlay appeared to be less saturated and narrower than in the surround, and the filters appeared to be less "colored" than in other conditions. Satisfactory matches were obtainable with just the two controls provided in the experiment. To test whether darker colors on the overlaid chromatic side were fully responsible for the discrepant matches, we did an informal study where mean luminance of the achromatic overlay was equated to mean luminance of the chromatic overlay. Informal observations indicated that there were still appreciable degrees of underestimation of the saturation of the Match filters, suggesting that desaturated

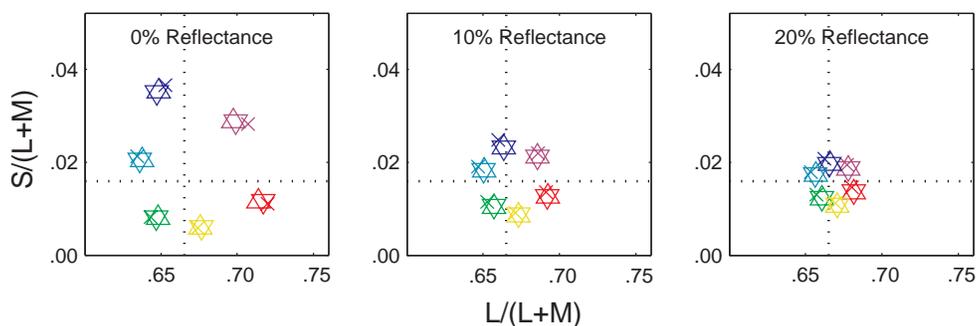


Figure 11. Simulation of filter matching strategies for Standard filters that have 0%, 10% and 20% reflectance. Mean chromaticities of the achromatic materials under Standard filter, i.e. veridical matches are shown as crosses. Up-triangles and down-triangles represent predicted chromaticities of the achromatic materials overlaid by the Match filters, under the strategies of equating cone ratios and chromaticity ratios, respectively.

colors in the overlaid regions can also contribute to underestimation. We do not yet have a unified explanation for the veridical and discrepant matches. The discrepant matches can either be considered as counter-examples to the simple neural strategies proposed above, or as low-probability special cases.

Filters With Non-Zero Reflectance

The filters we simulated had zero reflectance. In general, glass filters reflect back less than 5% of the illuminant multiplied by the double-pass transmittance plus 1.0 (Nakauchi et al., 1999). In an epicotister model, the reflectance of a filter creates an additive term. In terms of cone absorptions, for a filter of non-zero reflectance, the right-hand side of Equation 5 would acquire an additive vector as the intercepts in L, M, S graphs, such as Figure 9, would have positive values. This may seem to challenge the generality of strategies such as equating mean cone-ratios. In Figure 11, in a format similar to Figure 10, we have simulated veridical matches and predictions of the cone-ratio and chromaticity-contrast strategies for one of the background quadrants and our Standard filters with added reflectance of 0%, 10%, and 20%. As the reflectance increases, the crosses move closer to the achromatic point (i.e., the veridical matches are lower in saturation). However, as shown by the up and down triangles, the two strategies would still lead to close to veridical matches. We should point out that significant front-surface reflections from a filter could also reduce the perceived contrast inside the overlay, and some transparencies with non-zero reflectance, (e.g., fog) can blur surface edges due to light scatter (Hagedorn & D'Zmura, 2000). Measuring the accuracy of color scission for such filters would be an interesting but more complex project.

Discussion

This work examines the effects of background materials on the perception of transparency. We used

simulations of spectrally selective filters and materials in an asymmetric matching procedure to measure how accurately transparent layers placed on different sets of background materials are matched. Results showed that in the majority of cases observers were able to make close to veridical matches. We were quite surprised at the veridicality of filter matching in many conditions. The pixel-by-pixel colors are different on the two halves of the screen, yet the two extracted filters look identical when they have identical transmittances. The implication is that all retinotopic signals for the two overlaid regions differ up to the stage where transparency is extracted, and then some class of signals are equated. Most of the matches were predicted well by strategies that equate ratios of the mean cone absorptions or the mean chromatic contrast between the overlaid and exposed materials. However, in cases where spectra of filters and background materials had minimal overlap, Match filter transmittances were systematically broader than the transmittance of the Standard filters. Thus, this work suggests that the accuracy of color scission in the perception of transparency depends on the color composition of background materials.

Perceptual transparency involves perceptual separation of the stimulus into the filter component and the underlying surface component. This has been termed color scission (i.e., the reverse of optical fusion of two lights from the transparent and background surface) (Heider, 1932; Metelli, 1974; Gerbino et al., 1990; D'Zmura, Colantoni, & Hagedorn, 2001). The conditions under which perceptual scission occurs have been considered as prerequisites for the perception of transparency and quantitatively tested by Metelli (1974), Beck, Prazdny, and Ivry (1984) and Gerbino et al. (1990) in the case of achromatic transparency, and by D'Zmura et al. (1997) in the case of chromatic transparency. Metelli derived intensity relations between overlaid and exposed regions as constraints for the perception of achromatic transparency. Da Pos (1989) extended Metelli's theory to 3-D color space. D'Zmura and colleagues (D'Zmura et al., 1997; Chen & D'Zmura, 1998) have demonstrated that

correlated chromatic changes described as convergence, translation, or combinations of the two give rise to percepts of color transparency. These studies focused on the intensity or color relations between image regions that are required for perceptual transparency, whereas the present work tested color scission with simulations of real filters and materials, which enabled us to compare perceptual scission to veridical scission.

Perceptual scission could lead to invariance of the inferred color of a surface despite changes in illuminant, transparent layer, fog, or cast shadow, and despite changes in the sensed color (Lichtenberg, 1793; Katz, 1935). The key question is which components of the colors of an overlaid region are attributed to the overlaying medium and which to the underlying surface. If scission really functions as the inverse of image formation (Metelli, 1974), the inferred colors of the underlying surface and the overlaying layer should be invariant under variations of the other component. Thus, scission introduces constancy issues that are different from those of adaptation-based constancy (Ives, 1912). Gerbino et al. (1990) treated transparency perception of neutral density filters as a constancy problem and showed that transparent layers on different achromatic backgrounds were almost invariant. As an extension to the chromatic domain, we explored color scission for transparent layers sitting on different chromatic backgrounds. We found that the accuracy of color scission for spectrally selective transparent layers depends on the chromatic content of the backgrounds.

Recently, Khang and Zaidi (2002a) have examined the effects of perceptual scission for transparencies under different illuminants, namely sunlight and skylight, and showed that observers can identify colored filters under different illuminants almost as well as they can discriminate them under identical illuminants. Natural daylights in their study were broad-band and the materials used as the background included a wide distribution of chromaticities, similar to the balanced set in the present study. In their study, a few filter pairs were systematically confused across illuminants, but the causes of the discrepant performance were different from those caused by chromatically selective backgrounds such as those used in this study.

Khang and Zaidi (2002b) have measured the perceived colors of illuminants in different viewing conditions. The filter-matching experiment in this study can equivalently be conceived of as illuminant matching in the presence of a second illuminant. In this case, a perceptual model can be devised where the filter cone absorptions are extracted by estimating the cone absorptions from the two illuminants, and the predictions are identical to the model that equates ratios of the spatial means of cone absorptions. Nascimento and Foster (1997, 2000) showed that spatial ratios of cone absorptions mediate the discrimination of illuminant from non-illuminant changes. Perceptual estimates of

illuminant and filter properties have been indirectly obtained by measuring the appearance of illuminated and filtered surfaces (Brainard & Wandell, 1991; Brainard, 1998; D'Zmura et al., 2000). These estimates are obtained as part of a two-step framework for color constancy, where the image data are processed to yield an estimate of the illuminant, and then this estimate is used to correct the light reflected from each image location to yield a surface color. Thus the validity of these estimates depends on whether this two-step framework is a reasonable description of human color vision. The framework has only been directly tested for achromatic situations, and there it has been falsified (Rutherford & Brainard, 2002).

Conclusions

Color scission as measured by filter matching was in general accurate across background material collections. In the majority of cases, performances in filter matching could be predicted by the equality of the ratios of mean cone absorptions or of mean chromatic contrast across the chromatic and achromatic sides. These neural equations exploit the invariances presented by the stimulus situation. However, filter matching was not veridical in cases where the transmittance of the filter was highly dissimilar in shape to the reflectance of the background materials; thus, transparent layer constancy exists only under restricted conditions.

Acknowledgments

We would like to thank Lars Chittka, Justin Marshall, Larry Maloney, and Cuopio University for providing the reflectance functions, Fei Pan, Kaiyu Ma, and Susan Da Cruz for patient observations, and Andrea Li, Fuzz Griffiths, Rocco Robilotto, Hannah Smithson, Sei-ichi Tsujimura, and Brian Wandell for careful comments on the manuscript. This work was supported by National Eye Institute Grant EY07556 to Q. Zaidi. Commercial relationships: None.

References

- Beck, J., Prazdny, K., & Ivry, R. (1984). The perception of transparency with achromatic colors. *Perception & Psychophysics*, *35*, 407-422. [PubMed]
- Brill, M. H. (1994). The perception of a colored translucent sheet on a background. *Color Research and Application*, *19*, 34-36.
- Brainard, D. H. (1998). Color constancy in the nearly natural image. 2. Achromatic loci. *Journal of the Optical Society of America A*, *15*, 307-325. [PubMed]

- Brainard, D. H., & Wandell, B. A. (1991). A bilinear model of the illuminant's effect on color appearance. In M. S. Landy & A. J. Movshon (Eds.), *Computational models of visual processing* (pp. 171-186). Cambridge, MA: MIT Press.
- Chen, V. J., & D'Zmura, M. (1998). Test of a convergence model for color transparency. *Perception*, 27, 595-608. [PubMed]
- Chittka, L., Shmida, A., Troje, N., & Menzel, R. (1994). Ultraviolet as a component of flower reflections, and the colour perception of Hymenoptera. *Vision Research*, 34, 1489-1508. [PubMed]
- Da Pos, O. (1989). *Transparenze*. Padova: ICONA s.r.l.
- Derrington, A. M., Krauskopf, J., & Lennie, P. (1984). Chromatic mechanisms in lateral geniculate nucleus of macaque. *Journal of Physiology*, 357, 241-265. [PubMed]
- D'Zmura, M., Colantoni, P., & Hagedorn, J. (2001). Perception of color change. *Color Research and Application*, 26, S186-S191.
- D'Zmura, M., Colantoni, P., Knoblauch, K., & Laget, B. (1997). Color transparency. *Perception*, 26, 471-492. [PubMed]
- D'Zmura, M., Rinner, O., & Gegenfurtner, K. R. (2000). The colors seen behind transparent filters. *Perception*, 29, 911-926. [PubMed]
- Eastman Kodak Company (1962). Kodak Wratten filters for scientific and technical use. Rochester, NY: Eastman Kodak Company.
- Faul, F. (1997). "Theoretische und experimentelle Untersuchung Chromatischer Determinanten perzeptueller Transparenz," Dissertation, Christian-Albrechts-Universitaet, Kiel, Germany.
- Gerbino, W., Stultiens, C. I., Troost, J. M., & de Weert, C. M. (1990). Transparent layer constancy. *Journal of Experimental Psychology: Human Perception and Performance*, 16, 3-20. [PubMed]
- Hagedorn, J., & D'Zmura, M. (2000). Color appearance of surfaces viewed through fog. *Perception*, 29, 1169-1184. [PubMed]
- Heider, G. M. (1932). New studies in transparency, form and color. *Psychologische Forschung*, 14, 13-55.
- Hiltunen, J. (1996). Munsell color matts (spectrophotometer measured by Hiltunen). Retrieved September 10, 1999, from http://www.it.lut.fi/research/color/database/download.html#munsell_spec_matt.
- Ives, H. E. (1912). The relation between the color of the illuminant and the color of the illuminated object. *Transactions of the Illumination Engineering Society*, 7, 62-72.
- Katz, D. (1935). *World of color*. New York, NY: Johnson Reprint.
- Kersten, D. (1991). Transparency and the cooperative computation of scene attributes. In M. S. Landy & A. J. Movshon (Eds.), *Computational models of visual processing*. Cambridge, MA: MIT Press.
- Khang, B., & Zaidi, Q. (2002a). Cues and strategies for color constancy: Perceptual scission, image junctions and transformational color matching. *Vision Research*, 42, 211-226. [PubMed]
- Khang, B., & Zaidi, Q. (2002b, May). Illuminant color perception of spectrally filtered lights. Presented at the meeting of the Vision Sciences Society, Sarasota, FL.
- Krauskopf, J., & Gegenfurtner, K. (1992). Color discrimination and adaptation. *Vision Research*, 32, 2165-2175. [PubMed]
- Lichtenberg, G. C. (1793). Letter to Johann Wolfgang von Goethe on "Farbige Schatten" (B. Lee, U. Toost, & Q. Zaidi, Trans.). In *Color Research and Application* 27, 300-303, 2002.
- MacLeod, D. I. A., & Boynton, R. M. (1979). Chromaticity diagram showing cone excitation by stimuli of equal luminance. *Journal of the Optical Society of America*, A, 69, 1183-1186. [PubMed]
- Marshall, N. J. (2000). Communication and camouflage with the same 'bright' colours in reef fishes. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, 355, 1243-1248. [PubMed]
- Metelli, F. (1974). The perception of transparency. *Scientific American*, 230, 90-98. [PubMed]
- Nascimento, S. M., & Foster, D. H. (1997). Detecting natural changes of cone-excitation ratios in simple and complex coloured images. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 264, 1395-1402. [PubMed]
- Nascimento, S. M., & Foster, D. H. (2000). Relational color constancy in achromatic and isoluminant images. *Journal of the Optical Society of America A*, 17, 225-231. [PubMed]

- Nakauchi, S., Silfsten, P., Parkkinen, J., & Usui, S. (1999). A computational theory of color transparency: Recovery of spectral properties for overlapping surfaces. *Journal of the Optical Society of America A*, 16, 2612-2624.
- Rutherford, M. D., & Brainard, D. H. (2002). Lightness constancy: A direct test of the illumination-estimation hypothesis. *Psychological Science*, 13, 142-149. [PubMed]
- Smith, V. C., & Pokorny, J. (1975). Spectral sensitivity of the foveal cone photopigments between 400 and 700 nm. *Vision Research*, 15, 161-171. [PubMed]
- Vrhel, M., Gershon, R., & Iwan, L. S. (1994). Measurement and analysis of object reflectance spectra. *Color Research and Application*, 19, 4-9.
- Webster, M. (2001). Contextual influences on color naming [Abstract]. *Optic express*, 9, Electronic Meetings Abstracts: Color Workshop 6 Irvine, CA.
- Westland, S., & Ripamonti, C. (2000). Invariant cone-excitation ratios may predict transparency. *Journal of the Optical Society of America A*, 17, 255-264. [PubMed]
- Zaidi, Q. (2001). Color constancy in a rough world. *Color Research and Application*, 26, S192-S200.
- Zaidi, Q., Shapiro, A., & Hood, D. (1992). The effect of adaptation on the differential sensitivity of the S-cone color system. *Vision Research*, 32, 1297-1318. [PubMed]
- Zaidi, Q., Yoshimi, B., Flanigan, N., & Canova, A. (1992). Lateral interactions within color mechanisms in simultaneous induced contrast. *Vision Research*, 32, 1695-1707. [PubMed]