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LOCAL / GLOBAL MECHANISMS FOR COLOUR CONSTANCY

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This paper attempts to identify the signature of color constancy mechanisms from experimental measures of departures from "perfect" color constancy. Color matching experiments provide data consistent with nearly global normalization of independent long-, middle,- and short-wave mechanisms with corrections for absolute intensity. The evidence for this conclusion is the very high correlation between quantitative computer model predictions and quantitative color-matching experiments for a large variety of images.

1. INTRODUCTION

Color constancy experiments show that very large spectral changes in illumination cause only small changes in the appearance of objects. There is universal agreement that the magnitude of color constancy corrections is very large. There is universal agreement that the constancy is never perfect. When one makes a substantial global change in the illuminant, one finds that the appearance of the object is nearly constant, but never absolutely constant (1-6). One computational modeling approach to color constancy assumes that the constancy mechanism embodies a global correction. A second computational approach is that color constancy is a local calculation (7-8). Many investigators use the discrepancies between observed constancy and perfect constancy to identify the underlying mechanisms that account for color constancy. Since objects have nearly constant appearance, then the signature of the underlying mechanism has to be teased out from small departures from "perfect constancy". Furthermore, constancy experiments have multiple parameters that can affect experimental results. For example, when one changes the amount of the long-wave component of the illuminant, one changes both the relative amounts of long-, middle-, and short-wave illuminants, and the absolute amount of the long-wave illuminant. Both relative and absolute intensity changes have small, characteristic effects on the appearance of objects (5). In evaluating mechanisms for color constancy one needs to consider the local, the global, the spectral sensitivity, and the absolute sensitivity properties of any hypothetical mechanisms.

2. COLOR MATCHING EXPERIMENTS

Work in our laboratory has emphasized the quantitative measurements of departures from "perfect" color constancy. The data show the need for both a strong global component and local interactions to model the results of color constancy experiments. The experimental procedure used for all of the data presented here was first described in McCann, McKee, and Taylor (5). The idea was that the Munsell Book of Color in constant illumination and with a constant surround is a "standard catalog" of color sensations. The observer was asked to find a match to the test object in the standard catalog. In all the experiments described in this paper, we asked the observer to use one eye to study the test images, and the other eye to study the catalog. All matches were made sequentially. The object of these procedures was to let each eye reach its own independent state of dark adaptation and to prevent the image content of either the test or the catalog image from having an effect upon the other.

The McCann, McKee and Taylor (MMT) experiment measured the color appearance of 18 areas in a single Mondrian, in each of five different proportions of long-, middle-, and short-wave illuminants. Color appearance showed very poor correlation with the light absorbed by the long-, middle-, and short-wave cones. Color appearance showed very good correlation with Scaled Integrated Reflectance of the Mondrian papers. Integrated Energy is the integral of the spectral distribution of the light coming to the eye from a particular paper and the spectral sensitivity function of one of the cone pigments. In other words, Integrated Energy is the quantum catch of a cone mechanism. Integrated Reflectance is the ratio of the Integrated Energy coming from a particular paper, divided by the Integrated Energy coming from the highest reflectance paper in that waveband in the Mondrian. Scaled Integrated Reflectance is Integrated Reflectance shaped by an equal-lightness function such as Glasser (9). In each case, these Energies, Reflectances and Integrated Reflectances are calculated independently for each cone type. The experimental data showed strong correlation between Scaled Integrated Reflectance and observer matches(5). This result can be considered support for three major color constancy hypotheses.

1. Color constancy involves a global correction.
2. Global correction is made independently for each of the long-, middle-, and short-wave mechanisms.
3. Global correction is made with respect to the maximum in each waveband, not the average of the image.

In many ways these assumptions are very similar to those of the ideas of Von Kries with one important difference (10). Here we are arguing that the computational mechanism is the independent normalization of the long-, middle-, and short-wave mechanisms by the maximum in each cone mechanism. This idea follows directly from the fact that the colors chosen to match in color constancy show a very high correlation with reflectance measured with cone sensitivity response. These scaled integrated reflectances in McCann McKee and Taylor were computed using maxima not averages.

3. OTHER PARAMETERS AFFECTING COLOR CONSTANCY EXPERIMENTS

Three parameters have measurable effects on color appearance data. They are: spatial effects, absolute intensity effects, and spectral effects due to integrating under cone sensitivity functions. These parameters contribute to the lack of "perfect" constancy and may have variable importance depending on the particular experiment, but nevertheless must be evaluated in a quantitative model of color constancy.

3.1 SPATIAL EFFECTS

Spatial effects represent the most interesting part of the color constancy puzzle. Human vision exhibits properties that are fundamentally different from those of image reproduction technologies, such as photography and electronic imaging. In image reproduction technologies the output of a point in the image depends on the different color records at that point in the image. In vision, the color of a point is a function of the color response at that point, the response by the local environment, and the response everywhere in the image.

An extension of the McCann, McKee and Taylor experiment provides an interesting insight into the mechanisms of color constancy. There are many alternatives to normalizing the flux in an image by the maximum in each waveband. The visual system's color constancy mechanism could normalize to the global average of all the light in the field of view, the local average of an image segment or any number of alternative normalization mechanisms. The fact that normalization by the maximum in each wave band successfully predicts color in Mondrians does not mean that an alternative color constancy computational mechanism cannot predict the same results. Individual experiments are necessary to test the viability of alternative color constancy mechanisms.

We began by experimenting with the average of all the light in the field of view. In the following experiment we further tested the hypothesis that the visual system's color constancy mechanism normalizes the scene to the global average of all the light in the field of view(11). We made a new Mondrian in which all dimensions for individual papers were half the original McCann, McKee and Taylor Mondrian dimensions. We added a very large, uniform surround around the Mondrian to make the total display the same size as the MMT Mondrian. We started with a gray surround. We measured the flux from a gray paper and calculated the integrated flux from the entire display. We repeated the MMT experiment and changed the intensities of the three narrow-band illuminants such that a red paper sent to the eye the same flux that previously came from the gray paper. We measured the integrated change in flux from the entire display. The data showed an increase in middle- and short-wave light, and a decrease in long-wave light. In the next part of the experiment we used a second Mondrian with a red surround. The surround paper's spectra was carefully chosen to exactly offset the illuminant change, i.e. to preserve constant average flux over the whole display. We repeated the three other MMT experiments by changing the illuminant intensities and a surround paper that exactly compensated the illuminant change. If the color constancy mechanism uses the average of the entire image to normalize the entire image, then this experiment should produce dramatic results. Here all five Mondrians have the same average flux and the particular patches have the same triplets of fluxes. The five different papers should look identical because the stimuli at a point are identical and the integrated-average values are identical. If the color constancy mechanism uses normalization by the maxima, this experiment should produce the same results reported in McCann McKee and Taylor. The five different papers should not be identical, but should look different as they did in MMT since the experiment did not alter the maxima.

The color matching data showed considerable indifference to changes in the average reflectance. In other words, observers reported matches very similar to those in the original McCann, McKee and Taylor experiment. This supports the normalization by the maxima.

In a second experiment changed the local-average flux as much as we could with papers. In the previous experiment we compensated for substantial changes in illumination with changes in the surround paper spectra. These papers had to be very saturated to compensate for large illumination changes. The papers were N6.25/, Color-Aid RVR Hue, 5.0G6.0/8, 5.0Y8/14, Color-Aid B T2. How influential are the most saturated papers we can find in changing the appearance of the 18 papers in the Mondrian? We made new targets that resemble exploded-parts diagrams. These Mondrians were exactly the same in size, and global average properties as in the previous experiment. However instead of the entire Mondrian being totally enclosed within a surround, now each and every patch of Mondrian was embedded within a large local area of surround. If the color constancy mechanism uses the local-average of each image segment to normalize the image, then the surrounds in this experiment should change the appearance of individual papers quite substantially. Here four Mondrians have maximal departures of local-average from gray. The five different Mondrians should look very different from each other, because the local-average values are different. If the color constancy mechanism uses normalization by the maximum in each wave band this experiment should produce the same results reported in McCann McKee and Taylor. The five different Mondrians should look the same. This experiment changed the local-average values, but did not alter the maximum in each waveband. Figure 1 is a photograph of all five targets.

Fig. 1: The five Mondrians changed the local-average flux as much as possible with papers. Four Mondrians have maximal departures of local-average from gray. If the color-constancy mechanism uses a global normalization by the maximum in each waveband, then each of the 18 Mondrian papers in the five different Mondrians should look the same as its corresponding paper. The experiment changed the local average values, but did not alter the maximum in each waveband experiments.

We see small changes in appearance, despite the fact that we changed the local average as much as we could with papers. The average change is of the order one to two chips in the Munsell book. Local calculations alone cannot account for the magnitude of the color constancy corrections because color appearance is insensitive to changes in local surround. Why is it that changes in local surround had such a small effect on these Mondrian observations? All of us have seen simultaneous contrast demonstrations in which change of a background has produced large changes in the sensation of a center patch. The most dramatic departures from constancy are due to global normalization. Gelb's classical experiment is the most dramatic I know (12). Here a black piece of paper is the only object in the field of view, by itself it looks a dim white, but unquestionably white. When a white paper is put beside the black paper then white looks white and black looks black. This is an example of a global normalization process - one that changes a single object from white to black. Another familiar spatial experiment gives us important information about the limits of global normalization. Consider the gray-square-on-white and gray-square-on-black demonstration of simultaneous contrast. If global normalization of the entire field of view were complete, we would expect that observers would report the two gray squares with identical reflectances would have the identical appearance. If local mechanisms were the only consideration, then the gray square in the black surround should mimic the results found in the Gelb experiment, and should appear a white, since it is the maximum intensity in the local area. Observer results give important information about the relative importance of global and local interactions. The grey square in the black surround is one lightness unit out of nine lighter than the same gray in the white surround. If local spatial calculations were the only consideration, the gray in black should appear a 9.0. If global spatial considerations were the only consideration, the gray in black should appear a 5.0. The observer matched the gray in black to a 6.0 In other words, the spatial normalization mechanism is an imperfect global mechanism. Alternatively, it is a local mechanism that is significantly influenced by information from the entire image. The conclusion one draws from both sets of experiments is that the most powerful examples of local influence of a surround are found in situations in which the extent of the surround is large enough to influence the global normalizing mechanisms. The best examples of simultaneous contrast , such as Gelb involve changes in the maxima in the image. Experiments that change only the properties of local portions of the image produce only small changes in an observer's match -- only one or two chips in the Munsell Book.

3.2 OVERALL BRIGHTNESS EFFECTS

McCann, McKee and Taylor showed a small but consistent shift in the color matches due to changes in overall illumination. Their data showed that a change in intensity by a factor of 4 caused a change in lightness (on a scale of 0 to 10) of 0.8 units for long and middle-wave lights and 0.6 for short-wave light. As well, numerous other experiments show a corresponding shift in lightness as a function of overall illumination (13-14). Compared to the color shifts created by color constancy mechanisms, those created by overall brightness are small. Nevertheless, compared to the imperfections in color constancy they can be significant.

3.3 SPECTRAL INTEGRATION EFFECTS

MMT data show that the Integrated Reflectance of a particular paper changes with changes in spectral energy in the illuminant. Changes in the relative amounts of three narrow-band illuminants can cause changes in the Integrated Reflectance of papers because of the overlap in cone sensitivity functions. Obviously, the paper's reflectance does not change. Nevertheless, the ratio of light integrated by a cone intensity function for two papers with very different reflectances can be changed by large changes in the illuminant. In five illuminants the 5R5/12 paper had the following triplets (L,M,S) of scaled integrated reflectance: 6.5,3.6,3.6; 4.3,3.1,3.7; 6.9,4.1,3.7; 7.1,4.3,3.6; 5.9,3.5,3.7. The long-wave scaled integrated reflectances varied from 6.9 to 4.3; the middle-wave varied from 4.3 to 3.1; the short-wave varied from 3.7 to 3.6. This can be compared with the very small changes in scaled integrated reflectance with neutral gray papers. In five illuminants N6.75 had triplets (L,M,S) of scaled integrated reflectances:6.7,6.7,6.6; 6.8,6.7,6.8; 6.7,6.7,6.8; 6.7,6.7,6.8; 6.7,6.7,6.8. With highly saturated colored papers, changes in illumination have substantial effect on the quanta catches and hence a substantial effect on the scaled integrated reflectance. With neutral papers it has no effect.

So far this paper has restricted its scope to the narrow limits of explaining color constancy. The objective has been to limit the number of mechanism incorporated in the model so as to simplify the computation. So far there has not been a need for the opponent-color mechanisms found in human color vision (15-16). One idea is that opponent mechanism play an part neural transmission (5,17). A second idea is that opponent processes are needed to account for isotropic color space data. If one plots all of the papers in The Munsell Book of Color in a three-dimensional color space produced by the long-, middle-, and short-wave cone response functions, one sees the full gamut of color papers form an elongated, cigar-shaped space(18). It is much longer along the white to black axis; it is highly compressed along the yellow-blue axis, and it is extremely compressed in the red-green axis. This follows simply from the overlap in spectral sensitivity of the long- and middle-wave cone pigments. Opponent processes can transform LMS cone signals into a color space with isotropic color properties (19). Opponent transformations can effectively stretch the LMS color space into one that corresponds to experimentally-defined color isotropic spaces.

4. CONCLUSION

The color constancy experimental data are very well fit by a simple global normalization of long-, middle-, and short-wave cone response functions combined with appropriate quantitative corrections for spatial, absolute intensity, and spectral effects. In summary, our approach to modeling color constancy incorporates a number of assumptions:

1. Land's Retinex assumption -independent LMS processing.
2. Gelb's Global normalization combined with non-global propagation that accounts for local spatial effects.
3. Secondary dependence on overall intensity.
4. Scaled Integrated Reflectance varies with changes in the spectra of the illumination.
5. Opponent processes become important for isotropic color space and neural transmission properties.

The test of successful color constancy models is the range of different experimental images - complex and simple - for which it can quantitaively predict color matches(20).

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