Color Appearance in Images Measurements and Musings

Brian A. Wandell and E. J. Chichilnisky
Psychology and Neuroscience, Stanford University, Stanford, California

We suggest a framework for predicting color appearance of image data. The image data are converted by a series of *standardizing transformations* into a simpler stimulus with the same color appearance. By working through these standardizing transformations, we can build color appearance models for images without abandoning—or repeating—much of the work that has gone into defining the visual properties of the CIE standard observer.

Introduction

The best understood aspects of color science, and hence the most advanced topics in color engineering, have to do with the appearance of uniform patches of light. This is not an accident, but rather flows from the origins of color science and engineering as a response to the needs of the paint and textile industries. In these industries, uniform patches are the main product.

The focus of this paper will be to consider a set of new challenges posed by advances and widespread use of digital color imaging. The advances in imaging technology make it possible to display and print complex color images. This places new demands on scientists and engineers, who must now build models to predict and control the color appearance of a much broader class of images. The widespread use of these technologies in businesses and schools means that these new models, like the successful parts of the CIE standards, must be automated, not requiring hand-tuning by experts in production houses.

In this paper, we will present a framework for predicting and controlling color appearance in images. We will argue that one cannot predict appearance in images simply by applying CIE formulae designed for uniform patches to each point in an image. However, we still want to exploit the powerful insights and predictions of these formulae as we enlarge the stimulus domain. To predict the color appearance in an image, we suggest using spatial and color transformations that reduce the problem to a problem we know how to solve; namely, predicting the color appearance of a uniform patch.

An Architecture for Image Color Appearance

The architecture we propose for describing image color appearance is shown in Figure 1. We begin with an arbitrary image, and a region selected from that image. To predict the color appearance of this region, we develop a set of algorithms designed to compute the tristimulus coordinates of a *color-equivalent* uniform patch, i.e., a patch that has the same color appearance as the original region when seen on a large, neutral background. Many useful tools, including discrimination metrics, color categories for naming, and uniform color spaces, have already been developed to characterize the color appearance of uniform patches viewed on large neutral backgrounds. The value of this architecture for color images, then, is that it reduces a complex problem to one that has already been largely solved: by computing a color-equivalent uniform patch, we can make use of existing color appearance formulae.

The overview in Figure 1 shows three transformations that are needed to find the color-equivalent uniform patch. The first transformation accounts for the spatial structure of the general viewing context; the second accounts for the pattern (e.g., size and texture) of the object we are examining; the third transformation accounts for the average background. We will discuss each of these, beginning with the third, which is closer to the domain of traditional color science and hence the best understood.

Standardization: Background Color

The color appearance of a uniform patch superimposed on a background depends strongly on the background color. Many of the empirical studies of this effect, called *chromatic adaptation*, have used an *asymmetric color-matching* paradigm. In this paradigm, the observer sets an appearance match between two uniform patches seen on different backgrounds (Breneman, 1987; Wright, 1934; MacAdam, 1956; Burnham, et al., 1957; Wassef, 1958, 1959). The experimental results show that it is possible to predict the effect of the colored background by a simple mapping. The mapping, M_B, converts the cone tristimulus coordinates of the uniform patch into a new set of tristimulus coordinates, M_B: $(L, M, S) \rightarrow (L', M', S')$. A target with the tristimulus coordinates (L', M', S') seen on a neutral gray background appears the same as the original. Hence this transformation defines a color-equivalent uniform patch. Many of the tools developed by the CIE, such as those to represent color difference and color appearance, can be used to describe the appearance of the color-equivalent stimulus.

Several empirical studies have successfully predicted asymmetric color-matches using a background-dependent scale factor that is applied to each of the three cone coordinates (e.g., Brainard and Wandell, 1992; Brainard, et al., 1993; Chichilnisky and Wandell, 1994; Fairchild, 1991; Fairchild and Lennie, 1992; Walraven, 1976, 1979; Werner and Walraven, 1982).

Express the cone tristimulus coordinates as their difference from the mean background level, $(\Delta L, \Delta M, \Delta S)$. The matching patch on a gray background will differ from the gray background by the tristimulus coordinates

$$\begin{pmatrix} d_1(B) & 0 & 0 \\ 0 & d_2(B) & 0 \\ 0 & 0 & d_3(B) \end{pmatrix} \begin{pmatrix} \Delta L \\ \Delta M \\ \Delta S \end{pmatrix}$$

There are several models that predict how these scale factors, $d_i(B)$, depend on the background (Hunt, 1987, 1994ab; Fairchild and Berns, 1993; Nayatani, 1987; Nayatani, et al. 1990).

Standardization: Target Pattern

To extend the boundary of color science to the broad range of spatial structures in image data, we must include explicit models of the spatial sensitivity of the visual system. There are several ways to become convinced that including the spatial sensitivity of the eye is important to a general theory of color appearance. First, suppose we wish to predict the colors in the digital data used to print a colored halftone. A point-by-point analysis of the image data would reveal only a few different colors corresponding to the halftone elements. Yet, we know that the individual dots cannot be resolved by the eye and that color appearance of the blended halftone dots will create the appearance of a wide variety of colors.† Hence, color appearance theory must include aspects of spatial resolution of the eye. Second, consider the color encoding principles used by the members of the National Television Standards Committee (NTSC). They were aware that high fine spatial frequency patterns generally appear desaturated, even though the pattern is evident. We can demonstrate this effect easily using one-dimensional squarewave patterns, that is a set of stripes that alternate between two colors. The color appearance of the stripes in a high spatial frequency pattern appear as light dark modulations; when part of a low spatial frequency pattern these same modulations appear highly saturated. Again, we must be able to account for the spatial structure in the image in order to create a complete model of color appearance.

Poirson and Wandell (1993) studied the color appearance of patterned stimuli by searching for a transformation that maps the cone tristimulus coordinates of patterned stimuli into the cone tristimulus coordinates of a color-equivalent uniform patch. In their experiments, an observer set the color appearance of a uniform patch to be the same as the appearance of each of the stripes in a squarewave pattern. These experiments are a direct measurement of the mapping, M_P, that standardizes the image target appearance according to the spatial pattern of the target. Poirson and Wandell (1993) summarize the results of their measurements using a pattern-color separable model. The model begins with a color representation of the target. Express the

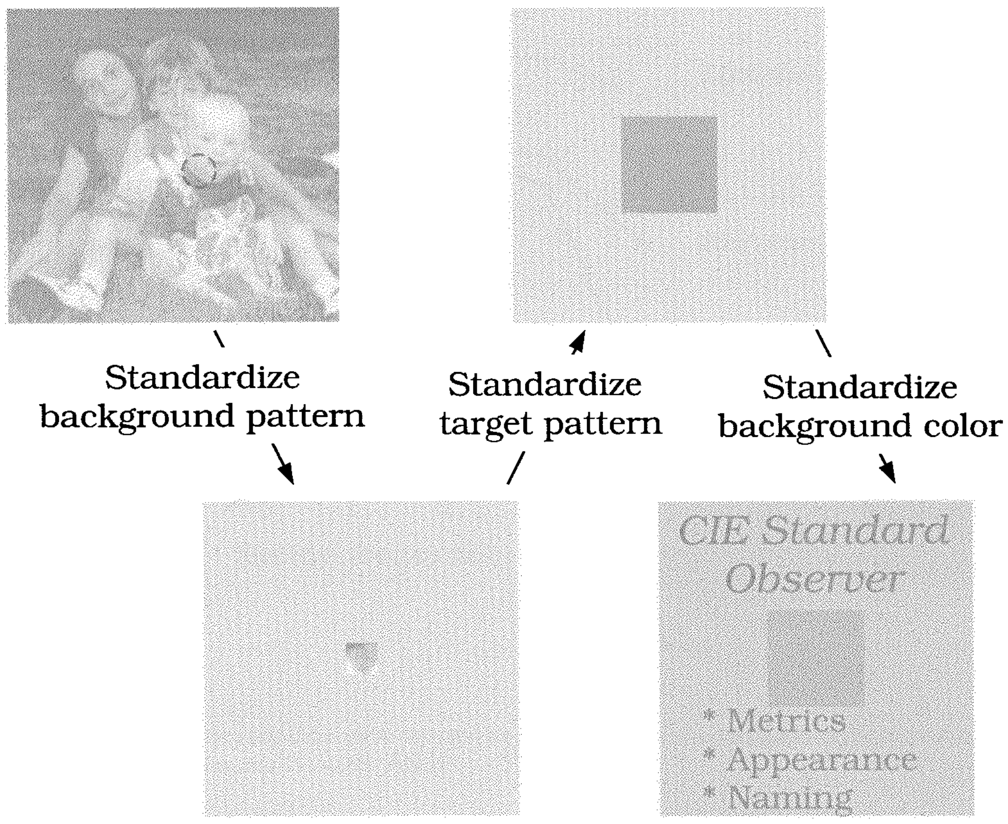

Figure 1. An architecture for predicting and controlling color appearance of images. The architecture consists of a set of standardizing transformations that convert image data to a simpler but visually equivalent stimulus.

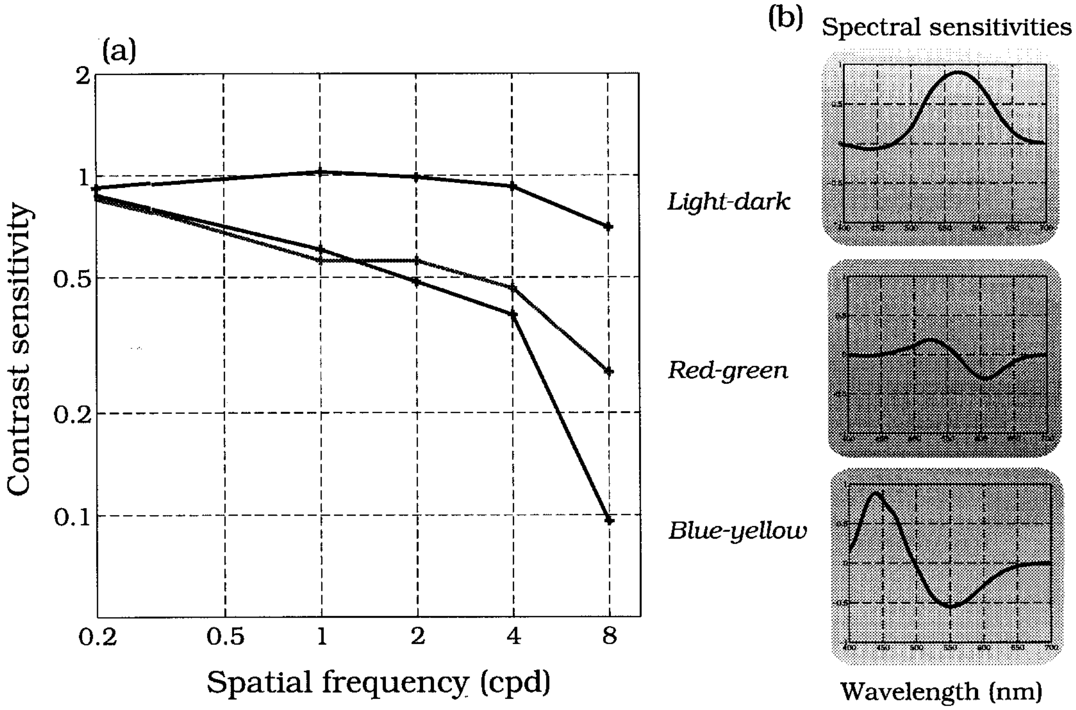

Figure 2. The spatial and chromatic properties of three pattern-color separable mechanisms used to predict the appearance of colored patterns. (Source: Poirson and Wandell, 1993)

squarewave bars as modulations about the mean background level, (ΔL, ΔM, ΔS). To predict a color-equivalent patch, the cone coordinates of the target are converted into an opponent-color coordinate frame, and these coordinates are scaled by a term that depends on the spatial frequency of the target. We can write the transformation as a single matrix expression,

$$\begin{pmatrix} d_1(F) & 0 & 0 \\ 0 & d_2(F) & 0 \\ 0 & 0 & d_3(F) \end{pmatrix} \begin{pmatrix} 0.990 & -0.106 & -0.094 \\ -0.669 & 0.742 & -0.027 \\ -0.212 & -0.354 & 0.911 \end{pmatrix} \begin{pmatrix} \Delta L \\ \Delta M \\ \Delta S \end{pmatrix}$$

The spatial frequency selectivities of these mechanisms, corresponding to the frequency dependent diagonal terms $d_i(F)$, are shown in the large graph on the left of Figure 2. The spectral responsivities of the three mechanisms, calculated from the three rows of the color transformation matrix, are shown on the right of Figure 2. (The basic results reported in these measurements have been confirmed and extended in several ways by Bäuml and Wandell in as yet unpublished results.)

Standardization: Background Pattern

The largest gap in our understanding is the question of how the spatial structure in the image background can be standardized into an equivalent uniform background. That is, we would like to find a mapping M_S that converts the target seen on a patterned background into a color-equivalent patch seen on a uniform background. In practice, it is widely assumed either that the patterned background can be replaced by a uniform background with the same space-average color, or by a background that would appear white in the original scene. Both of these suggestions are controversial, and some authors even suggest that it is impossible to standardize the patterned background to a single uniform background at all (Brown and Macleod, 1991).

To model this final standardizing transformation we must understand how the visual system integrates information across the image. There are very few studies of how the visual system does this, and the suggested mechanisms range from temporal integration by eye movements (e.g., D'Zmura and Lennie, 1986), comparison of intensities at edges (Horn, 1974), or a thorough scene analysis including shading and transparency (Adelson, 1993). In any event, there is very little empirical data on this question and no practical theory.

Conclusions

We have proposed an architecture for predicting and controlling image color appearance. The architecture consists of a series of standardizing transformations that compute a color-equivalent uniform patch for a region of interest. We have described some of the encouraging progress that has been made in understanding these standardizing transformations. Many aspects of color appearance of uniform patches on neutral backgrounds have been studied extensively. By defining the mappings that reduce complex image data to color-equivalent uniform patches, we extend the powerful insights embodied in the CIE standard formulae to the broader stimulus domain of digital images.

Acknowledgments

Supported by the Hewlett-Packard Corporation, NASA 2-307, and NEI RO1 03167. E. J. Chichilnisky is a Howard Hughes Medical Institute Predoctoral Fellow.

References

a. In this example, one of the most important factors is the optical quality of the retinal image. Two recent studies of optical factors are Marimont and Wandell (1994) and Williams, Brainard and McMahon (1994).

1. E. H. Adelson, Perceptual organization and the judgment of brightness, *Science*, **262**, 1993, 2042-2044.
2. D. H. Brainard and B. A. Wandell, Asymmetric color-matching: how color appearance depends on the illuminant, *Journal of the Optical Society of America A*, **9**, 1992, 1433-1448.
3. D. H. Brainard, B. A. Wandell and E. J. Chichilnisky, Color constancy: from physics to appearance, *Current Directions in Psychological Science*, **2**, 1993, 165-170.
4. E. J. Breneman, Corresponding chromaticities for different states of adaptation to complex visual fields, *Journal of the Optical Society of America A*, **4**, 1987, 1115-1129.
5. R. O. Brown and D. I. A. Macleod, Induction and constancy for color saturation and achromatic contrast variance, *Investigative Ophthalmology and Visual Science*, **32**, 1991, 1214.
6. R. W. Burnham, R. M. Evans and S. M. Newhall, Prediction of Color Appearance with Different Adaptation Illuminations, *Journal of the Optical Society of America*, **47**, 1957, 35-42.
7. E. J. Chichilnisky and B. A. Wandell, Photoreceptor sensitivity changes explain color appearance shifts induced by large uniform backgrounds in dichoptic matching, *Vision Research*, **35**, 239–254 (1994).
8. M. D'Zmura and P. Lennie, Mechanisms of color constancy, *Journal of the Optical Society of America A*, **3**, 1986, 1662-1672.
9. M. D. Fairchild, Formulation and Testing of an Incomplete-Chromatic-Adaptation Model, *Color Research and Application*, **16**, 1991, 243-250.
10. M. D. Fairchild and R. S. Berns, Image color-appearance specification through extension of CIELAB, *Color Research and Application*, **18**, 1993, 178-190.
11. M. D. Fairchild and P. Lennie, Chromatic adaptation to natural and incandescent illuminants, *Vision Research*, **32**, 1992, 2077-2086.
12. B. K. P. Horn, Determining lightness from an image, *Computer Vision, Graphics, and Image Processing*, **3**, 1974, 277-299.
13. R. W. G. Hunt, A model of colour vision for predicting color appearance in various viewing conditions, *Color Research and Application*, **12**, 1987, 297-314.
14. R. W. G. Hunt, An improved predictor of colourfulness in a model of colour vision, *Color Research and Application*, **19**, 1994, 23-26.
15. R. W. G. Hunt and M. R. Luo, Evaluation of a model of colour vision by magnitude scalings: Discussion of collected results, *Color Research and Application*, **19**, 1994, 27-33.
16. D. L. MacAdam, Chromatic adaptation, *Journal of the Optical Society of America*, **46**, 1956, 500-513.
17. D. Marimont and B. Wandell, Matching color images: The effects of axial chromatic aberration, *Journal of the Optical Society of America A*, **12,** 3113–3122 (1993).
18. Y. Nayatani, K. Hashimoto, K. Takahama and H. Sobagaki, A non-linear color-appearance model using Estevez-Hunt-Pointer primaries, *Color Research and Application*, **12**, 1987, 231-242.
19. Y. Nayatani, T. Mori, K. Hashimoto and K. Takahama, Comparison of Color-Appearance Models, *Color Research and Application*, **15**, 1990, 272-284.
20. Y. Nayatani, H. Sobagaki and K. Hashimoto, Illuminance dependency of equivalent lightness on chromatic object colors, *Color Research and Application*, **18**, 1993, 123-128.
21. A. B. Poirson and B. Wandell, Appearance of colored patterns: pattern-color separability, *Journal of the Optical Society of America A*, **10**, 1993, 2458-2470.
22. J. Walraven, Discounting the background — the missing link in the explanation of chromatic induction, *Vision Research*, **16**, 1976, 289-295.
23. J. Walraven, No additive effect of backgrounds in chromatic induction, *Vision Research*, **19**, 1979, 1061-1063.
24. E. G. T. Wassef, Investigation into the theory of prediction of the appearance of colors and its bearing on the theory of color vision, *Optica Acta*, **5**, 1958, 101-108.
25. E. G. T. Wassef, Linearity of the relationship between the tristimulus values of corresponding colours seen under different conditions of chromatic adaptation, *Optica Acta*, **6**, 1959, 378-393.
26. J. S. Werner and J. Walraven, Effect of chromatic adaptation on the achromatic locus: the role of contrast, luminance and background color, *Vision Research*, **22**, 1982, 929-944.
27. D. R. Williams, D. Brainard, M. McMahon and R. Navarro, Double pass and interferometric measures of the optical quality of the eye, *Journal of the Optical Society of America A*, **11,** 3123–3135 (1994).
28. W. D. Wright, The measurement and analysis of colour adaptation phenomena, *Proceedings of the Royal Society of London B*, **115**, 1934, 49-87.

published previously in the IS&T 1994 Color Imaging Conference Proceedings, page 1