Adaption and Spatial Frequency Effects on Color Reproduction

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The use of color on printed paper is increasing due to the influence of the desktop computer. This new growth in color has brought along the need to get beyond "good enough color."

The need for improved tools for color description, transmission and reproduction can be seen in the number of conferences on Desktop Publishing, Device Independence, WYSIWYG Color, Color Portability, and Page Description Languages.

The purpose of this paper is to show the limitation of CIE Uniform Color spaces in predicting gray scale and color differences when a color is placed in a complex field and/or when the complex field has a high spatial frequency content. The appearance modeling of Guth[1] is used as the basis of this paper. At best these models blaze a trail for future work. The current color vision model does predict all the known visual adaption and color difference data.

The fundamental color data, which is the foundation of the CIE color system, was collected by doing color matching on large bipartite visual fields (Figure 1). This method was used to determine the color matching functions which in turn were linearly transformed to produce the CIE color matching primaries (Figure 2).

The works of MacAdam[2] on color differences has shown the need to transform the CIE color measurements into a more useful form as illustrated in Figure 3. The figure illustrates an example three dimensional visualization of a uniform color space. The vertical axis is used for lightness and the equal lightness planes are used to describe the chromatic nature of the visual response.

These color order systems are based on the CIE color matching functions or on named colors. The problem with these static vision models is that they fail to account for small field adaptation. Figure 4 shows two gray scale step wedges placed in a gray vignette. The appearance of the step wedges are quite different. The perception of difference between adjacent gray patches is diameter. The differences seem small in the lower gray wedge and large in the upper wedge.

Figure 5 shows a change in appearance produced by a very small field. The individual blocks of the gray wedges are surrounded by a thin black line. As you scan from Figure 4 to Figure 5, you will see that the Mach band effects seen in Figure 4 are reduced in Figure 5 by the introduction of black line boundary.

In Figure 6, the gray scales have been rotated to vertical to show how lightness scaling is affected by the mean lightness of the small field surround. The selection of a "50%" gray block will be found to be located differently in each of the gray scales. This figure shows how strongly the appearance of an individual gray patch depends on the surrounding field.

Figures 4, 5, and 6 are simple examples that show the importance of adaptation on the perception of lightness. This illustration shows that a simple metric such as CIELAB will not accurately predict either color or lightness differences without some nature of the adapting surround.

The outline for a solution to these problems has been presented by a color vision model developed by Guth. This model is based on the response of cone vision in the adapting surrounding field and assumes that the fundamental basic functions for color vision are the cone spectral responses shown in Figure 7. Guth combines the cone responses in an opponent color model as shown in Figure 8. His model involves these vectors that represent the neural actions of the vision system. The achromatic brightness response is attributed to the A vector. The chromatic response is broken into two opponent color systems. The first, the T vector, models a red-green color opponent mechanism. The second, the D vector, models a yellow-blue opponent mechanism. The combined color vector is denoted the ATD space or model. In addition, the ATD space accounts for a large number of adaption effects known in human vision. Therefore, the color vector space proposed by Guth is a reasonable candidate for an appearance uniform color space.

The appearance of color is not only a function of the surround but also a function of the size of the color sample being described. To illustrate the importance of size on color, imagine color halftones being imaged at two different sizes. The first example, the dots are made 20 times the size of normal dots, and the second, using normal dots. The large dot pattern will produce dots that have clearly distinguished color differences. The size of the color difference would be predicted by any of the uniform color models.

In contract, the same color dots reproduced a normal halftones are no longer distinguished as individual colors. The visual system sees only the smoothed average of the color. At this scale, the entire uniform diagram is collapsed to a single point. The color differences between dots no longer have meaning when the dots cannot be resolved by the color mechanism.

This example shows that Guth's model needs to be modified to account for the Modulation Transfer Functions (resolving power) of the A, T, and D channels. Figure 9 shows the response of a typical opponent receptive field in the visual field of a monkey. The small dots indicate that when cones in that portion of the visual field were stimulated, the mechanism responded by producing an increased number of neural impulses. The large data show the action of the opponent cell reducing the neural output when light fell on other cones in the visual field. Since the opponent cell covers a field much larger than a single cone, we would expect that the ability of the visual system to estimate color and lightness differences would be a strong function of the size of the detail.

The MTF of the A, T, and D functions have been measured by Granger[3,4] and are shown in Figure 10. The lightness and chromaticity transfer functions have different natures. The lightness function has a high frequency bandpass nature. In contrast, the chromatic channels are low pass filter functions. The T or red-green opponent has a greater frequency response than does the yellow-blue or D channel.

To illustrate the features of Guth's model modified by the spatial MTF of the A, T, and D, the OSA Color System was used to test model. This system places color on a regular rhombohedra arrangement. The regular rhombohedral system of color sampling adopted by the Optical

Society Committee on Uniform Color Sealer provides the maximum possible variety of relationships among color. In this system, colors are arranged in a euclidean color space which has equal distances between points. These distances correspond to equal color differences between corresponding color. The rhombohedral space arranges the colors to have the greatest number of interlocking colors. Every color has 12 equally-spaced different nearest neighbor.

The lattice coordinates have been denoted L, j, g. The L coordinate correlates with the lightness scale. The j and g coordinates correlate with the color aspects of the regular rhombohedral system. In the test of the color space, we have elected to look at the L = O plane to show the action of the two chromatic channels.

The L = O plane of the OSA color space has a CIELAB Y value of 30. The X, Y, and Z tristimulus values of the OSA color chips were found and used to compute the R, G, and B cone responses required for Guth's model. If Guth ATD space is a uniform color difference space, the transformed lattice values will lie on equal spacing on a plot of T vs D.

In all the T-D chromaticity plots that follow, the data points being plotted are equally spaced in perceptual color units on the OSA lattice. The plots shown in Figure 11 show how the spatial frequency modified T vs D plots vary as a function of spatial frequency. The lowest frequency, 0.3 cycles per degree, sets the perceptible scale since the T and D functions are not attenuated at this frequency. The crowding of the points at other spatial frequencies on the T-D chromaticity diagrams is a measure of the loss of color discrimination of a sinewave modulated between two adjacent lattice points in the OSA color space.

Therefore, while the distance between lattice points could be taken as unity, the data at 3.0 cycles per degree shows that the space has collapsed in the D or blue-yellow direction so that 10 lattice points now span a just noticeable color difference. This correlates with the reports of small field color blindness for color modulation alined with the D axis.

In like manner, the A channel lightness discrimination follows the A channels spatial transfer curve. The A channel peaks near the minimum response of the color channels. We have found that the subjective quality of images correlates well with information in the region of the peak of the A channel. This implies that the encoding of image data would place a much greater weight on the lightness channel than the chromaticity channels. The model opens the opportunity for the development of new spatial frequency adaptive color image compression schemes.

In summary, we have found that the straightforward use of uniform color spaces can lead to the improper selection of steps between colors in a uniform color space. Large and small field adaptation needs to be modeled to determine the change in color appearance.

In addition, we have shown that both adaptation and spatial content have a large effect on the appearance of both black and white and color images. Simple use of the CIELAB or CIELUV color spaces will not predict color differences in strong adapting field like the samples shown. New models are needed if we are to further improve the reproduction process. This is particularly true for computer-generated images using named colors.

We have offered a new vision model that, at best, is a guide to the future developments in vision and color graphics. We hope that researcher in the field will find this useful in defining new experiment in color coding and data compression that will advance color graphics in new and novel directions.

REFERENCES

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2 D.L. MacAdam, J. Opt. Soc. Am. **33**, 247 (1943).

3 E.M. Granger, PhD. dissertation, The Institute of Optics, University of Rochester (1975).

4 E.M. Granger and J.C. Heurtly, J. Opt. Soc. Am. **63**, 1173 (1973).

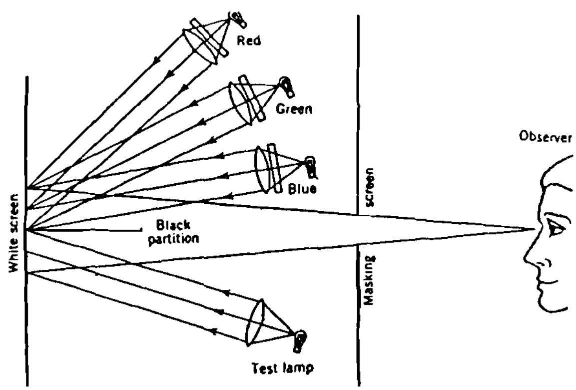

Figure 1 Color Matching

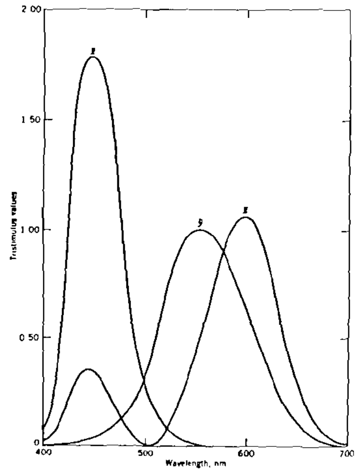

Figure 2 Color Matching Primaries

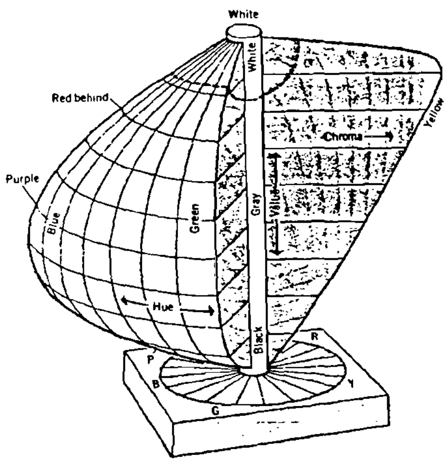

Figure 3 Uniform Color Space Model

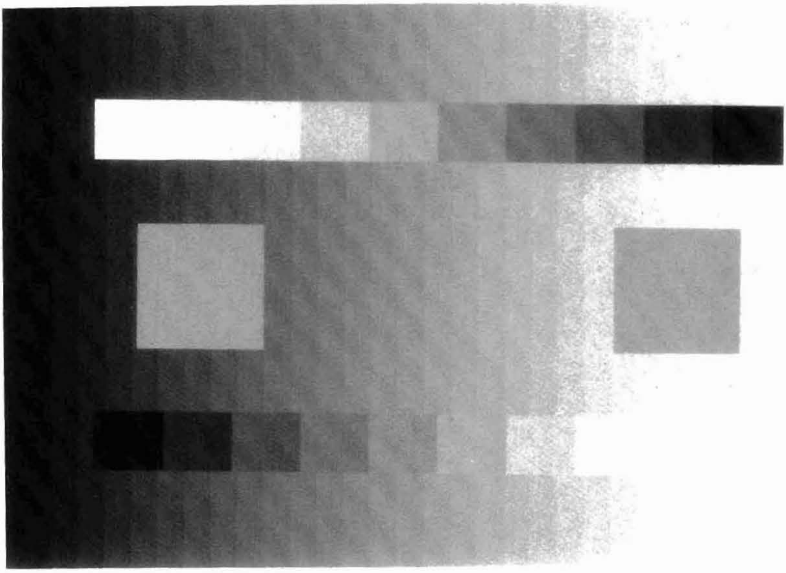

Figure 4 Simple Adapting Field

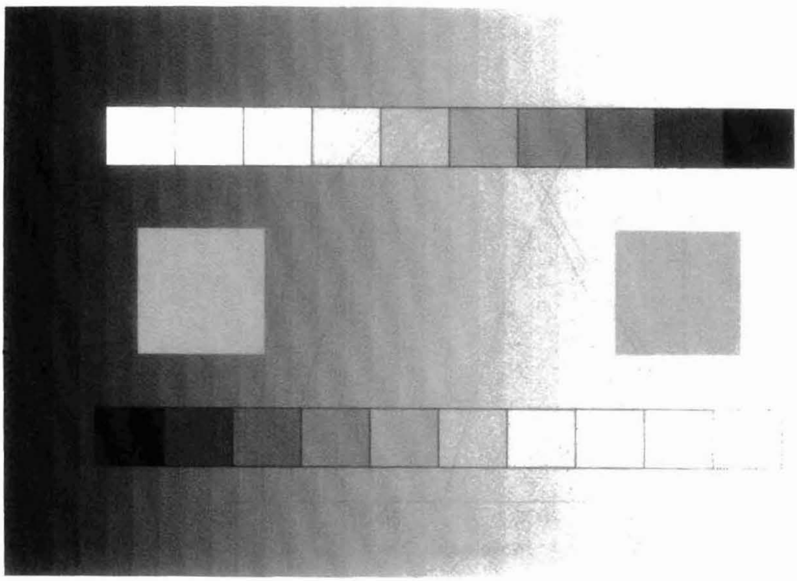

Figure 5 Small Field Adaptation

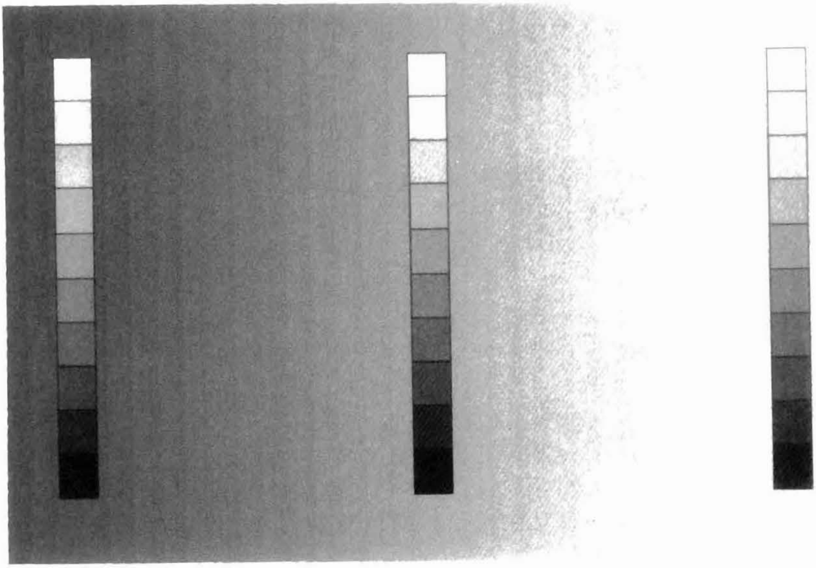

Figure 6 Lightness as a Function of Adaptation

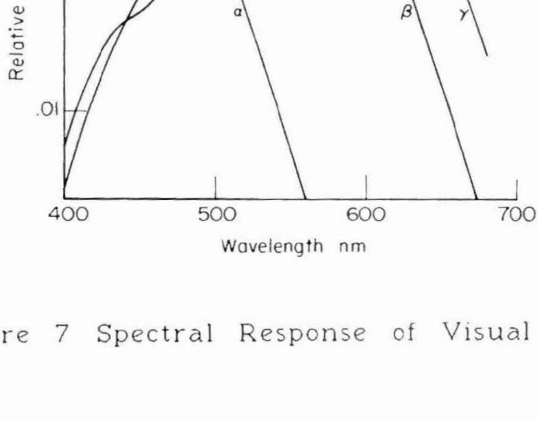

Figure 7 Spectral Response of Visual Cones

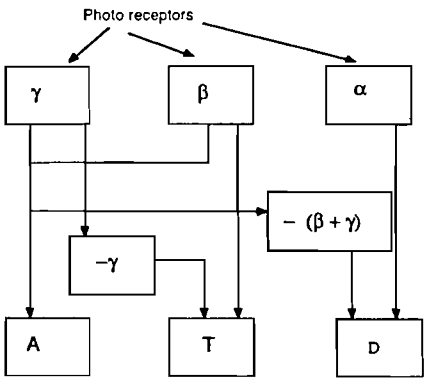

Figure 8 Opponent Color Model

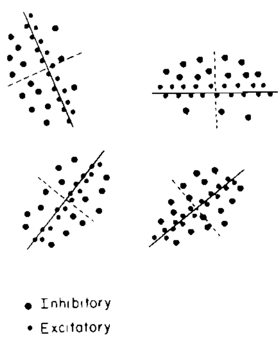

Figure 9 Opponent Visual Field

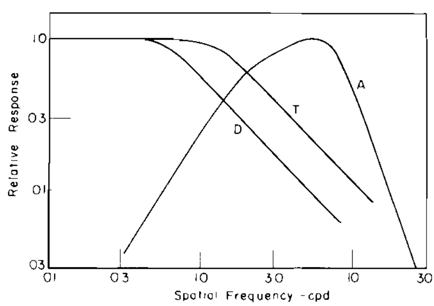

Figure 10 ATD Opponent MTF Response

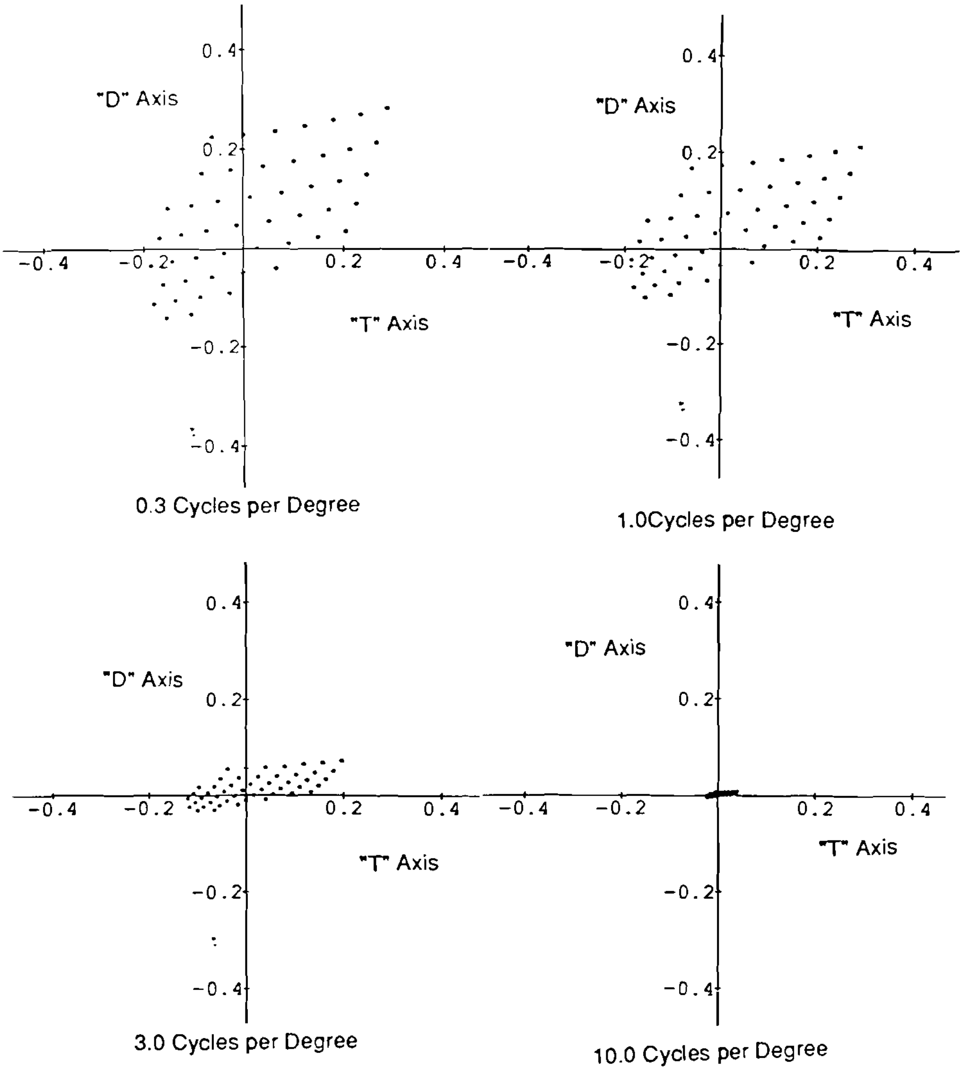

Figure 11 A and T Channel Responses
as a Function of Spatial Frequency