CHROMATIC ADAPTATION TO IMAGE DISPLAYS

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Abstract: The human visual system has evolved with a sophisticated set of mechanisms to produce stable perceptions of object colors across changes in illumination. This phenomenon is typically referred to as chromatic adaptation or color constancy. When viewing scenes or hard-copy reproductions, it is generally assumed that one adapts almost completely to the color and luminance of the prevailing light source. This is likely not the case when soft-copy image displays are viewed. Differences in the degree of chromatic adaptation to hard-copy and soft-copy displays point to two types of chromatic-adaptation mechanisms: sensory and cognitive. Sensory mechanisms are those that act automatically in response to the stimulus, such as retinal gain control. Cognitive mechanisms are those that rely on observers' knowledge of scene content. For example, an observer knows the color of his own skin or a piece of paper and therefore can "discount" the effects of colored illuminants. A series of experiments that measured the spatial, temporal, and chromatic properties of sensory chromatic-adaptation mechanisms are discussed. The results show that these mechanisms are chromatically incomplete, spatially localized, and have a time course on the order of tens of seconds. In addition, the influence of cognitive factors is presented quantitatively through experiments that measured the state of chromatic adaptation to hard-copy and soft-copy displays with various amounts of recognizable scene content. A mathematical model for predicting these chromatic adaptation effects is presented along with some practical recommendations, based on psychophysical experiments, on how to approach these problems in typical cross-media color reproduction situations

Introduction

'Yes,' I answered her last night;
'No,' this morning sir, I say,
Colours seen by candle-light
Will not look the same by day.

There is a great deal of insight in that short verse by Elizabeth Barrett Browning. It points out that many of us believe the color appearance of objects to be invariant upon changes in illumination until a more analytical viewpoint is taken. These important phenomena are mediated by a variety of visual mechanisms, both sensory and cognitive,

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responsible for chromatic adaptation, color constancy, and memory color. Since color images are viewed in a variety of media and illumination conditions, understanding these phenomena becomes fundamental to successful cross-media color reproduction. Chromatic adaptation is defined as the independent sensitivity modulation of the visual color mechanisms. Color constancy refers to the apparent invariance of object color appearance across changes in illumination. Memory color is a related phenomenon whereby the color appearance of recognizable objects tends to be as expected based on previous experience. This paper explores the properties of various chromatic adaptation mechanisms.

Chromatic-Adaptation Mechanisms

For the purposes of this paper, chromatic-adaptation mechanisms are classified into two groups, sensory mechanisms and cognitive mechanisms. Chromatic adaptation mechanisms that respond automatically to the stimulus energy are referred to as sensory. Cognitive chromatic-adaptation mechanisms are those that respond based upon observers' knowledge of scene content.

Sensory chromatic-adaptation mechanisms are well-known and have been widely discussed in the vision and color science literature. The physiological locus of such mechanisms is generally believed to be sensitivity control in the photoreceptors and neurons in the first few stages of the visual system. The specific site, or sites, of chromatic-adaptation mechanisms is beyond the scope of this paper. The interested reader can refer to the many reviews that have been written on chromatic adaptation such as those by Bartleson (1978), Wright (1981), and Lennie and D'Zmura (1988). Most modern theories and models of sensory chromatic adaptation trace their roots to the work of von Kries (1902) who wrote:

> ... the individual components present in the organ of vision are completely independent of one another and each is fatigued or adapted exclusively according to its own function. [trans. MacAdam, 1970]

von Kries' words are known to not be precisely correct today, but the concept is accurate and they provide useful insight. To this day, the idea that chromatic adaptation takes place through normalization of cone signals by the maximum signal (white) is known as the von Kries coefficient law or the von Kries model. Modern models of chromatic adaptation and color appearance by Nayatani *et al.*(1990), Hunt(1991), and Fairchild(1991a,b) and color spaces such as CIELab are all extensions of the von Kries model.

Cognitive mechanisms have also been long recognized in the literature. However, perhaps because of difficulty quantifying cognitive effects, they are usually discussed briefly and are not widely recognized or understood. To understand the idea of cognitive chromatic-adaptation mechanisms it might be best to quote some of those that have mentioned them in the past 2 centuries. Helmholtz (1866) in his treatise on physiological optics discussed object color appearance:

> We learn to judge how such an object would look in white light, and since our interest lies entirely in the object color, we become unconscious of the sensations on which the judgement rests.[trans. Woodworth, 1938]

Hering (1920), who is known for hypothesizing the opponent-colors theory of color vision, discussed the concept of memory color:

> *All objects that are already known to us from experience, or that we*
> *regard as familiar by their color, we see through the spectacles of*
> *memory color.[trans. Hurvich and Jameson, 1964]*

Judd (1940) who made innumerable contributions to the field of color science referred to two types of chromatic-adaptation mechanisms:

> *The processes by means of which the observer adapts to the illuminant*
> *or discounts most of the effect of a nondaylight illuminant are compli-*
> *cated; they are known to be partly retinal and partly cortical.*

Lastly, Evans (1943) who wrote and lectured on many aspects of color photography and color perception discussed reasons why the colors in photographs look acceptable:

> *... in everyday life we are accustomed to thinking of most colors as not*
> *changing at all. This is in large part due to the tendency to remember*
> *colors rather than to look at them closely.*

Jameson and Hurvich (1989) discussed the value of having multiple mechanisms of chromatic adaptation to provide important information both about changes such as weather, light, and time of day and constant physical properties of objects in the scene. Hunt (1991) includes parameters in his color appearance model that change depending on whether "discounting the illuminant" occurs. Finally, Davidoff (1991) has published a monograph on the cognitive aspects of color and object recognition.

Image Displays

While it is clear that chromatic adaptation is complicated and relies on both sensory and cognitive mechanisms, it is less clear how important it is to distinguish between the two types of mechanisms when viewing image displays. If an image is being reproduced in the same medium as the original and viewed under similar conditions, it is safe to assume that the same chromatic-adaptation mechanisms are active when viewing both the original and the reproduction. But, what happens when the original is presented in one medium, such as a soft-copy display, and the reproduction is viewed in a second medium, such as a hard-copy output? A series of experiments are discussed in this paper that quantify some of the characteristics of chromatic-adaptation mechanisms and indicate that the same mechanisms are not active when soft-copy displays are viewed as are active when hard-copy displays or original scenes are viewed.

When hard-copy images are being viewed, the image is perceived as an object that is illuminated by the prevailing illumination. Thus both sensory mechanisms that respond to the spectral energy distribution of the stimulus and cognitive mechanisms that discount the "known" color of the light source are active. When a soft-copy display is being viewed, it cannot easily be interpreted as an illuminated object. Therefore there is no "known"

illuminant color and only sensory mechanisms are active. This can be demonstrated by viewing a white piece of paper under incandescent illumination and comparing the appearance to that of a CRT display of a uniform field with exactly the same chromaticity and luminance. The paper will appear white or just slightly yellowish. The CRT display will appear relatively high-chroma yellow.

Incomplete Chromatic Adaptation

The fact that an incandescent chromaticity (CIE illuminant A) retains its yellow appearance when produced on a CRT display implies that chromatic adaptation is incomplete. If chromatic adaptation were complete, the display would appear achromatic after adaptation. To investigate incomplete adaptation and other characteristics of adaptation mechanisms, a series of experiments was performed (Fairchild, 1990). The technique used throughout most of these experiments was memory matching to achromatic appearance. Wright (1981) speculated on the value of this technique referring to the fact that an achromatic appearance (gray) is the only unambiguous memory color. Therefore knowledge of what stimuli appear achromatic under various adapting conditions can provide a rather direct measurement of the performance of chromatic-adaptation mechanisms.

A 10° adapting background of random lightnesses and equal chromaticity was displayed on a colorimetrically-calibrated CRT display. The maximum luminance of the display was 125 cd/m² and the mean luminance was 20% of the maximum. Three observers adjusted the chromaticity of a 1° test patch flashed in the center of the background for 200 msec. every 2 sec. until it appeared achromatic. The luminance of the test stimulus was equal to the mean luminance of the background. Sixteen replicates were performed for each observer and adapting chromaticity. Eight adapting chromaticities were used, D65, A, F2, Planckian 2000K, 10000K and K, and green and pink appearing chromaticities. The agreement between observers was excellent. Therefore overall mean results are plotted in figure 1. Standard errors of the mean estimates are approximately the size of the plotting
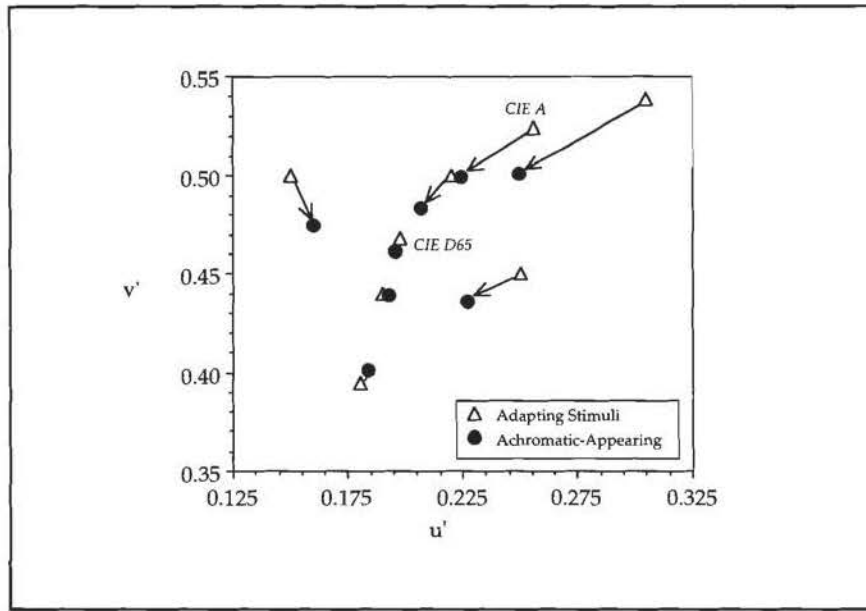
Figure 1. Adapting and achromatic-appearing stimulus chromaticities illustrating incomplete chromatic adaptation.

symbols. The open symbols in figure 1 are the chromaticities of the adapting background and the filled symbols are the achromatic-appearing chromaticities. Pairs of chromaticities are indicated by arrows. It is clear that adaptation to these displays was not complete for adapting chromaticities significantly different than D65. For example, the achromatic appearing chromaticity under adaptation to an illuminant A display lies significantly away from the chromaticity of illuminant A in the direction of D65. In other words, the achromatic point is substantially bluer (or less yellow) than the adapting background. The incomplete chromatic adaptation found in this experiment is corroborated by the results of Hunt and Winter (1975) and Breneman (1987). This experiment is described in greater detail in Fairchild (1990, 1991a).

Spatial Extent of Sensory Mechanisms

The same experimental technique was used to measure the spatial extent of the mechanisms responsible for chromatic adaptation. In this experiment, an illuminant A adapting background of various spatial extent from 0.5° to 10° with a D65 surround was used. The objective was to determine how large the illuminant A adapting field had to be for the state of adaptation to be the same as if the adapting field had infinite extent. The experiment was performed two ways: using 1° test stimuli and unrestricted fixation and using 0.25° test stimuli and the observers instructed to fixate the center of the display. The mean results for

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3 observers are plotted in figure 2, which shows the percent adaptation from D65 (daylight) to A (incandescent) as a function of the extent of the illuminant A adapting field.
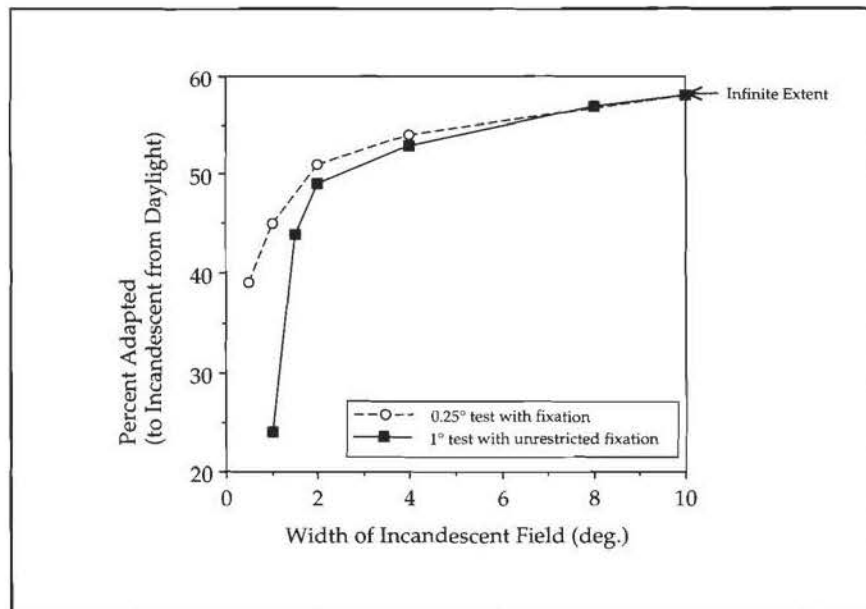

Figure 2. Degree of adaptation to an illuminant A background as a function of its spatial extent.

The extent of the adaptation mechanisms was smaller when eye movements were restricted. This is expected since eye movements would allow receptors to integrate over a larger area. However, even when eye movements were unrestricted, the extent of the mechanisms is quite small, effectively 4°. Note that the curves asymptote at 58% since adaptation to an illuminant A field is never complete. The substantial spatial localization of chromatic adaptation-mechanisms can also be illustrated through afterimages, which occur through local adaptation to spatially defined stimuli. Fairchild and Lennie (1992) discuss these results in more detail.

Time-Course of Sensory Mechanisms

In the experiments discussed above, observers made responses over an extended period of time to track any changes and determine the time-course of these mechanisms. However, it was found that observers' choices of achromatic appearance as soon as 30 sec. after exposure to the adapting backgrounds were not different than their choices after 30 minutes or longer. This observation directly contradicts a common belief that it takes several minutes to adapt to a change in illumination color.

An experiment was performed to measure the time-course of chromatic-adaptation mechanisms. An illuminant A adapting background was alternated with an illuminant D65 adapting background. The duration of exposure to each background was varied from 1 to 16 seconds with each background having equal exposure times. A test stimulus was presented for 200 msec. at the end of the illuminant A adapting exposure and adjusted by the observers until it appeared achromatic. Figure 3 shows the percent adaptation from D65 to A as a
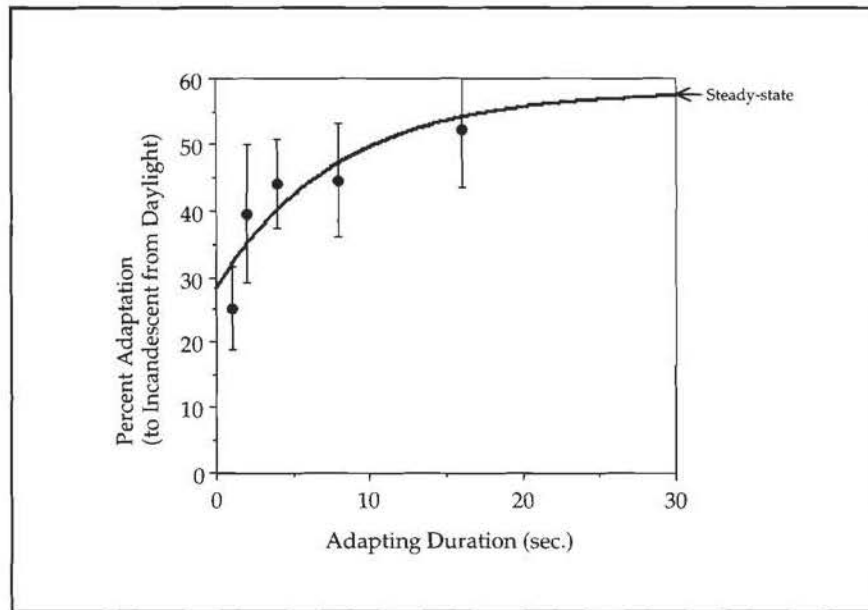

Figure 3. Degree of adaptation to an illuminant A background as a function of adapting duration.

function of the adapting duration of the illuminant A background. Error bars represent plus-and-minus 2 standard errors of the mean estimates for 3 observers. An exponential curve was fitted to the data passing through 26% for a 0 sec. adapting duration since the D65 and A backgrounds were alternating and asymptoting at 58% since adaptation to illuminant A is never more complete for these displays. These results show chromatic adaptation to have an exponential time-constant of 8.4 sec. and be essentially complete after 20 sec. The rather fast action of the chromatic-adaptation mechanisms might seem surprising, but it should be noted that this is the time-course of adaptation to changes in chromaticity at constant luminance. Previous experiments such as those of Hunt (1950) measured the time-course of adaptation when the changes were made from dark to some adapting condition. When there is a luminance change, adaptation can take several minutes. However, this is a combination of light-adaptation and chromatic-adaptation mechanisms. Chromatic-adaptation mechanisms on their own are quite rapid. This result can also be illustrated through afterimages, which

can be created quite easily by fixating colored stimuli for only a few seconds. Fairchild and Lennie (1992) also discuss this experiment.

Effect of Instructions

Berns and Gorzynski (1991) reported an experiment in which observers choose the most achromatic stimulus from a range of nearly achromatic samples under a variety of adaptation conditions using both soft- and hard-copy displays. Their results for CRT displays with average chromaticities corresponding to a tungsten source agreed well with the results discussed above. Adaptation was incomplete. However when the experiment was repeated using a hard-copy display viewed under a tungsten light source a strikingly different result was obtained. For a hard-copy (reflecting object), the chromaticity that appeared achromatic was nearly identical to the chromaticity of the light source. In other words, adaptation was essentially complete for hard-copy displays, but incomplete for soft-copy displays. The difference comes from the cognitive mechanisms that are generally credited with the ability to "discount the illuminant." The hard-copy display was interpreted as an illuminated object and the yellowish color of the illuminant was automatically discounted. (Note that incomplete adaptation allows the observers to know that the illumination is yellowish. This is necessary to provide the cognitive mechanisms with information about both the object and the light source.) Observers can easily report that the lighting is yellowish, but at the same time, when viewing reflecting objects will choose the same chromaticity as appearing achromatic. The soft-copy display could not be interpreted as an object with a yellowish light source and therefore the cognitive mechanisms did not function and adaptation was incomplete.

An interesting twist on the above experiment was also performed. The observers were asked to look at a hard-copy sample that appeared achromatic under tungsten illumination and adjust an image of the same object on a tungsten-balanced CRT until it looked like an image of the hard copy object. With these instructions, observers produced a patch on the CRT with nearly the same chromaticity as the tungsten balance — in effect, adaptation was now complete to the CRT as well. However, it should be noted that the CRT patch did not appear achromatic — it simply matched the appearance of a hard-copy patch that appeared achromatic!

Arend and Reeves (1986) published similar results. They simultaneously showed a variety of colored patches to observers on a CRT. One half of the display simulated the patches under daylight illumination while the other half simulated the patches under tungsten illumination. When observers were asked to match a patch from one half of the display to one on the other half, they made simple colorimetric matches. There was no change in adaptation from one side of the display to the other. If, instead, the observers were asked to make a patch on one side of the display look as if it were cut from the same piece of paper as the patch on the other side, they made matches as if they had adapted completely to each side of the display. These results show how instructions to the observers can vary experimental results and point to cognitive mechanisms as the causes of these differences.

Effect of Image Content

It is clear that the differences between sensory and cognitive mechanisms could be highlighted by changing the mode of viewing a stimulus (illuminated object vs. self-luminous) and by changing the instructions to observers. An additional experiment (Fairchild, 1992) was designed to determine whether the image content of an adapting background could be changed in a manner such that a CRT display might be interpreted as an illuminated object rather than a self-luminous stimulus without giving the observers specific instructions on how to interpret the display. Rea, Robertson, and Petrusic (1990) illustrated the importance of observers seeing their own hands under a given light source when evaluating the source's color rendering properties. This led to the hypothesis that a soft-copy display of a pair of hands holding an image might be interpreted more like an illuminated reflection print than a simple CRT display of the image (as is typical). An adapting background consisting of a mosaic of random-lightness, equal-chromaticity patches was designed and two surrounds constructed for this image. One was simply a uniform gray. The other was an image of a small white border held by two hands on a uniform gray background. Ten observers adjusted $1°$ test stimuli presented in the center of the display for 200 msec. every 2 sec. until they appeared achromatic (16 replicates each). The luminance of the test stimulus was 20% of the maximum luminance of the display ($125\,cd/m^2$). Observations were performed using 2 adapting chromaticities, CIE illuminants D65 and A. Thus, there were 4 experimental conditions illuminant D65 with and without hands and illuminant A with and without hands. Observers were asked to adjust the test stimulus to appear achromatic and given no further instructions.

Figure 4 shows the mean adapting and achromatic-appearing chromaticities for the 4 test conditions. Adaptation is essentially complete for the D65 adapting backgrounds whether the hands were present or not. This agrees with the results of previous experiments
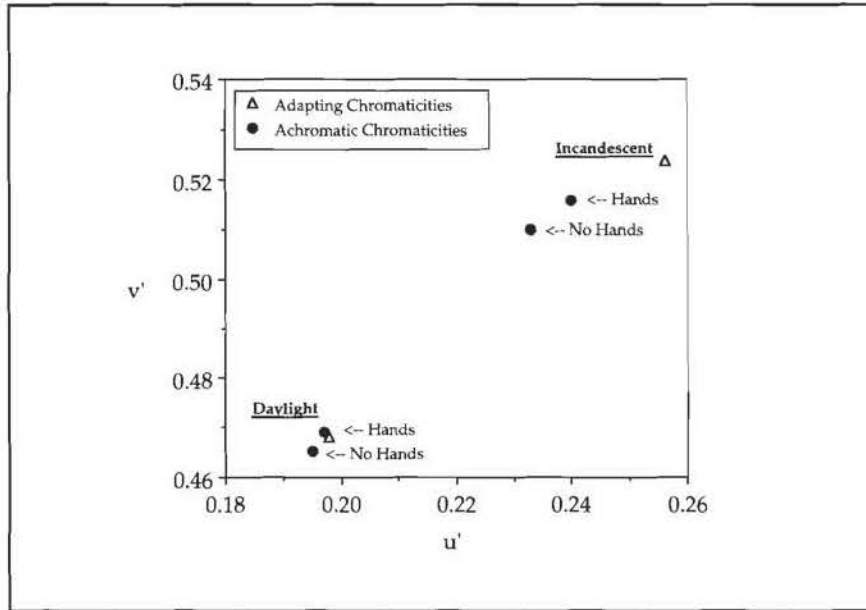
Figure 4. Achromatic-appearing chromaticities for illuminant D65 and A adapting stimuli with and without hands in the background.

discussed earlier in this paper. Complete adaptation to D65 regardless of mode of viewing or instructions explains why D65 white points are popular for television and CRT computer displays. (Adaptation is also essentially complete for illuminant D93, which is commonly used for computer graphics displays. However a D93 display does retain a slight bluish appearance.) Adaptation to the illuminant A background without hands was incomplete and the result agrees well with the previous experiment illustrated in figure 1. However, when the hands were present in the adapting background, the achromatic-appearing chromaticity shifted significantly toward the adapting chromaticity. Adaptation was more complete when the hands were present. However, the achromatic chromaticity did not shift completely to the adapting chromaticity as it would have for an actual hard-copy display. Therefore a CRT image of hands holding an image is perceived more like a hard-copy display than a simple CRT image, but the effect is not complete.

An observation made during demonstrations of chromatic adaptation to CRT image displays was that if an illuminant A-balanced image was viewed before an illuminant D65-balanced version of the same image, adaptation to the A-balanced image seemed more complete than if the images were viewed in the reverse order. To see if this apparent effect was quantifiable, half of the observers in the above experiment were presented with the D65 versions of each image before they saw the A versions and the other half of the observers were presented the images in the reverse order. Figure 5 shows the achromatic-appearing

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chromaticities when the data are separated according to order of presentation. Order had little effect on the results for the D65 images, but the both achromatic points for the illuminant A images shifted significantly toward the adapting chromaticity when the illuminant A images were viewed before seeing the daylight images. There is a clear hysteresis that cannot be
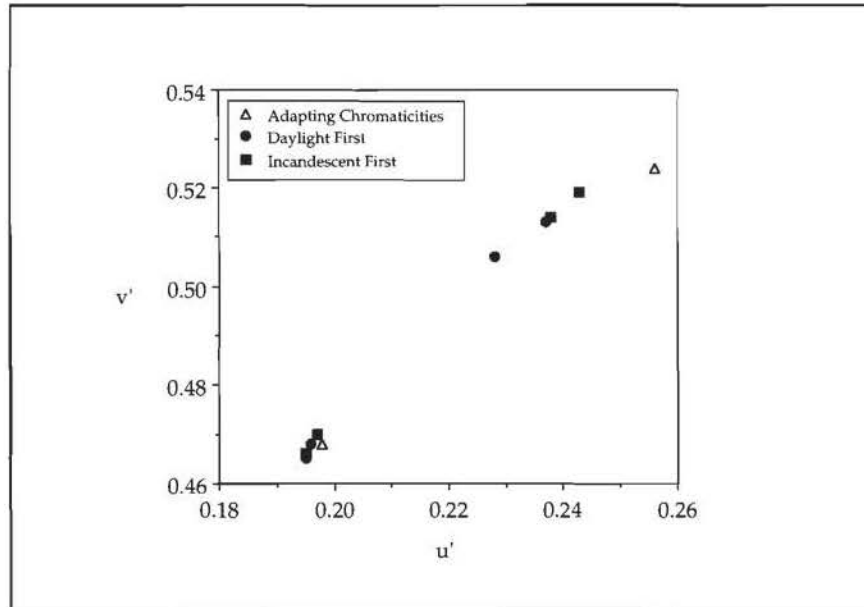

Figure 5. The effect of presentation order on achromatic-appearing chromaticities.

explained by slowly integrating mechanisms of adaptation (This possibility is eliminated by the time-course results presented in figure 3 and by the series of images in this experiment that always alternated between D65- and A-balanced images.). The effect must be due to some cognitive effect that the first presentation of an image appears more "normal" and adaptation to it is more complete. An important note to these results is that they were obtained for both naive observers and observers aware of the objectives of the experiment. Therefore the cognitive mechanisms go beyond knowledge and instructions; they are partially automatic but rely on scene content and interpretation.

Mathematical Model of Chromatic Adaptation

A model capable of predicting incomplete chromatic adaptation was recently published (Fairchild, 1991a) and enhanced to account for the Hunt effect and to allow for differences between CRT (no cognitive mechanisms) and hard-copy (cognitive mechanisms active) displays (Fairchild, 1991b). This model is applicable to predicting color appearance matches between images presented in different media and under different viewing conditions. The mathematical formulation of the model follows.

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The model is most clearly formulated as a series of matrix multiplications. The first step is a transformation from CIE tristimulus values, XYZ, to fundamental tristimulus values, LMS, for the first viewing condition. The Hunt-Pointer-Estevez transformation is used.

$$\begin{bmatrix} L_1 \\ M_1 \\ S_1 \end{bmatrix} = M \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} \tag{1}$$

$$M = \begin{bmatrix} 0.4002 & 0.7076 & -0.0808 \\ -0.2263 & 1.1653 & 0.0457 \\ 0.0 & 0.0 & 0.9182 \end{bmatrix} \tag{2}$$

The next step is to apply a modified form of the von Kries chromatic adaptation transform that takes into account the well-established fact that chromatic adaptation is incomplete.

$$\begin{bmatrix} L'_1 \\ M'_1 \\ S'_1 \end{bmatrix} = A_1 \begin{bmatrix} L_1 \\ M_1 \\ S_1 \end{bmatrix} \tag{3}$$

$$A = \begin{bmatrix} a_L & 0.0 & 0.0 \\ 0.0 & a_M & 0.0 \\ 0.0 & 0.0 & a_S \end{bmatrix} \tag{4}$$

$$a_L = \frac{P_L}{L_n} \tag{5}$$

$$P_L = \frac{(1 + Y_n^v + 1_E)}{(1 + Y_n^v + {}^1/1_E)} \tag{6}$$

$$1_E = \frac{3(L_n/L_E)}{L_n/L_E + M_n/M_E + S_n/S_E} \tag{7}$$

The a terms for the short- (S) and middle-wavelength (M) sensitive systems are derived in a similar fashion. Y is the luminance of the adapting stimulus in cd/m² and terms with n

subscripts refer to the adapting stimulus while terms with E subscripts refer to the equal-energy illuminant. The exponent, n, is set equal to 1/3.

The final step in the calculation of post-adaptation signals is a transformation that allows luminance-dependent interaction between the three cone types.

$$\begin{bmatrix} L_a \\ M_a \\ S_a \end{bmatrix} = C_1 \begin{bmatrix} L'_1 \\ M'_1 \\ S'_1 \end{bmatrix} \tag{8}$$

$$C = \begin{bmatrix} 1 & c & c \\ c & 1 & c \\ c & c & 1 \end{bmatrix} \tag{9}$$

$$c = 0.219 - 0.0784 \log_{10}(Y_N) \tag{10}$$

The c term was derived from the work of Takahama *et al.* (1977) In the Fairchild (1991a) version of this model the C matrix was, in effect, set to an identity matrix.

To determine corresponding chromaticities for a second adapting condition, the A and C matrices must be derived for that condition, inverted, and applied as shown below.

$$\begin{bmatrix} L'_2 \\ M'_2 \\ S'_2 \end{bmatrix} = C_2^{-1} \begin{bmatrix} L_a \\ M_a \\ S_a \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} L_2 \\ M_2 \\ S_2 \end{bmatrix} = A_2^{-1} \begin{bmatrix} L'_2 \\ M'_2 \\ S'_2 \end{bmatrix} \tag{12}$$

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = M^{-1} \begin{bmatrix} L_2 \\ M_2 \\ S_2 \end{bmatrix} \tag{13}$$

The entire model can be expressed as a single matrix equation.

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = M^{-1} A_2^{-1} C_2^{-1} C_1 A_1 M \begin{bmatrix} X_1 \\ Y_1 \\ Z_t \end{bmatrix} \qquad (14)$$

The model, as described above, should only be used when the observer is unable to use cognitive mechanisms to discount the illuminant (*e.g.*, CRT and projection displays). When cognitive mechanisms function (*e.g.*, reflecting objects), the diagonal elements of matrix A should be set equal to the inverse of the appropriate fundamental tristimulus values of the adapting stimulus.

Currently, this model can be used only to predict matches between stimuli or images presented in different media or under different light sources. It does not include predictors of various appearance attributes such as lightness, chroma, and hue. These predictors are not necessary when the objective is to produce matches or corresponding colors. However they could become useful in cross-media reproduction when one wants to manipulate the image to change its colors or to perform operations such as gamut mapping. Another limitation of this model is that it does not account for changes in apparent image contrast due to changes in the luminance of a surround. For example, projected transparencies in a dark surround have a lower perceived contrast than an identical distribution of image intensities viewed in a light or average surround. A simple extension to this model has been formulated to address these limitations and should appear in a future article.

Cross-Media Reproduction

Figure 6 is a flow chart illustrating the steps required for successful, accurate, cross-media color reproduction. The image exists in some original medium and is procured via an input device. The first step is a colorimetric characterization of the input device that converts the original image from device dependent coordinates such as RGB or CMYK to device-independent CIE tristimulus values. In this step, variables such as illuminating and viewing geometry, source spectral power distribution, and observer color matching functions must be appropriately set. The second step is to account for viewing conditions such as illumination color, type of medium, luminance level, and surround by transforming from CIE tristimulus values to a "viewing-conditions independent" color appearance space. At this point image manipulations such as color preference editing, gamut mapping, and compositing are performed. The entire process is then reversed for the output device. First by transforming from the color appearance space to the appropriate CIE tristimulus values for the new viewing conditions and then by transforming from CIE tristimulus values to the appropriate output device color coordinates. This flow chart highlights the necessity for simple inversion of any appearance models that are to be used for color image reproduction.
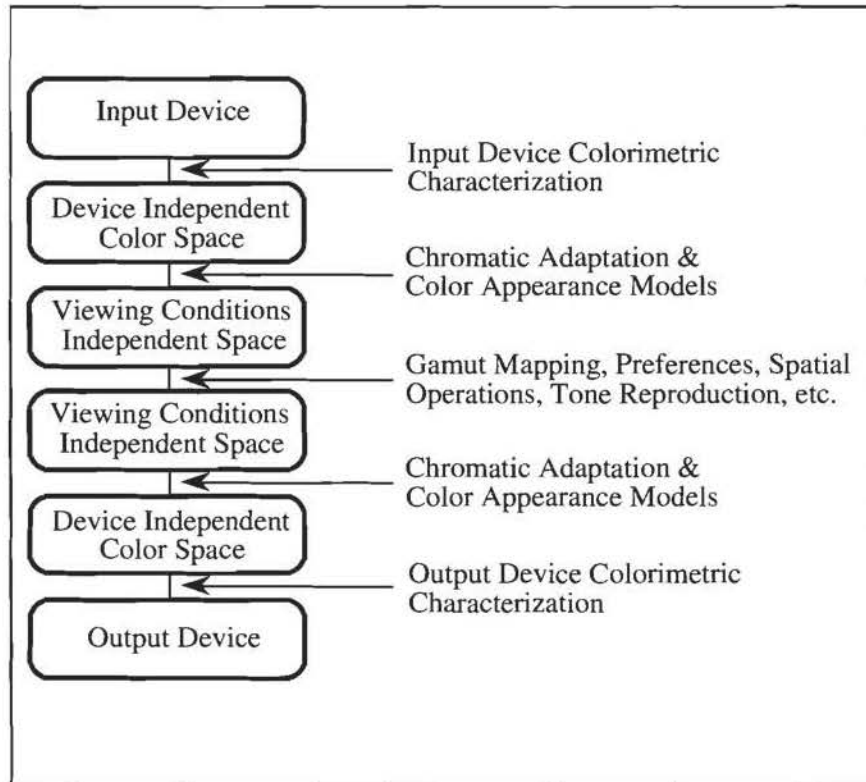
Figure 6. Flow chart of the process of cross-media color reproduction.

An experiment was designed to test a few models and displays using the system outlined in figure 6. Six 4x6" photographic prints with various image content ranging from portraits to natural landscapes were used as originals. Each print was mounted with a 0.5" white border on a medium gray mount board. The images were digitized using a Howtek Scanmaster 300 flatbed scanner with a resolution of 380x570 pixels. This is the resolution required to display the digital images on a Sony GDM-1950 CRT display with a size of 4x6". The scanner RGB values were converted to CIE 2° tristimulus values using a statistically optimized empirical model. Separate models were derived for obtaining the CIE tristimulus values for photographic print originals under CIE illuminants D50, D65, and A. The photographic prints were viewed in a light booth with a black surround and illuminant D50 or A simulators. The luminance of an illuminated white PTFE sample (99.2% reflectance) in the booth was 161 cd/m^2 for D50 and 206 cd/m^2 for A. Three models were used to reproduce these images on the CRT display, CIE tristimulus values (XYZ), CIELab coordinates, and the Fairchild (1991b) chromatic adaptation model (referred to as F91). The CRT display was set -up with a D65 white point and a maximum luminance of 61 cd/m^2.

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Images were displayed with a 0.5" white border on a medium gray background rendered as an image of a pair of hands holding the images on the background. The chromaticity of the border and background was that of illuminant D65. The CRT display was surrounded by darkness. The white border and gray background were held constant on the CRT display, only the images they surrounded were manipulated. An analytical model of the CRT was used to characterize the relationship between the desired CIE tristimulus values and the RGB signals required to drive the display. The CRT reproductions determined using XYZ tristimulus values were created by simply reproducing the relative tristimulus values of the prints under each illuminant on the CRT. The CIELab reproductions were constructed by calculating the CIELab values of the prints in the light booth and then producing the same CIELab values on the CRT using a D65 white point. Thus the CIELab reproductions accounted for the changes in white point from A or D50 in the booth to D65 on the CRT. The F91 model was implemented in a similar fashion, accounting for the changes in white point, luminance level, and medium.

The light booth and CRT were arranged such that an observer could view one or the other by rotating 90°. Both displays were arranged at an equal viewing distance of approximately 50cm. The observers could view only one of the displays at time, but could switch between them at will. Two sessions were completed; one with D50 illumination in the booth and a second with A illumination in the booth. Observers would place one of the hard-copy images in the back of the light booth and examine it for several seconds. They would then view the CRT display where they could toggle between 3 different reproductions of the image (XYZ, CIELab, & F91). Observers were instructed to choose which of the 3 CRT images was the best reproduction of the hard-copy. They were allowed to gaze back and forth between the CRT and hard-copy, but were instructed to view each for at least several seconds each time. After they chose the best reproduction, the observers also responded as to whether the reproduction was acceptable or not. A context of consumer photographs being reproduced for video display was given to each observer for the acceptability judgements. Fourteen color-normal observers with a wide variety of prior experience in color reproduction took part in this experiment.

The experiment was modified and repeated 2 more times with 6 additional observers. For these experiments, the CRT image background was replaced with a uniform medium gray (D65) and a uniform black. The objective for the using the gray background was to determine whether the constant white border had any influence on the results. The black background was used to simulate typical CRT image viewing in which the image completely fills the display.

Figure 7 shows the percentage of trials for which each model was chosen as the best reproduction method for D50 illumination. The XYZ-tristimulus reproductions were rarely
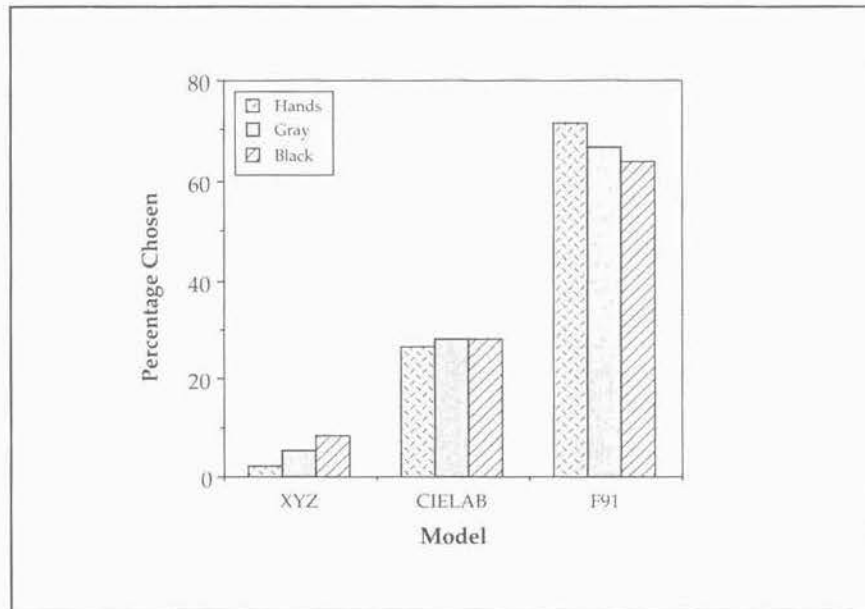
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Figure 7. Percentage of trials on which each model was chosen as producing the best cross-media color reproduction from an illuminant D50 light booth to a D65 CRT.

chosen despite the rather small change in white point from D50 to D65. The largest number of XYZ choices were made with the black background. The CIELab reproductions were chosen on between 26 and 28% of the trials. Background had no significant effect on the CIELab results. The F91 reproductions were the most preferred on all 3 backgrounds, chosen on between 64 and 71% of trials. The reproductions chosen best were found to be acceptable 69.1% of the time on the hands background and 88.9% for both the gray and black background. The lower acceptability on the hands background was due to a discrepancy between the white border and white areas in some of the images. This could easily be corrected by treating the white border as part of the image rather than part of the background. Several of the observers reported that they found the reproductions unacceptable for reasons other than color reproduction such as low resolution or scanner noise. These results indicate that useful cross-media color reproduction is possible using fairly simple adaptation models.

The results for incandescent hard-copy illumination are more ambiguous. The white point difference between the illuminant A booth and the illuminant D65 CRT might be too large for accurate use of the uncontrolled successive inspection technique used in this experiment. The results are illustrated in figure 8. The results are most ambiguous for the
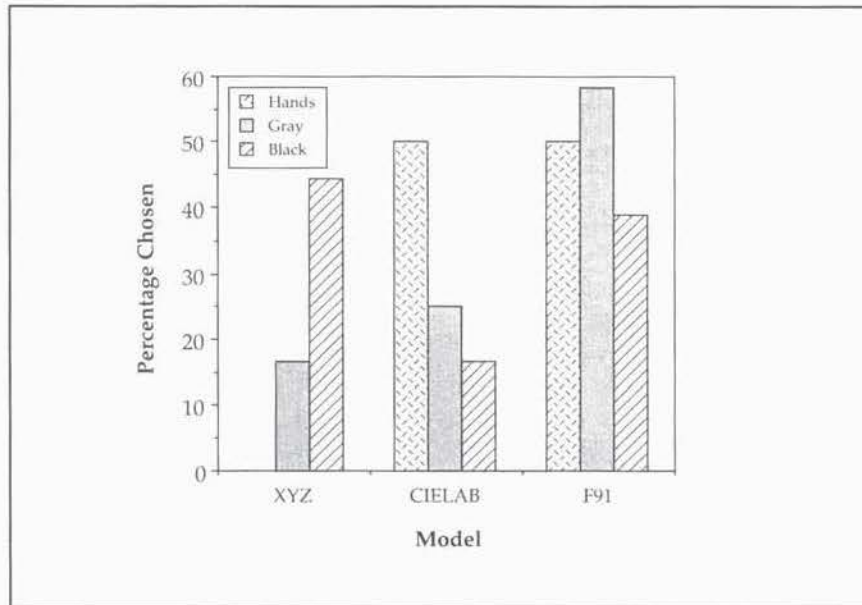
Figure 8. Percentage of trials on which each model was chosen as producing the best cross-media color reproduction from an illuminant A light booth to a D65 CRT.

black background since the CRT effectively has an illuminant A white-point for the XYZ reproduction and an illuminant D65 white-point for the CIELab and F91 reproductions. This presents a rather confusing display to the observers who chose the XYZ reproduction on 44% of the trials, the F91 reproduction of 39%, and CIELab on only 17% of the trials. Only 50% of the best reproductions were acceptable for a black background. These results highlight the importance of having CRT images presented in an environment that produces a stable state of chromatic adaptation. The hands and gray backgrounds help to provide this stable environment. With the gray background, the F91 model was chosen best on 58% of the trials and the acceptability rate was 75%. With the hands background, the F91 and CIELab reproductions were each chosen on 50% of the trials with an acceptability rate was 64%. The illuminant A results illustrate that for such a large change in adaptation under relatively uncontrolled (*i.e.* typical) viewing conditions, an adaptation model more accurate than that incorporated in CIELab might not be required. Further experiments are being designed to expand these tests to include other appearance models under such practical cross-media reproduction conditions.

CONCLUSION

The processes that occur in the human visual system when an image is viewed are complex and likely to never be fully understood. The experiments described in this paper

have been designed to quantify the performance of some of these mechanisms. In summary, measurements of the performance of sensory chromatic adaptation mechanisms have shown them to be chromatically incomplete, spatially localized, and temporally active with a time course on the order of tens of seconds. Explorations of the differences between adaptation to soft-copy and hard-copy image displays have highlighted differences between cognitive mechanisms that are active when recognizable objects are viewed under recognizable illumination and sensory mechanisms that respond directly to the stimulus spectral power distribution.

Independent support for this interpretation has been found in the field of cognitive science. Davidoff (1991) published a monograph on the recognition of objects and color appearance. In Davidoff's model, the generation of color names (and therefore color appearance) depends on input from two different pathways; one driven by the knowledge of attributes of recognized objects and the other driven more directly be visual data. Therefore color names for recognizable objects (such as hard-copy images) depend on both pathways, while the color names for stimuli that cannot be recognized as objects (such as CRT displays) can only depend on the data-driven pathway. This model, from an entirely independent scientific field, accurately corroborates the concepts of chromatic adaptation to various image displays outlined in this paper.

Lastly, a model that accounts for many of the properties of the cognitive and sensory mechansims of chromatic adaptation (Fairchild, 1991b) has been used to reproduce color images in different media under different viewing conditions with promising results.

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LITERATURE CITED

Arend, L. and Reeves, A.
    1986. "Simultaneous color constancy," **J. Opt. Soc. Am. A 3**, 1743-1751.

Bartleson, C.J.
    1978. "A review of chromatic adaptation," **AIC Proceedings, Color 77**, Troy, 63-96.

Berns, R.S. and Gorzynski, M.E.
    1991. "Simulating surface colors on CRT displays: The importance of cognitive clues," **AIC Proceedings, Light and Color**, Melbourne, in press.

Breneman, E.J.
    1987.   "Corresponding chromaticities for different states of adaptation to complex visual fields," **J. Opt. Soc. Am. A 4**, 1115-1129.

Davidoff, J.
    1991.   "Cognition through color" (MIT Press, Cambridge), 217pp.

Evans, R.M.
    1943.   "Visual Processes and Color Photography," **J. Opt. Soc. Am. 33**, 579-614.

Fairchild, M.D.
    1990.   "Chromatic Adaptation and Color Appearance," Ph.D. Thesis, University of Rochester, 162pp.
    1991a.   "Formulation and Testing of an Incomplete-Chromatic-Adaptation Model," **Color Res. Appl. 16**, 243-250.
    1991b.   "A Model of Incomplete Chromatic Adaptation," **Proceedings of the CIE 22nd Session**, 33-34.
    1992.   "Chromatic Adaptation and Color Constancy," **OSA Advances in Color Vision**, in press.

Fairchild, M.D. and Lennie, P.
    1992.   "Spatial and temporal properties of chromatic adaptation to natural and incandescent illuminants," **Vision Res. 32**, in press.

Helmholtz, H. v.
    1866.   "Handbuch der physiologischen Optick," (Voss, Hamburg), 1st ed.

Hering, E.
    1920.   "Outlines of a theory of the light sense," (Harvard Univ. Press, Cambridge), trans. by L.M. Hurvich and D. Jameson, 1964.

Hunt, R.W.G.
    1950.   "The effects of daylight and tungsten light-adaptation on color perception," **J. Opt. Soc. Am. 40**, 362-371.
    1991.   "Revised Colour-appearance model for related and unrelated colours," **Color Res. Appl. 16**, 146-165.

Hunt, R.W.G. and Winter, L.M.
    1975.   "Colour adaptation in picture-viewing situations," **J. Phot. Sci. 23**, 112-115.

Jameson, D. and Hurvich, L.M.
    1989.   "Essay concerning color constancy," **Ann. Rev. Psychol. 40**, 1-22.

Judd, D.B.
    1940.   "Hue, saturation, and lightness of surface colors with chromatic illumination," **J. Opt. Soc. Am. 30**, 2-32.

Lennie, P. and D'Zmura, M.
    1988.   "Mechanisms of color vision," **CRC Critical Reviews in Neurobiology 3**, 333-400.

MacAdam, D.L.
    1970.   "Sources of color science," (MIT Press, Cambridge), 282pp.

Nayatani, Y., Takahama, K., Sobagaki, H. and Hashimoto, K.
    1990.   "Color-Appearance Model and Chromatic Adaptation Transform," **Color Res. Appl. 15**, 210-221.

Rea, M.S., Robertson, A.R. and Petrusic, W.M.
    1990.   "Colour rendering of skin under fluorescent lamp illumination," **Color Res. Appl. 15**, 80-92.

Takahama, K., Sobagaki, H. and Nayatani, Y.
    1977.   "Analysis of chromatic-adaptation effect by a linkage model," **J. Opt. Soc. Am. 67**, 651-656.

von Kries, J.
    1902.   "Chromatic adaptation," **Festschrift der Albrecht-Ludwig-Universität**, (Fribourg).

Woodworth, R.S.
    1938.   "Experimental psychology," (Holt, New York) 889pp.

Wright, W.D.
    1981.   "Why and how chromatic adaptation has been studied," **Color Res. Appl. 6**, 147-152.