Color-Defective Vision

Color-Defective Vision and Computer Graphics Displays

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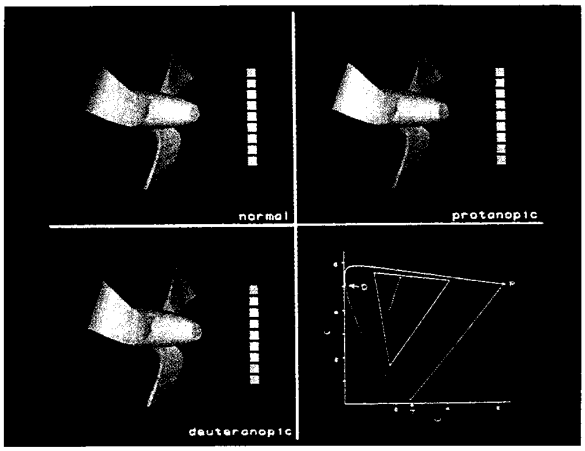

The fundamental spectral sensitivity functions of the human visual system define a color space that can help in designing better color user interfaces. In particular, this color space makes it possible to accommodate individuals with color-deficient vision. To screen potential users of computer graphics systems, traditional color vision tests, such as the Farnsworth-Munsell 100-hue test, can be implemented using a digitally controlled color television monitor, and these tests can be extended in ways that improve the specificity of their diagnoses. To assist in the design of computer graphics displays, a picture of the world as seen by color-deficient observers can be synthesized, and guidelines can be given for the selection of colors to be presented to color-deficient observers.

The 1931 CIE standard observer color-matching functions form the basis for color reproduction work in computer graphics. There is, however, a more fundamental color space based on the spectral sensitivity functions actually found in the human visual system. This space has important implications for color work in computer graphics. With some assumptions about the nature of color-defective vision, the transformation between the CIE *XYZ* space of the 1931 standard observer and this fundamental space can be derived.

This article introduces the above-mentioned fundamental color space and shows how it can be used to assist in the design of computer graphics displays for color-deficient users. First, the fundamental spectral sensitivity functions of the human visual system are derived in terms of the CIE standard observer color-matching functions. Next the Farnsworth-Munsell 100-hue test, a widely used color vision test administered using physical color samples, is implemented on a digitally controlled color television monitor. The flexibility of this computer graphics medium is then used to extend the Farnsworth-Munsell test in a way that improves the specificity of the diagnoses rendered by the test. Then the issue of how the world appears to color-deficient observers is addressed, and a full-color image is modified to represent a color-defective view of the scene. Finally, specific guidelines are offered for the design of computer graphics displays that will accommodate almost all color-deficient users.

Principles of color science

Color science is based on the results of a set of color-matching experiments. In these experiments, a subject matches a series of spectral light sources with the light from three independent sources *R*, *G*, and *B*. The three sources produce an additive mixture in which the composition at any wavelength is the result of adding the power present at that wavelength in each of the constituent lights. The amount of each light source necessary

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to achieve a match with the spectral light is recorded, and the resulting matching functions $\overline{r}(\lambda)$, $\overline{g}(\lambda)$, and $\overline{b}(\lambda)$ can be used to compute the amount of light necessary to match an arbitrary spectral energy distribution $E(\lambda)$

$$\begin{aligned} R &= \int E(\lambda)\overline{r}(\lambda)\, d\lambda \\ G &= \int E(\lambda)\overline{g}(\lambda)\, d\lambda \\ B &= \int E(\lambda)\overline{b}(\lambda)\, d\lambda \end{aligned} \tag{1}$$

The mean data of Guild[1] and Wright[2] have been adopted by the CIE as a standard set of matching functions and will therefore be used in this article. However, because of the technology available at the time, these data have limitations. The more recent work of Stiles and Burch[3] may be better for careful vision research.[4]

The 1931 CIE XYZ standard observer color-matching functions $\overline{x}(\lambda)$, $\overline{y}(\lambda)$, and $\overline{z}(\lambda)$ (see Figure 1) are a linear transform of the Guild and Wright color-matching data. Color matches are preserved under linear transformation because color matching obeys the laws of proportionality and additivity.[5] Tristimulus values XYZ can be computed through the expressions

$$\begin{aligned} X &= \int E(\lambda)\overline{x}(\lambda)\, d\lambda \\ Y &= \int E(\lambda)\overline{y}(\lambda)\, d\lambda \\ Z &= \int E(\lambda)\overline{z}(\lambda)\, d\lambda \end{aligned} \tag{2}$$

Even though these tristimulus values no longer refer to the amount of three real light sources, two different spectral energy distributions with the same tristimulus values will match in color. This property is important for color reproduction work.

The XYZ tristimulus values can be thought of as the endpoints of vectors extending from the origin of a 3D space. Vectors for spectral colors must pass through the locus formed by the matching functions, and these vectors must lie on the cone shown in Figure 2. Since this cone is convex, the vector that results from the integration performed in Equation 2 must lie inside of the cone. The direction of each vector can be specified by the point where the vector pierces the plane $X+Y+Z = 1$ in the space (see Figure 2). An orthographic projection of this plane onto the XY plane is referred to as a chromaticity diagram. Chromaticity coordinates (x,y) are computed from the expressions

$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z} \tag{3}$$

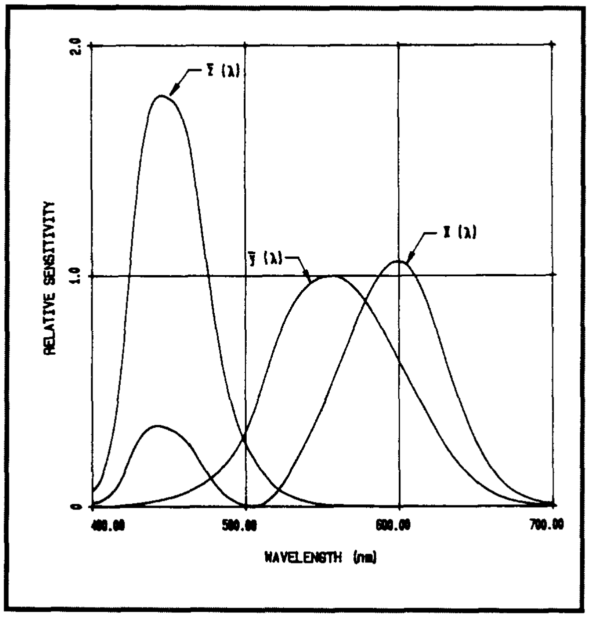


Figure 1. CIE *XYZ* matching functions.

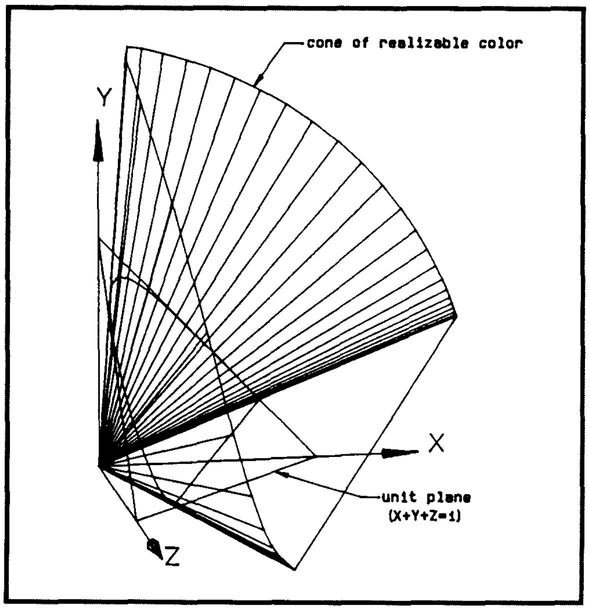


Figure 2. Cone of realizable color and unit plane in CIE *XYZ* space.

The CIE has proposed a linear transform of XYZ space that yields a color space with a perceptually uniform chromaticity diagram. This was done because color-difference loci plotted on the 1931 CIE XYZ chromaticity diagram are not circular. The uniform chromaticity diagram adopted by the CIE in 1960 improved the situ-

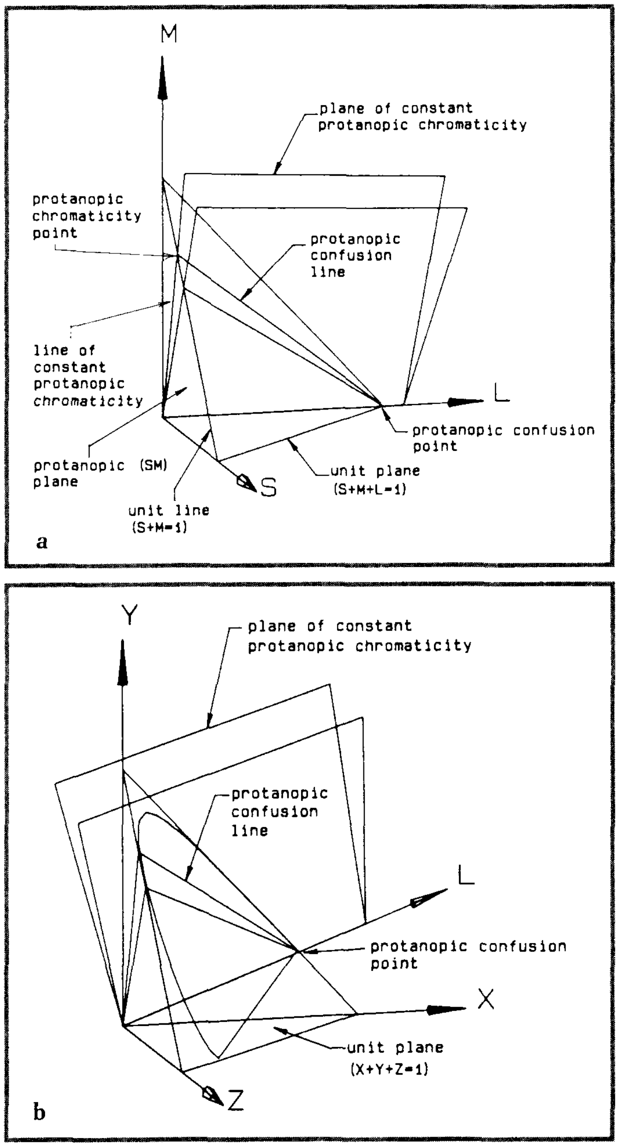


Figure 3. Intersection of the planes of constant protanopic chromaticity defines the position of the *L* axis in (a) *SML* and (b) CIE *XYZ* space.

ation. A further refinement was suggested[6] in 1976 to yield the final nonlinear transformation

$$u = \frac{4X}{X + 15Y + 3Z} \qquad v = \frac{9Y}{X + 15Y + 3Z} \tag{4}$$

where u and v are referred to as the 1976 CIE Uniform Chromaticity Scale (UCS) coordinates.

The fundamental spectral sensitivity functions

The fundamental human spectral sensitivity functions characterize the physical response of the visual system to individual wavelengths of light. From a physiological standpoint these functions are a product of the transmission characteristics of the ocular medium and the spectral sensitivity of the receptors in the eye. The current evidence is that there are three functions with broad spectral sensitivities lying in the short-, medium-, and long-wavelength regions of the spectrum.[7]

From a psychophysical standpoint, the fundamental spectral sensitivity functions should be a linear combination of the color-matching functions described in the preceding section. Using certain assumptions about the nature of color-defective vision, a linear transform of the color-matching functions to the fundamental spectral sensitivity functions can be derived from the results of color-matching experiments on people with color-deficient vision. The psychophysical nature of the fundamental spectral sensitivity curves is the primary concern of this article.

A color-normal person has three fundamental spectral sensitivity functions and is therefore called a trichromat. The fundamental spectral sensitivity functions are designated $\overline{s}(\lambda)$, $\overline{m}(\lambda)$, and $\overline{l}(\lambda)$ for short, medium, and long wavelengths respectively. The *SML* tristimulus values are computed from the expressions

$$\begin{aligned} S &= \int E(\lambda)\overline{s}(\lambda)\,d\lambda \\ M &= \int E(\lambda)\overline{m}(\lambda)\,d\lambda \\ L &= \int E(\lambda)\overline{l}(\lambda)\,d\lambda \end{aligned} \tag{5}$$

Trichromatic chromaticity coordinates for *SML* space are found from the relations

$$s = \frac{S}{S + M + L} \qquad m = \frac{M}{S + M + L} \tag{6}$$

They represent the point of intersection between a color vector and the unit plane $S + M + L = 1$ in *SML* space.

A dichromat is a person who has only two of the three fundamental spectral sensitivity functions. Even though a complete lack of color discrimination can occur only in individuals with a single type of receptor, dichromats are commonly referred to as being color blind.[8-10] They are categorized as protanopes, deuteranopes, or tritanopes, depending on whether the long-, medium-, or short-wavelength receptor is missing. Since S, *M*, or *L* is zero, the color space of a dichromat collapses to one of the trichromat's coordinate planes, and the chromaticity diagram of a dichromat becomes one edge of the trichromat's unit plane. With a protanope the color space becomes the *SM* plane and the chromaticity diagram becomes the unit line $S+M = 1$ (see Figure 3a). Planes in *SML* space that pass through the *L* axis collapse to lines of constant protanopic chromaticity on the *SM* plane. The *SML* tristimulus values that constitute these planes therefore have constant protanopic chromaticity.

The lines of intersection between these planes and the unit plane in *SML* space are called protanopic confusion lines. Protanopes have difficulty distinguishing between colors with trichromatic chromaticities that lie along one of these lines. The protanopic confusion lines all intersect at the protanopic confusion point. This is the point where the axis of the missing *L* fundamental pierces the trichromat's unit plane. A similar analysis holds for deuteranopes and tritanopes, as illustrated in Figures 4a and 5a.

Assuming a linear transform from *SML* space to CIE *XYZ* space, the planes of constant protanopic chromaticity from Figure 3a transform as planes and define new protanopic confusion lines and a new protanopic confusion point on the unit plane in CIE *XYZ* space. As shown in Figure 3b, the CIE *XYZ* chromaticity coordinates of the protanopic confusion point define the position of the *L* axis in CIE *XYZ* space. Color-matching experiments performed on protanopes yield chromaticity confusion lines in CIE *XYZ* space consistent with this prediction. When planes of constant deuteranopic and tritanopic chromaticity are transformed from *SML* space to CIE *XYZ* space, similar results are obtained, as can be seen in Figures 4b and 5b.

Given the chromaticity coordinates of the dichromatic confusion points in CIE *XYZ* space, the transformation from CIE *XYZ* space to *SML* space can be derived. The basic form for this expression is

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} x_t & x_d & x_p \\ y_t & y_d & y_p \\ 1-x_t-y_t & 1-x_d-y_d & 1-x_p-y_p \end{bmatrix} \begin{bmatrix} k_t S \\ k_d M \\ k_p L \end{bmatrix} \tag{7}$$

where x_p, y_p, x_d, y_d, x_t, and y_t are the confusion points, and k_p, k_d, and k_t are normalization factors. From the wide array of proposals for the confusion points,[11-22] the points suggested by Estevez[4] have been selected because his study was the only one that considered all three loci simultaneously with the express intention of defining a set of fundamental spectral sensitivities. The confusion points proposed by Estevez have the values

$$\begin{array}{lll} x_p = .735 & x_d = 1.14 & x_t = .171 \\ y_p = .265 & y_d = -.14 & y_t = -.003 \end{array} \tag{8}$$

To avoid negative values for the fundamentals, $x_p = .735$ was used for the protanopic confusion point instead of the $x_p = .73$ recommended by Estevez. Here y_p was found from the relation $y_p = 1.0 - x_p$. Equations 8 lead to the transformation

$$\begin{bmatrix} S \\ M \\ L \end{bmatrix} = \begin{bmatrix} 0.0000 & 0.0000 & 0.5609 \\ -0.4227 & 1.1723 & 0.0911 \\ 0.1150 & 0.9364 & -0.0203 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{9}$$

where the normalization factors have been selected so that the fundamental spectral sensitivity functions that result from applying this transformation to the 1931 CIE *XYZ* standard observer color-matching functions all peak at 1.0. The fundamental spectral sensitivity functions that result are shown in Figure 6. The cone of realizable color that this produces in *SML* space is shown in Figure 7.

Other derivations of the fundamental spectral sensitivity functions have been proposed.[23] A number of these are based on the Judd modification[24] to the 1931 CIE *XYZ* standard observer color-matching functions. These color-matching functions are widely used in vision research but are not currently used for the practical colorimetric calculations that are the focus of this article. Among the most frequently used fundamental spectral sensitivity functions derived in this way are those of Smith and Pokorny[25] and Vos.[26] Boynton has proposed that an *SML* system based on the Smith and Pokorny fundamentals be adopted as an alternative to the current CIE *XYZ* system.[27]

Color vision tests using television displays

Color vision tests can be an important tool for screening the users of a computer graphics system. Standard tests, such as the Farnsworth-Munsell 100-hue test,[28,29] can be easily implemented on a digitally controlled color television monitor. The flexibility of this hardware also makes it possible to extend the standard tests and devise new color vision tests.

The Farnsworth-Munsell 100-hue test

In the 100-hue test subjects' color vision is judged by how well they can rearrange a set of color samples into

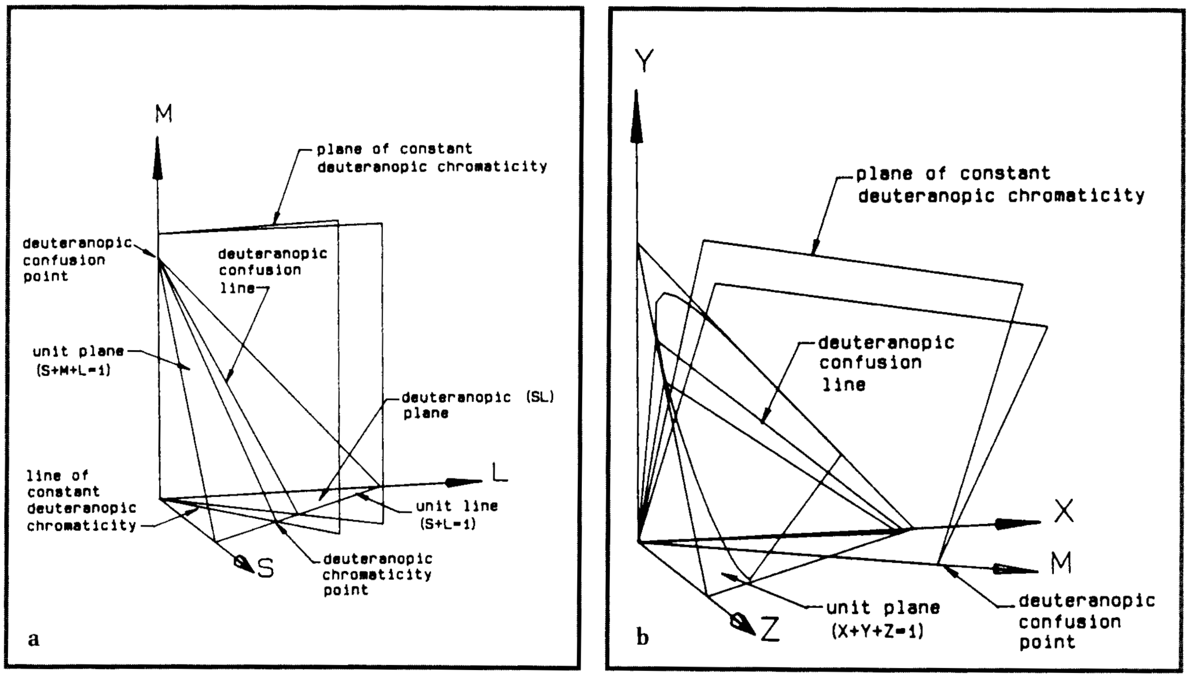


Figure 4. Intersection of the planes of constant deuteranopic chromaticity defines the position of the *M* axis in (a) *SML* and (b) CIE *XYZ* space.

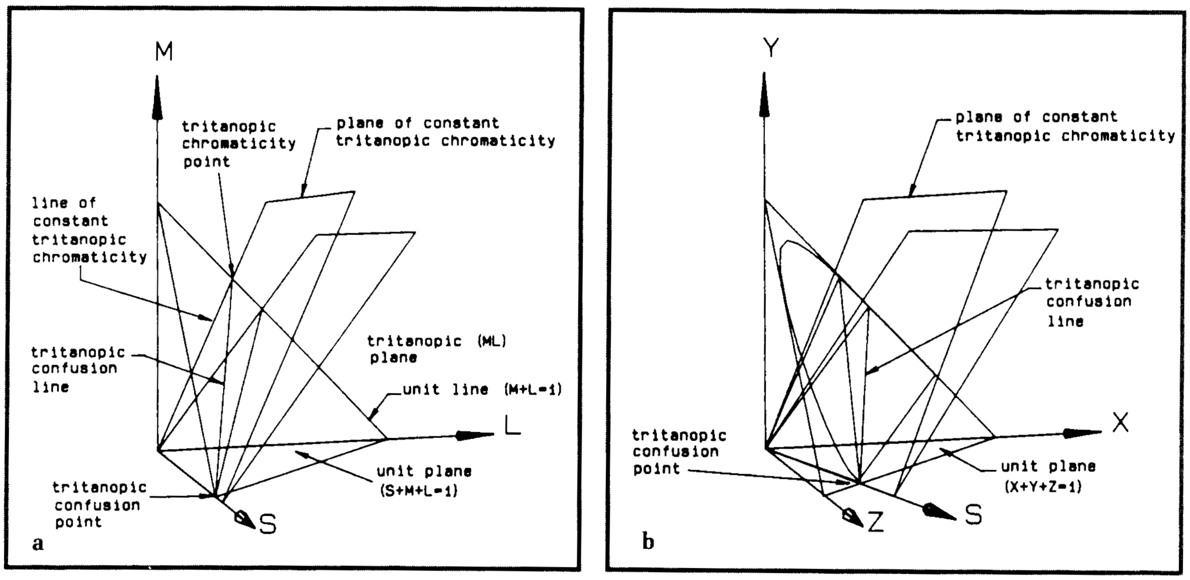


Figure 5. Intersection of the planes of constant tritanopic chromaticity defines the position of the *S* axis in (a) *SML* and (b) CIE *XYZ* space.

a continuous hue circuit. Of the 100 colors originally considered, 85 different Munsell hues are used for the samples, and each sample has Munsell value 6.0 and chroma 6.0. The hue circuit is divided into four quadrants, with one tray of 21 samples for each quadrant. The samples at each end of a tray are fixed, and the subject is given the tray with the rest of the samples in random order. The subject is instructed to organize the samples into a continuous color sequence.

Each of the color samples is assigned a number from

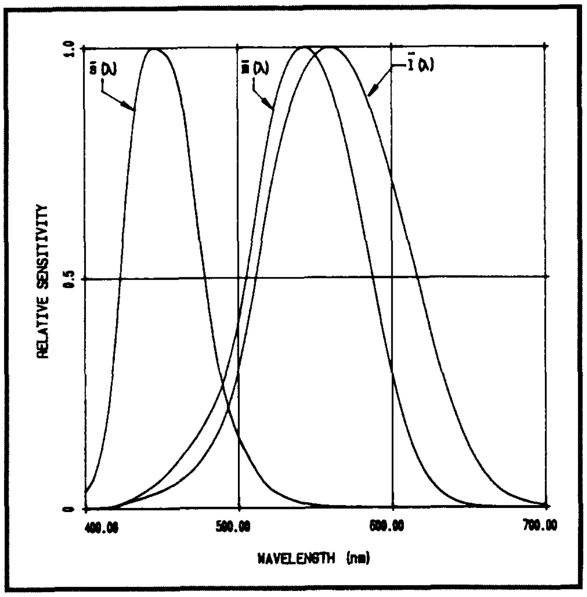


Figure 6. Fundamental spectral sensitivity functions.

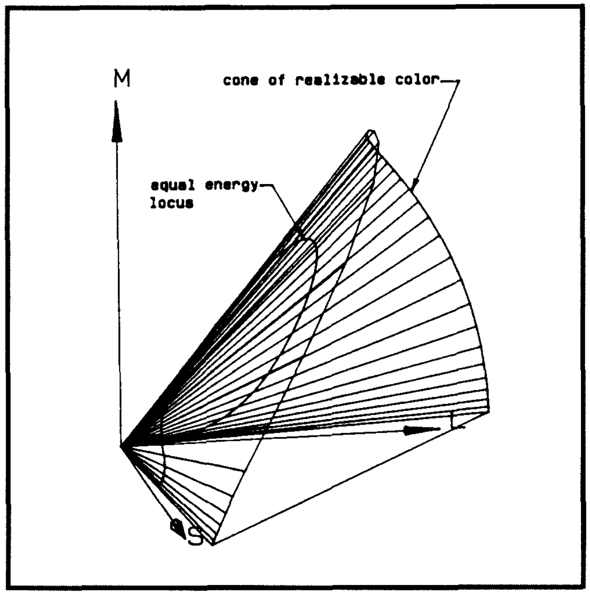


Figure 7. Equal energy spectrum locus and cone of realizable color in *SML* space.

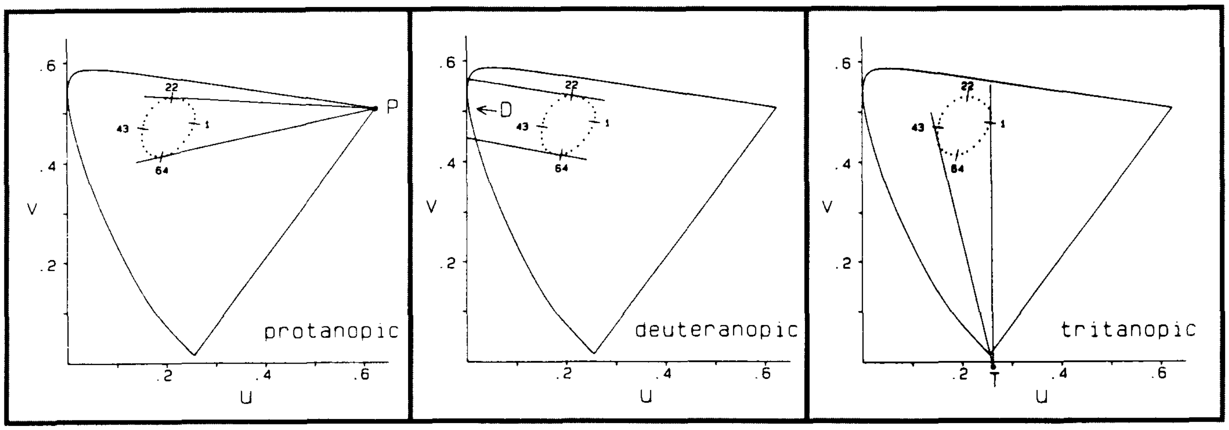


Figure 8. Protanopic, deuteranopic, and tritanopic confusion lines and the chromaticities of the Farnsworth-Munsell 100-hue test.

1 to 85, depending on its position in the hue circuit. When the test is complete, an error score is computed for each sample by adding together the differences between the sample number and the number of the sample on its left and the number of the sample on its right.[30] For instance, if sample 11 is surrounded by samples 8 and 13 in the final ordering, the error for sample 11 will be (11−8)+(13−11) = 5. The error scores are then plotted using a polar coordinate system where angle corresponds to hue and radius to error.

The theory behind the test and the significance of the error scores can be seen in Figure 8. The chromaticities of the 85 color samples are plotted along with the confusion lines for the three different types of dichromats. The points at which the confusion lines are tangent to the hue circuit are the places where each type of dichromat could be expected to make errors in arranging the color samples. Lakowski[29] has suggested that samples 14 to 24 and 57 to 72 for protanopes, samples 12 to 22 and 52 to 64 for deuteranopes, and samples 80 to 9 and 42 to 54 for tritanopes are the regions where the most errors should be expected.

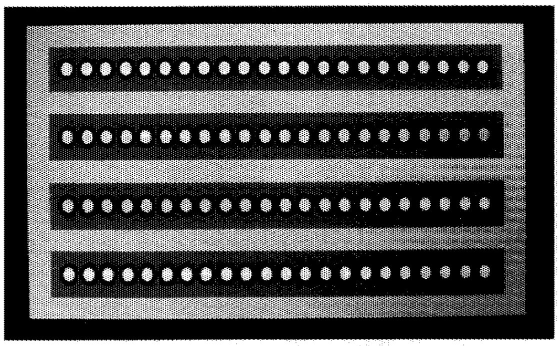
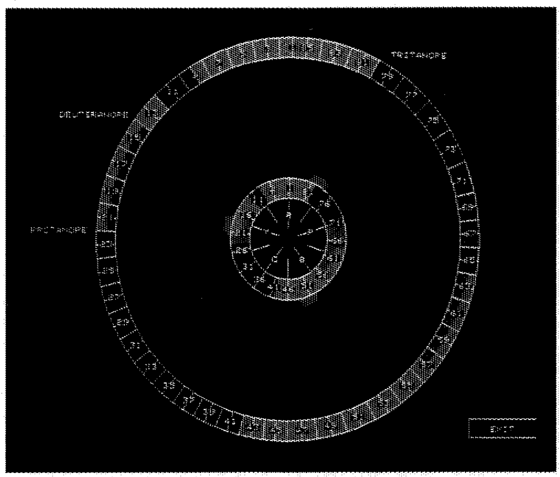


Figure 9. The Farnsworth-Munsell 100-hue color trays.



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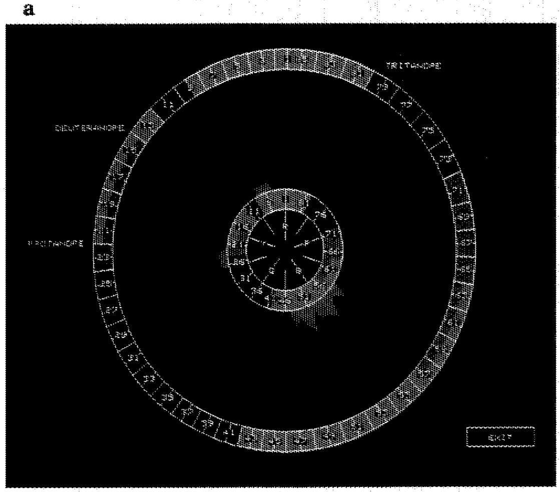

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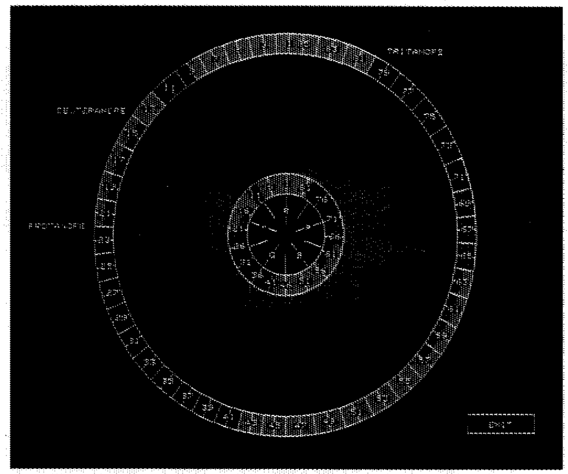
Figure 10. Farnsworth-Munsell 100-hue error plots for two color-normal subjects.



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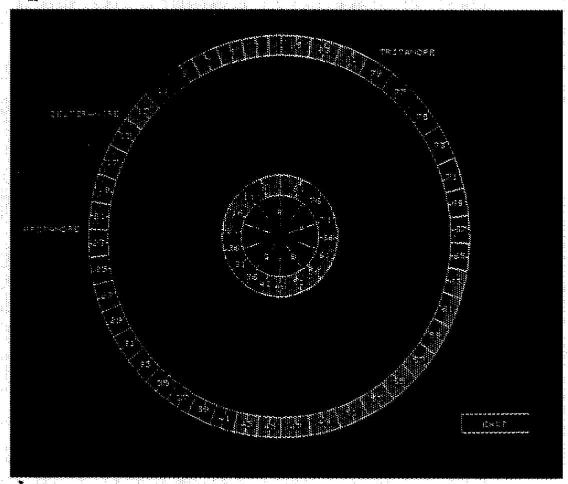

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Figure 11. Farnsworth-Munsell 100-hue error plots for two protanopic subjects.

Using computer graphics hardware, a video version of the 100-hue test can be created. (Breton, Ryan, and Fonash[31] have implemented a modified version of the Farnsworth D-15 test on a video display.) Figure 9 shows the trays (correctly ordered) that are displayed one at a time by the program. The color for each sample is determined by converting the Munsell notation for the sample to the *RGB* values necessary to drive the television monitor.[32,33] The subjects rearrange the tray by using a tablet and a stylus to point at two samples that should be switched. As each sample is selected, a small arrow appears below it and then disappears after the samples have been swapped. After completing a tray, a subject specifies termination and proceeds to the next tray. When the test is complete, the error score for each sample is automatically computed, and a plot of the error is made on the display using the traditional 100-hue polar plot format.

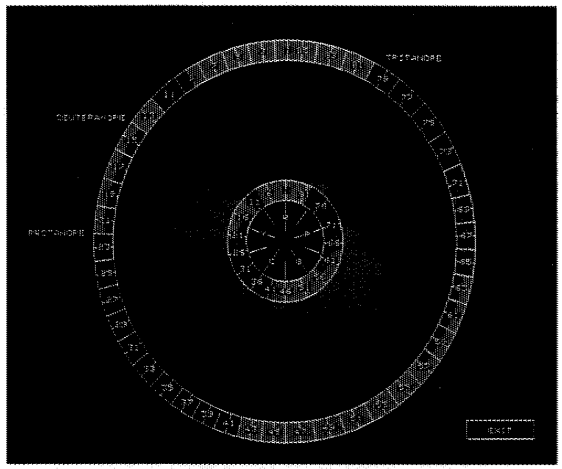
The program was tested on several color-normal subjects and on several subjects known to be color deficient, although the specific nature of their defect was unknown. The results from these tests are shown in Figures 10, 11, and 12. For each type of color-defective vision, errors are expected at positions on the hue circuit roughly opposite one another. In the figures these positions are identified by a specific color for each type of color deficiency. Because the errors cluster at opposite sides of the hue circuit, the error plot for each type of color deficiency has a distinct axis along which error scores are expected to be high. Figures 10a and 10b show representative results for two color-normal subjects. Although the error is quite low around the entire circle, it is not zero. This gives some indication of the difficulty of the task. Figures 11 and 12 show the results for four color-defective subjects. In Figures 11a and 11b the patterns are typical of the results obtained with protanopes, and in Figures 12a and 12b the results are consistent with those for deuteranopes.

An extension to the Farnsworth-Munsell 100-hue test

The flexibility of a color television monitor connected to a digital frame store makes it possible to extend the 100-hue test in a way that provides a more positive identification of dichromatism. The points at which the confusion lines intersect the hue circle on a chromaticity diagram identify the color samples in the 100-hue test that each type of dichromat will have trouble ordering. Because of the way that the color samples are divided among the four trays, the only color samples that can actually be misplaced are those that lie near the six points at which the confusion lines are tangent to the hue circle. There are only two or three color samples near each of these points of tangency (see Figure 8). In addition, the points of tangency for protanopic and deuteranopic vision are close to one another, making it difficult to use the error scores to differentiate between the two types of dichromacy.

If each tray were composed of color samples with chromaticities that all fell along a single confusion line and if there were trays that passed through the middle of the chromaticity diagram in addition to being tangent to the current hue circuit, error scores would be higher because more samples would be confused. Distinguishing between protanopic and deuteranopic vision would be easier because each tray would be uniquely designed to identify a specific type of defective color vision. In the past, using the color reproduction technologies available when the 100-hue test was invented, these specific color scales would have been difficult to produce, but they are now easy to create with a digitally controlled color television monitor.

The extended color vision test consisted of nine trays of 15 color samples, with each tray arranged in a manner similar to the way the trays in the 100-hue test were arranged. There were three trays for each type of dichromacy. Two of the three trays consisted of colors



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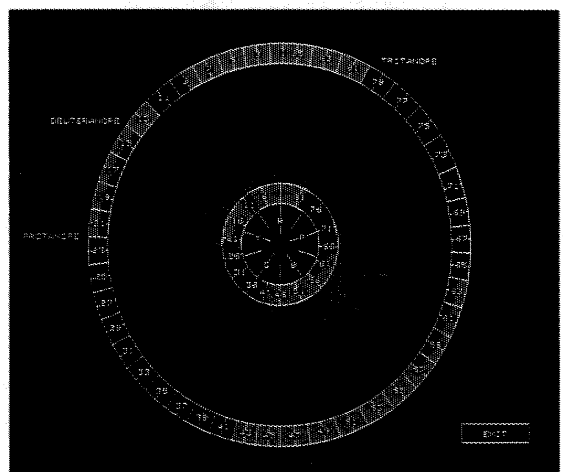

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Figure 12. Farnsworth-Munsell 100-hue error plots for two deuteranopic subjects.

that lay on the confusion lines tangent to the hue circle of the 100-hue test. The center color in each of these trays was the same as the color sample from the 100-hue test at the point of tangency. These points of tangency were found to be color samples 21 and 66 for protanopes, 20 and 62 for deuteranopes, and 6 and 50 for tritanopes. The remaining tray for each type of dichromacy was located on the confusion line through the Munsell color with chroma 0 and value 6.0, and it was centered on the color.

The distance covered on the 1976 CIE UCS chromaticity diagram by an entire tray and the distance from color sample to color sample within a tray were held constant to keep the difficulty of organizing the trays constant. Table 1 gives the chromaticities of the endpoints of each tray. Figure 13 shows plots of the chromaticities spanned by each tray. The luminance of the samples in

Table 1. Endpoints on the 1976 CIE UCS diagram of the color scales used in the extension to the Farnsworth-Munsell 100-hue test.

	begin		end	
	u	v	u	v
protanope	0.175	0.533	0.255	0.528
	0.161	0.457	0.241	0.465
	0.159	0.406	0.237	0.423
deuteranope	0.179	0.536	0.258	0.524
	0.161	0.468	0.240	0.454
	0.143	0.421	0.221	0.407
tritanope	0.258	0.534	0.259	0.454
	0.196	0.501	0.206	0.421
	0.142	0.480	0.161	0.402

be a further refinement of the test.

This extension to the Farnsworth-Munsell 100-hue test was given to several people with normal color vision and to the protanopes and deuteranopes whose results from the 100-hue test are shown in Figures 11 and 12. The trays were presented to the subjects in random order and the scores were computed using the same algorithm as was used for the 100-hue test. A total error score for each type of dichromat was obtained by summing the errors for the appropriate three trays. The results are shown in Table 2.

It is difficult to compare directly the graphical presentation of the Farnsworth-Munsell 100-hue test scores with the tabular listing of the error scores from the extended test. Interpreting the error plot for the Farnsworth-Munsell 100-hue test requires identification of an axis along which most of the errors have occurred. This is difficult to do accurately, and the axes for the two

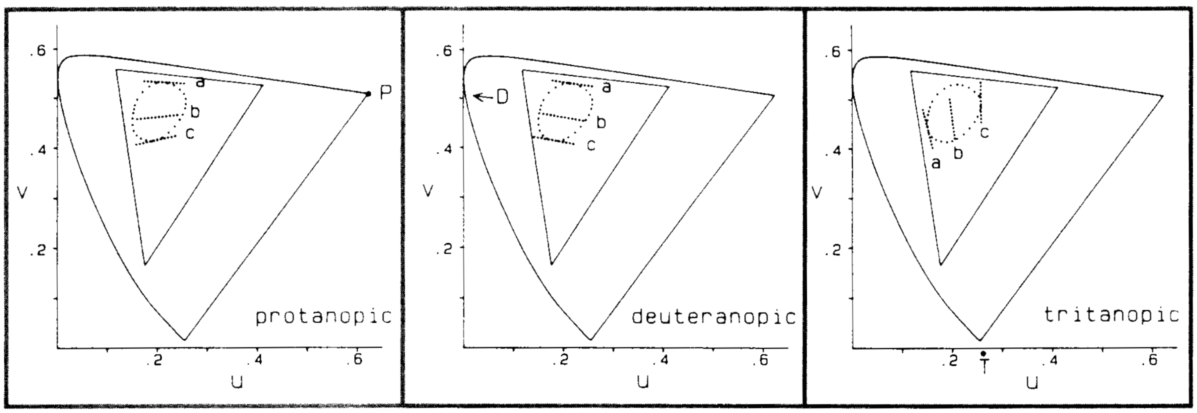


Figure 13. Chromaticities of color trays used to test for protanopic, deuteranopic, and tritanopic color vision in the new color vision test.

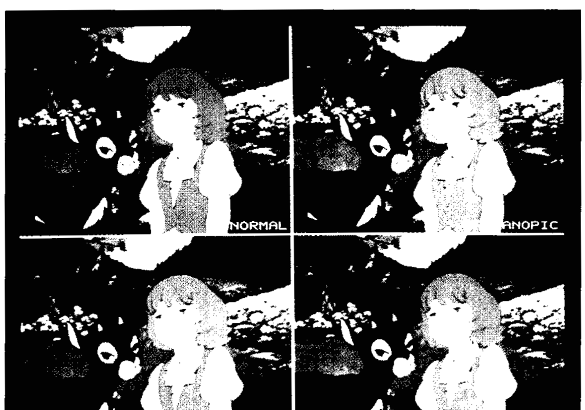


Figure 14. Dichromatic versions of a full-color image.

each tray was held constant to keep the new test similar to the 100-hue test. The use of the appropriate dichromatic luminous efficiency function for each tray could

most common types of color deficiency are located very close to one another. In the extended test, identification of the axis is not necessary because each tray used is already associated with one of the three types of color deficiency. To obtain a diagnosis, it is necessary only to compare the numeric value of the error scores obtained for each tray category. This makes it easier to use the extended test to identify the type of color deficiency present.

Synthesis of a dichromat's view of the world

Trying to synthesize a picture of the world as it appears to dichromats is a problem that touches on a basic philosophical issue. Even though it is possible to create a reproduction that two people with normal color vision accept as a match to an original scene, it is impossible to determine whether the colors as perceived by each individual are the same. Similarly, it is possible to state which colors from a trichromat's color space a dichro-

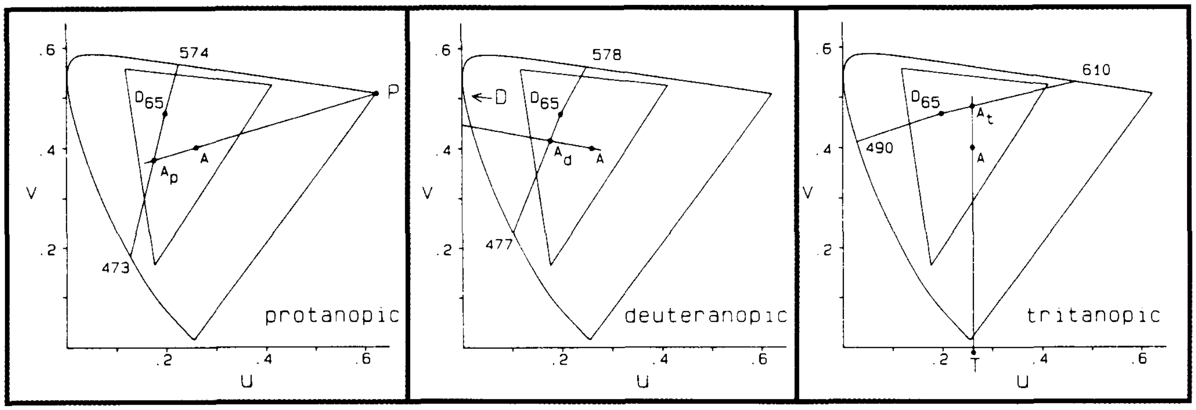


Figure 15. Axes of colors actually seen by dichromats and adjustments made to a single chromaticity point to create a dichromatic version of an image.

mat confuses, but it is impossible to know what colors they see instead. However, a few individuals have been discovered who are protanopes or deuteranopes in one eye and trichromats in the other eye. The weight of the evidence from research on these people[34-36] is that the hue circuit for normal trichromats becomes a hue line for protanopes and deuteranopes with blue (approximately 575 nm) and yellow (approximately 470 nm) as the endpoints of the line and a neutral gray at the midpoint.

Another problem in attempting to synthesize such a picture is that the size of the field of view can affect the severity of an individual's dichromacy. If the field of view is small, full dichromacy is possible, but if it is large (over 8 degrees) some residual trichromacy has been detected.[37] In this work we assumed that the field of view was small.

Given the chromaticity confusion points and the preceding information on the colors actually seen in small fields by protanopes and deuteranopes, we were able to take a full-color picture and manipulate it so that a trichromat can see how the image might appear to a dichromat. In the article where he first described the 100-hue test,[28] Farnsworth proposed one of the first uniform chromaticity diagrams and showed how it would collapse to nearly a line for each of the three types of dichromat. This defines a "major axis" on the uniform chromaticity diagram, and in the case of protanopes and deuteranopes, these lines are very close to the line that runs through the 470 nm and 575 nm endpoints of the hue line determined by experiments on people with one dichromatic and one trichromatic eye. If we assume that these major axes represent the colors actually seen by dichromats, we can easily map a full-color image into the color space of a dichromat.

Dichromatic versions of the image in the upper left-hand corner of Figure 14 were produced using this approach. The *RGB* values for each pixel were first transformed into CIE *XYZ* space and the chromaticity and luminance were determined. Next the confusion line that passes through the chromaticity point of each pixel for each type of dichromat was found. The point of intersection between this confusion line and the major axis for each type of dichromat represents the color as it would appear to that type of dichromat (see Figure 15). The major axes were defined as the line through 473 nm and 574 nm for protanopes, the line through 477 nm and 578 nm for deuteranopes, and the line through 490 nm and 610 nm for tritanopes. Since the exact path of each of these lines through the center of the chromaticity diagram is unknown, we decided for consistency to make them all pass through D6500 white. This new chromaticity and the original luminance were then transformed back into *RGB* space. If the new color fell outside the monitor gamut, it was adjusted either by holding its dominant wavelength constant and reducing its purity, or by holding its chromaticity constant and adjusting its luminance. In some cases both types of adjustment were required. The resulting pictures for each type of dichromat are shown in Figure 14.

Because the colors were adjusted by moving them along the chromaticity confusion lines, the original should appear the same as the new picture to the dichromat whose way of seeing is approximated in the new picture. In fact, when the video version of Figure 14 was displayed on a calibrated color television monitor and was shown to the protanopes and deuteranopes whose 100-hue test results are depicted in Figures 11 and 12, each selected the "correct" quarter of the screen (upper right for protanope and lower left for deuteranope) as being the most similar to the full-color version in the upper left corner. They all said that the blouse and hair were the only things that appeared slightly different. This is not surprising since these colors were quite saturated in the original and required some adjustment in the deuteranopic and protanopic versions.

Table 2. Error scores on each type of tray from the extension to the Farnsworth-Munsell 100-hue test for subjects whose error scores on the original Farnsworth-Munsell 100-hue test are shown in Figures 10, 11, and 12.

	normal		protanope		deuteranope	
	(a)	(b)	(a)	(b)	(a)	(b)
protanopic trays	0	4	168	200	76	80
deuteranopic trays	4	12	72	84	360	336
tritanopic trays	8	8	4	0	4	8

Color selection for color-deficient users

Display design for color-deficient users is an important consideration in computer graphics. Approximately eight percent of the male population and less than one percent of the female population suffer from some form of anomalous color vision. Complete dichromatism afflicts approximately two percent of the male population and a fraction of one percent of the female population.[38] The Farnsworth-Munsell 100-hue test and the extensions made to it in this article can be used to identify those users who may have trouble interpreting the output of a computer graphics system. These tests and the dichromatic view of the world described in the previous section also provide guidelines for designing displays that are unambiguous to color-deficient users.

Colors that appear different to dichromats and are thus better in displays designed for them differ at least in luminance and preferably do not lie on the same confusion line in the chromaticity diagram. (The luminance calculation should be performed using the appropriate dichromatic luminous efficiency function, which can be found in Wyszecki and Stiles.[23]) The best such color scales would be more or less orthogonal to the confusion lines. The colors used to produce the dichromatic version of the full-color picture in Figure 14 have such a property (see Figure 15). They also correspond to the colors actually seen by a dichromat. Further confirmation that color scales orthogonal to the confusion lines are to be preferred is given by the results for the new color vision test in Table 2. The protanope and deuteranope both had little trouble organizing the tritanopic color trays because the tritanopic confusion lines are roughly perpendicular to the protanopic and deuteranopic confusion lines. (Sensitivity to short-wavelength light decreases with age because of an increase in density of the eye lens pigment.[23] This could decrease the effectiveness of the proposed scales for both protanopes and deuteranopes.)

Although there are three distinct forms of dichromacy and anomalous variations of each type, designing a single display that will accommodate virtually all color-defective users is still possible. Tritanopia occurs in only .002 percent of the male population and .001 percent of the female population.[38] Thus almost all people with color-defective vision suffer from some form of protanopia or deuteranopia. Because the confusion lines are roughly parallel for protanopes and deuteranopes, the preferred color scales for both types of color deficiency have the same chromaticity loci, as can be seen in Figure 15. (This is reflected in the fact that the protanopic and deuteranopic versions of the picture in Figure 14 are so similar.) Finally, the fact that dichromatic vision is a more restrictive form of defective color vision than anomalous trichromatic vision means that a display designed for dichromats will also work for anomalous trichromats. Given the above facts we can select a single set of colors that can be distinguished by virtually all color-defective users.

Table 3. Endpoints on the 1976 UCS diagram of the color scales used in Figure 16.

	begin		end	
	u	v	u	v
parallel	0.177	0.402	0.219	0.535
perpendicular	0.266	0.454	0.129	0.482

A qualitative test involving the display of engineering data was performed to check this result. Two color scales were chosen that had the 1976 UCS endpoints given in Table 3. All colors in the scales had the same Munsell value, and the difference in chromaticity between colors in each color scale was a constant distance on the 1976 UCS diagram. One of the scales was chosen so as to lie roughly parallel to the protanopic and deuteranopic confusion lines, and the other scale was selected to be approximately perpendicular. The result of using these color scales to display the displacement of a propeller blade is shown in Figure 16, along with dichromatic versions of these pictures. As can be seen, the color scale that lies roughly perpendicular to the protanopic and deuteranopic confusion lines allows people with these types of color deficiency to see the results of the analysis more clearly than does the color scale that lies parallel to their confusion lines.

Summary and conclusions

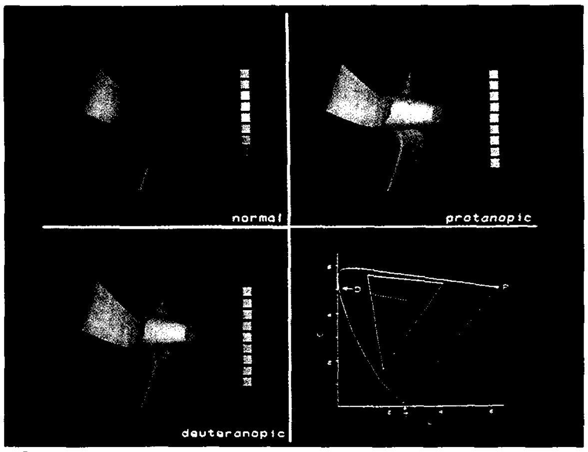
The fundamental spectral sensitivity functions define an important color space for workers in the field of computer graphics. Color reproduction work can be accomplished with the CIE *XYZ* matching functions alone. This is only possible, however, because the CIE *XYZ* matching functions are a linear transform of the fundamental spectral sensitivity functions. This transform can be derived if the chromaticity coordinates of the dichromatic confusion points are known. Once specified, the fundamental spectral sensitivity functions provide insights into the nature of human color vision and guidance for the design of displays for color-deficient users.

Color vision tests for screening the users of a computer graphics system are easy to implement on a digitally controlled color television monitor. A traditional test, the Farnsworth-Munsell 100-hue test, can be successfully reproduced and more efficiently administered. Extensions can also be created. Colors aligned along known confusion loci are easy to reproduce and can be used as the samples in the test. The results allow a clearer identification of the specific types of dichromatic vision.

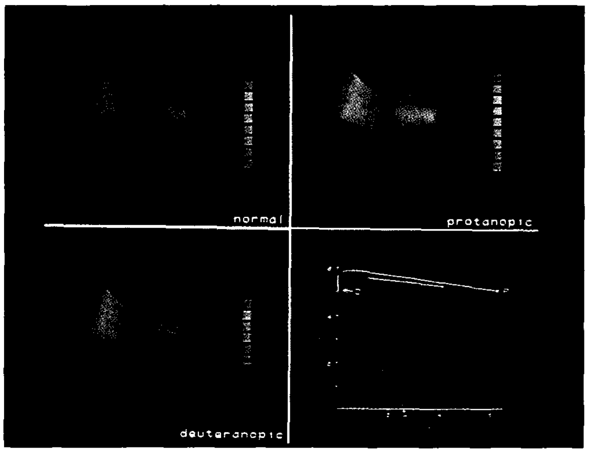
We can also produce an image that approximates for a person with normal color vision how the world appears to a dichromat. This is accomplished first by finding for this type of dichromat the confusion line that passes through the chromaticity of each pixel in the picture. These confusion lines are then followed until they intersect the line that represents the colors actually seen by the dichromat.

Most importantly, computer graphics images can now be synthesized to accommodate color-defective users. The two dominant types of dichromacy are protanopic and deuteranopic vision. These two types of color deficiency have almost parallel confusion lines. In addition, dichromatic vision is a more restrictive form of color vision than anomalous trichromacy. This leads us to recommend that color scales with chromaticity loci perpendicular to the protanopic and deuteranopic confusion lines be used for people with color-deficient vision.

The work described in this article represents a first step in using the power of digitally controlled color television displays to identify color-defective individuals and to create effective user interfaces for them. Future CRT-based color vision tests must be able to differentiate between dichromats and anomalous trichromats. Once the specific nature of the color deficiency has been identified with these tests, colors can be selected to take full advantage of whatever color discrimination abilities the individual has. This will move us one step closer to the day when all user interfaces are custom tailored to the needs of the individual. ■



a



b

Figure 16. Color scale used to display displacement with chromaticity loci (a) parallel and (b) perpendicular to protanopic and deuteranopic confusion line.

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