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# MANAGING COLOR APPEARANCE IN SELF-LUMINOUS DISPLAYS


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This report has been reviewed and is approved for publication.

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This report discusses color-appearance problems arising in self-luminous displays (SLDs), with special emphasis on computer-generated displays. Since no color appearance system designed for SLDs is yet available, many users apply one of the color appearance systems that have been developed for use with reflective materials. These systems can be helpful for managing color appearance in SLDs, especially when the display is intended to simulate a natural scene containing reflective objects and surfaces. The report provides guidelines for simulating samples from four such systems (Munsell, NCS, DIN, and OSA) on SLDs, pointing out the essential role played by context and background in determining color appearance. Figures and graphs are used to illustrate the differences between reflective samples and SLDs with respect to their gamuts of realizable colors. Attention is drawn to problems inherent in the concepts of brightness, lightness, colorfulness, and grayness since these problems have special implications for SLDs. The report suggests different uses for which each of the four color appearance systems is particularly well suited.

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Brightness; Chromaticness; Color; Color appearance; Color order systems; Computer-generated displays; CRT; DIN; Displays; Lightness; Self-luminous; Self-luminous displays; SLDs; Munsell; NCS; OSA

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# PREFACE

This effort was conducted at the Aircrew Training Research Division of Armstrong Laboratory's Human Resources Directorate (AL/HRA) in Mesa, AZ. The work supports training and research development of flight simulator visual scene and display requirements.

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# MANAGING COLOR APPEARANCE IN SELF-LUMINOUS DISPLAYS

Color became available to computer-generated displays in the 1970s following the development of color television in the 1950s and 1960s. Both television and computer-generated displays have the common property of being *self-luminous* instead of depending upon reflected light. But color television arose out of color photography and motion pictures, with which it shares certain kinds of color-appearance problems and from which it borrows procedures to solve them. Computer-generated displays, without the benefit of camera input, face a much wider range of color-appearance problems and employ a technology that requires new solutions for these problems. This report is concerned primarily with color-appearance problems arising in self-luminous displays (SLDs) that are computer-generated, although some of its conclusions will also apply to SLDs in general.

## What is "color appearance"?

Color science incorporates concepts at three broadly distinguishable levels. At the level of *physics*, it borrows physical concepts related to radiant energy, reflective properties of surfaces, transmissive properties of optical media, and the distribution of all three across the visible spectrum. At the level of *psychophysics*, color science has developed concepts of luminance and illuminance based on experimental measurement of the effectiveness of radiant energy as a stimulus to human vision. It has also developed the concept of chromaticity, using data from color-matching experiments to formulate a representation of average human color-discrimination performance in a two-dimensional color space (the CIE 1931 x,y-chromaticity diagram). Further data on relative color-discrimination thresholds in different regions of this space have been used to transform the CIE 1931 space into a CIE 1976 Uniform Chromaticity Space (u¢, v¢ coordinates), in which the distances more accurately (but still not perfectly) represent the actual size of small color discrimination thresholds.

Concepts from ordinary human color language such as brightness, lightness/darkness, whiteness/blackness, and colorfulness belong at the third level of color science, usually designated as the *perceptual* level. These concepts are color appearance terms, and hue names like "red," "green," "yellow," and "blue" also belong at this level, along with the names "white," "gray," and "black." The psychophysical level can handle chromaticity of a visual stimulus; there is a place in the CIE diagrams to which each stimulus can be assigned on the basis of its CIE 1931 or 1976 chromaticity coordinates. But the chromaticity of a stimulus does not fully determine its color appearance. Color appearance depends heavily upon the context in which the visual stimulus is displayed, as well as on many other factors including the visual sensitivity of the observer.

## Color Appearance Systems

A number of *color order systems* are available for the specification of pigment color samples. Some of these systems are based on principles of color appearance, and users of SLDs have often chosen to specify their display colors by reference to such a system. The Munsell Color Order System has been most widely used for this purpose. Occasionally, display colors have been referred to the Swedish Natural Color System (NCS), the DIN Color System, or the OSA Uniform Color Space.

These four systems will be referred to here as the Munsell, NCS, DIN, and OSA color appearance systems. Because they anchor the specification of color appearance for the domain of *object colors*, these systems can be helpful for managing color appearance in SLDs, especially when the display is intended to simulate a natural scene containing reflective objects and surfaces. However, they must be used with caution. The user must never forget that the system one employs was developed for printed pigment samples, viewed on a standard background (usually a particular white or gray paper) under a specified illumination (usually daylight or CIE Illuminant C). It is not easy to keep this in mind when one is working with the spatial array of light output on a cathode ray tube (CRT), instead of manipulating illumination and reflective surfaces in a natural environment.

**Simulating Munsell Samples on a CRT**

It has been generally assumed that the universe of object colors cannot be represented in fewer than three dimensions: one qualitative dimension for hue (differences among red, yellow, green, blue, and so on), one quantitative dimension for amount of light reflected (differences along a continuum from dark or blackish colors to light or whitish colors), and one quantitative dimension for degree of colorfulness (differences along a continuum from achromatic or neutral objects to highly colored or "saturated" objects). In fact, all color order systems in present use do employ three dimensions, but it is significant that they do not use the *same* three dimensions. At least one close student of color appearance has concluded that four dimensions are really necessary (Evans, 1974).

The Munsell and OSA systems present ordered sets of color samples identified through *perceptual scaling procedures*. In each of these systems, it is intended that the perceived differences between adjacent samples should be equal throughout the ordered set. It makes sense to anchor the measurement of color appearance to physical samples chosen as representing equal intervals in perceptual space. The OSA system is relatively new, having been first demonstrated in 1977. The first Munsell color atlas was published in 1915, based on a conceptual structure already developed by 1905. Thus for many years the Munsell system was the only equal-interval system available. It is still the most influential color appearance reference, and it has been widely used as a basis for SLD simulations of reflective surfaces.

In Munsell notation, hue is designated by a number and one or two letters (e.g., 5R for a middle red, 10 BG for the blue-green closest to blue). The first quantitative dimension, called "value" (V), and the second quantitative dimension, called "chroma" (C), are written as numbers separated by a slash (e.g., 5R 4/4 for a red of low chroma, 5R 4/14 for a red of the same hue and value but higher chroma).

Munsell value is determined by the *luminous reflectance* of the sample; thus, V is easily quantified through measurements of *luminance.* This feature makes it a good starting point for talking about CRT simulation of pigment samples. All Munsell samples having the same value will also have the same luminous reflectance when viewed in the standard illuminant, and they will have the same luminance when viewed at a particular level of that illuminant. However, this statement should not be taken to mean that samples having the same value will appear to have the same *lightness*; value and lightness are related concepts, but they are not interchangeable.

The CIE chromaticity coordinates x and y for any Munsell sample can be found in a table (such as Table I(6.6.1) found on pages 840-852 of Wyszecki & Stiles, 1982) or calculated from a computer program (available from Macbeth division of Kollmorgen Instruments Corporation). The table also includes the sample reflectance Y, expressed as a proportion of the light reflected by a perfect reflector in the same illumination. These Y values range from 0 to 1 (see Table 1). They are therefore *normalized* Y values, not *tristimulus* Y values.

Table 1. Converting Munsell Value to Reflectance, Luminance, and CIE L*

| Munsell Value | Y (reflectance) | Tristimulus Y (A) | Tristimulus Y (B) | CIE L* |
|---|---|---|---|---|
| **9.5/** | **0.9001** | **54.0 cd/m$^2$** | **60 cd/m$^2$** | **95.37** |
| **9/** | **0.7866** | **47.2 cd/m$^2$** | **52.4 cd/m$^2$** | **91.08** |
| **8/** | **0.5910** | **35.5 cd/m$^2$** | **39.4 cd/m$^2$** | **81.35** |
| **7/** | **0.4306** | **25.8 cd/m$^2$** | **28.7 cd/m$^2$** | **71.60** |
| **6/** | **0.3005** | **18.0 cd/m$^2$** | **20.0 cd/m$^2$** | **61.70** |
| **5/** | **0.1977** | **11.9 cd/m$^2$** | **13.2 cd/m$^2$** | **51.60** |
| **4/** | **0.1200** | **7.20 cd/m$^2$** | **8.00 cd/m$^2$** | **41.22** |
| **3/** | **0.0655** | **3.93 cd/m$^2$** | **4.37 cd/m$^2$** | **30.76** |
| **2/** | **0.03126** | **1.88 cd/m$^2$** | **2.09 cd/m$^2$** | **20.54** |
| **1/** | **0.0121** | **0.726 cd/m$^2$** | **0.807 cd/m$^2$** | **10.63** |

Simulating any individual sample on an SLD requires converting the sample's x,y,Y values into RGB digital codes suitable for that display, and this conversion uses XYZ tristimulus values with Y in luminance units (cd/m$^2$). How high should this Y luminance be? Given that the range of luminances available on an SLD is low relative to natural daylight, it is perhaps natural to respond, "As high as my SLD will permit." But this answer will have some unintended consequences if it is applied to each of several colors without regard to their context.

For example, in a brightness matching experiment reported by Mandra (1989), 25 test colors were selected according to criteria based on Munsell notation. All 25 were at value 5/, and 14 were at chroma /6, with the remaining 11 at other chroma levels from /4 to /16. Since these test colors were all presented on a white surround, their tristimulus Y value was determined in relation to a white tristimulus Y of 60 cd/m$^2$, close to the maximum white achievable by the Hitachi color CRT display. The column "Tristimulus Y (A)" shows the tristimulus Y values that will give an appropriate simulation of Munsell samples viewed in an illumination such that a perfect reflector would have luminance 60 cd/m$^2$. In Mandra's experiment these test colors, simulating Munsell samples at value 5/, were all assigned a tristimulus Y of 11.9 cd/m$^2$ and presented on a white background at 60 cd/m$^2$.

It is instructive to consider several other possibilities. Recognizing that the Munsell samples belong to a color order system with properties that depend on a standard background and a standard illumination, one could argue that the standard background is certainly *not* a perfect reflector (with value 10/). It is a white with value approximately 9.5/, and therefore the white background of 60 cd/m$^2$ ought not to be the reference used for determining the luminances of the test colors. Instead, 60 cd/m$^2$ should be assigned to the 9.5/ background white, and the reference becomes 60/0.9001 = 66.66, shifting all luminances upward as shown in Table 1, "Tristimulus Y (B)."

But what if the experiment required a black or gray instead of a white background? It is not uncommon for experimenters to study Munsell samples against backgrounds that are not white. The technical report of CIE TC 1-21 (CIE 1994, p. 57) describes a study using actual, not simulated, Munsell samples viewed on a background gray at value 3/. Taking Munsell samples onto a different background is perfectly permissible, provided the user realizes that their color appearance will be changed by this change of background. I discuss changes in color appearance induced by background at greater length in a later section. Unfortunately, it is often assumed that Munsell samples, real or simulated, carry their color appearance character along with them regardless of background. This is not true. Moving the samples from the standard background and illumination should be recognized as merely a useful way of finding out *how pigment samples with a particular reflectance profile will appear in a different environment.*

Real samples on a gray background can be simulated on an SLD, and *unless a white sample must be displayed at some time or place*, use of a gray background for the Experiment 1 samples would enable the simulation to be created at a higher luminance level than the two levels shown in Table 1. Instead of being limited by the maximum white luminance available on the display, all the test color luminances could be raised together to the highest luminance achievable by the entire group. This is likely to be the maximum luminance available for the bluest color in the set, since the CRT blue phosphor has less luminance available than the red or green phosphors.

Suppose, now, that the experimenter decides to raise *each* test color luminance to the highest level possible on the display. Since different maxima are available for each color, the set of colors will no longer be of equal luminance, and the display will no longer *simulate* the original set of Munsell samples whose x,y values were found on the assumption that V = 5/. It is possible that it will now no longer simulate *any possible set of Munsell samples*, or, indeed, any possible set of real object colors viewed in a single illuminant. The x,y-chromaticity coordinates of these colors will no longer have their original meaning by reference to a color appearance system, and they *may* have no meaning with reference to any existing color appearance system at all. This is particularly true when the samples are displayed individually (or in small sets) as "unrelated colors" on a black background.

In summary, two lessons can be learned from this discussion. (a) A simulation of Munsell samples on an SLD will be a true simulation *if and only if* the Y (reflectance) values of all the samples are converted to luminance (Y tristimulus) values by using the same assumed or real value of luminance for the perfect reflector white. Such a conversion keeps all sample luminances at the same position relative to each other that they occupy in the Munsell color order system. (b) Presentation of Munsell samples, real or simulated, on any background other than the standard white or in any illumination other than the standard illuminant will produce shifts away from the color appearance which the Munsell notation is intended to describe. *The color appearance designated by 5R 4/14 is not intrinsic to the sample which carries this designation in the Munsell series.* The real sample does not carry with it even its tabled x,y,Y values (0.5734, 0.3057, 0.1200) unless it is presented under the standard illuminant (CIE Illuminant C). The designation "5R 4/14" is a perceptual color appearance description in Munsell terms. A simulated sample with x,y,Y (0.5734, 0.3057, 0.1200) does not carry the color appearance 5R 4/14 unless it is presented on a background simulating white paper in the standard illuminant.

## The CIE 1976 L*u*v* (CIELUV) Color Space

Munsell, in the early 1900s, started with painted paper samples and built an approximately uniform color space. By 1943 the 1931 x,y-chromaticity diagram was well established, and Munsell workers were able to provide the x,y,Y equivalents of the system's reflective samples. Could the problem of color appearance now be approached from the *psychophysically defined* CIE concepts of luminance and chromaticity? The CIELUV color space, one of two approximately uniform color spaces proposed by the CIE in 1976, can be regarded as an attempt to relate the Munsell arrangement of colors (based on *psychological scaling*) to the CIE XYZ tristimulus system (based on *psychophysical* color difference data).

The x,y-chromaticity diagram shows only *proportions* of tristimulus values, not their actual magnitudes. A chromaticity diagram describes colors at a single luminance level, and the same diagram is used for *any* luminance level. To create a three-dimensional space, the Y tristimulus value is converted to a quantity called CIE 1976 *lightness*, L*. As Table 1 shows, the L* scale is similar to Munsell V, but its numbers range from 0 to 100; therefore, L* for a given reflectance is about 10 times as great as Munsell V for that same reflectance. Computing L* requires assigning a value to the luminance $Y_n$ of a perfect reflector in the same illumination. For $Y/Y_n > 0.008856$,

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16 \qquad (1)$$

The XYZ values for the perfect reflector define the *reference white* for these color spaces.

Cross sections of the CIELUV space at constant L* are linear transformations of u¢,v¢ space, in which the u¢,v¢ distance of a color from the reference white is weighted by L* to produce CIELUV coordinates u* and v*. This weighting reflects the fact that colorfulness (a perceptual quantity) increases as lightness increases. Colors with the same u¢,v¢ coordinates will appear more "colorful" at higher lightness levels. Figure 1 shows Munsell colors of constant hue (radial lines) and constant chroma (roughly concentric circles) for value 5/, plotted as values of u* (abscissa) and v* (ordinate). These cartesian coordinates can be transformed to polar coordinates hue angle (corresponding roughly to hue) and C* (distance from reference white). Figure 2 shows the use of CIELUV space to display the gamut of realizable colors for a typical CRT monitor.

CIELUV thus provides a space within which the p*sychophysically defined* chromaticity and luminance of a set of colors, all referred to a common reference white, can be visualized in three dimensions. Each of the color order systems (Munsell, NCS, DIN, OSA) is in fact a set of psychophysically defined colors referred to a common reference white, namely, a perfect reflector in the standard illumination. Therefore, each color order system can be represented in CIELUV space, but it undergoes some distortion through the transformation to CIELUV coordinates. Transforming Munsell V to L* does not introduce distortion, since value itself is tied to luminance. But as Figure 1 shows, Munsell's perceptually equal chroma steps do not translate to equal distances from the center along different hue radii, and its perceptually equal hue steps do not translate to equal angular

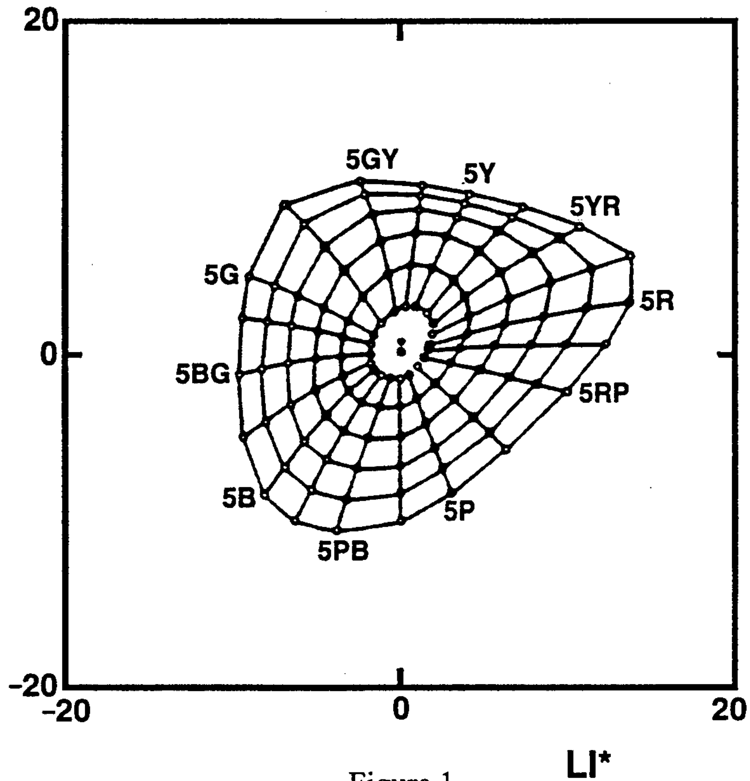


Figure 1
Munsell constant-hue lines and constant-chroma lines at value 5/.
Reproduced with permission from Derefeldt, 1991, p. 247.

differences around the hue circle. The CIELUV representation of Munsell colors is thus not a satisfactory c*olor appearance* system. Nevertheless, CIELUV is widely used as a method of quantifying small color *differences* because it provides an equation for calculating the total luminance and chromaticity difference between two colors,

$$\Delta E^* = \left[(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2\right]^{1/2} \tag{2}$$

The concept of DE* as a measure of small color differences is widely used in industry, even though a unit value for DE* (DE* = 1) obviously cannot represent a difference which has the same perceptual size in all regions of CIELUV space. It works best in cases where the differences being compared are all in the same region of color space.

At the same time in 1976, the CIE also recommended CIEL*a*b* (CIELAB). Like CIELUV, CIELAB uses the XYZ tristimulus values to derive chromaticity measures, but the defining equations are different. Choice between CIELUV and CIELAB is largely a matter of local preference, although there has been a tendency for users of SLDs to prefer CIELUV while users of reflective samples (paints, textiles, inks) often prefer CIELAB. Both spaces are intended to serve as *approximately uniform* color spaces, but neither of them represents color appearance in a fully satisfactory manner. They are more comparable to the Munsell than to the OSA, DIN, or NCS color systems because the CIE 1976 spaces define lightness *exclusively* in terms of luminance.

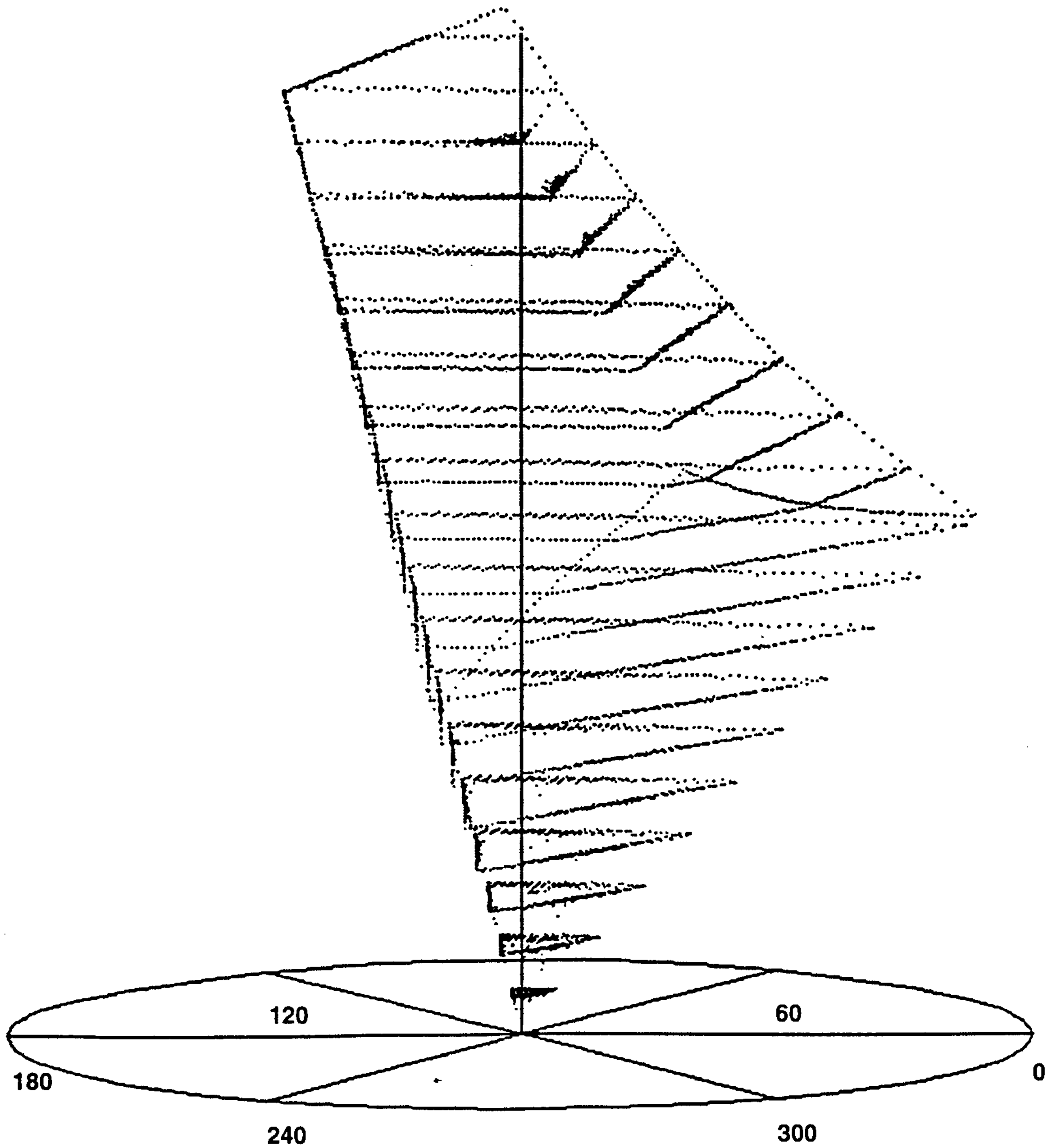


Figure 2

Gamut of a typical CRT monitor shown in CIELUV color space with D65 as reference white. The gamut is represented by a maximum of 7200 points, each being that point greatest C* in one of 7200 categories (360 in hue angle *h*Y20 on lightness L*). Reprinted from Howard (1992), p. 720.

## Problems Involving the Concepts of "Brightness" and "Lightness"

Lay persons use both "brightness" and "lightness," often interchangeably, to name the dimension of visual experience most closely correlated with "amount of light." In the CIE definitions of basic color perception terms, brightness names the appearance that an area emits "more or less light," and its variations range from "bright" to "dim." Lightness names a kind of *relative* brightness; it names the appearance that an area emits "more or less light in proportion to that emitted by a similarly illuminated area perceived as a 'white' stimulus." Its variations range from "light" to "dark."

The CIE definition of lightness implies a *relation* between an area being judged and other areas; it implies *related colors*, as distinguished from situations (common in visual research) in which only one or two illuminated areas are viewed in a black surround. One can judge the brightness of such an *unrelated color*, but no judgment of relative brightness (lightness) is possible. Since a single color in darkness appears self-luminous rather than illuminated, there is no way to imagine a unique "similarly illuminated" white with which to compare it.

Brightness. Brightness can be judged in both unrelated and related color situations, but it is most easily applied to unrelated colors. When only a single area of light is presented, judgments of brightness are correlated with its luminance (luminous energy level). However, the correlation between brightness and luminance is not perfect; brightness judgments are affected by both hue and saturation. "All chromatic colours appear brighter than achromatic colours of identical retinal illuminance, i.e., a red light of 10 trolands will always appear brighter than a 10-troland white light. In an equiluminant plane, the brightest colours are spectral blues, followed by spectral reds and greens. Spectral yellow appears only modestly brighter than white. As these lights are desaturated by reducing their colorimetric purity, their brightness decreases." (Pokorny, Shevell, & Smith, 1991, p. 45) These facts describe a *chromatic contribution to brightness perception*; when post-retinal processing results in a brightness channel and two chromatic channels, the brightness channel receives contributions according to the luminance of the retinal inputs without regard to color, and it receives additional contributions through activation of the chromatic channels.

At luminance levels below 10 cd/$m^2$, the measurement of brightness encounters an additional problem. "Luminance" generally is understood to mean "photopic luminance," i.e., the radiant energy evaluated in terms of its effectiveness as a stimulus to retinal *cones* at daylight (photopic) illumination levels. But retinal rods are active at levels up to 100 cd/$m^2$, and their role increases as illumination declines. Many large-screen SLDs operate at levels that include substantial rod activity. In the mesopic range where both rods and cones are active, radiant energy needs to be evaluated in terms of both photopic and scotopic luminous efficiency functions, and talk about "brightness" requires a photometric system for measuring what might be called "general brightness," a system that applies across all energy levels (about 14 log units) to which the human visual system is sensitive (Howard, 1994).

Some progress has been made toward such a photometric system through experiments in which chromatic test colors are matched in brightness with a standard or reference color at luminance levels that vary over a range of many log units. Efforts in this direction began in the 1960s, and in 1989 a technical committee of the CIE reported on six different proposed methods for solving the problems presented by the transition between rods and cones in mesopic vision and the chromatic contribution to brightness in photopic vision (CIE, 1989). This report underlined the seriousness of the errors introduced by using ordinary photopic photometers (such as the Pritchard 1980A) at low light levels: "The most important problem in this practice is the shift in the luminous efficiency of the eye toward the short wavelengths as the light level is reduced. If we use an ordinary light meter, bluish lights will be brighter and more effective for vision than they are given credit for, while yellowish and reddish lights will be over-evaluated for their light-producing capabilities....For example, at low mesopic levels, below 0.1 cd/$m^2$, a bluish light could be 10 times as effective as an ordinary tungsten source when the two measure exactly the same photopically." (CIE, 1989, p. 2)

In principle, all proposals for the measurement of general brightness can be understood as mathematical operations on radiometric data from the sample. In this respect they are analogous to the measurement of photopic luminance, in which the radiometric data (the spectral radiance distribution of the sample) are weighted by the photopic luminous efficiency function V(l), summed, and multiplied by certain constants. Some proposals make use of *both photopic and scotopic luminous efficiency functions*, combining them with weights that differ according to the radiance level. Other proposals use terms arising from four sensitivity functions (three for cones, one for rods).

Since 1987 a new technical committee has compared the ability of these proposed methods to predict experimental data from a variety of published studies. No method has been determined to be clearly superior, and all methods fail to give results corresponding to some data sets (CIE, 1994). But the data sets do not really provide a satisfactory database for this evaluation; they do not agree well with each other. Although all these data were obtained through brightness matches between test colors and a standard reference field, other experimental conditions differed, particularly with respect to the surround in which the comparison fields were presented. A general brightness measure cannot be established without attention to surround effects (Howard, 1994).

Lightness. Related colors can be judged both for brightness and for lightness. Moreover, the presence of more than one color in the visual field gives rise to contrast effects. An unrelated color can appear to be white, but it never appears to be gray or black; grayness and blackness arise only with related colors. As Evans (1974) has emphasized, related colors have an additional perceptual dimension, which varies along the continuum blackness-grayness-whiteness. This dimension is not the same as lightness, although it may often be confused with lightness when experimental judgments are being made.

Problems in brightness measurement also apply to lightness measurement. At photopic levels, lightness, like brightness, is affected by hue and saturation; strongly chromatic blues appear lighter than reds or greens which have the same *luminous reflectance*, evaluated by the photopic luminous efficiency function. However, it may be hard to find colored papers (such as samples from the color order systems) which demonstrate this fact because luminous reflectance is generally *lower* for blue papers than for red or green papers; the available blues therefore do not *look* lighter than the reds because their reflectance is in fact lower.

With SLDs, on the other hand, the effects of hue and saturation on lightness can be quite profound. It is perfectly possible to display blue, purple, red, and green patches that have the same photopic luminance but appear very different in both brightness and lightness. The reason lies in the significant *gamut differences* between the realm of realizable pigment colors and the realm of realizable SLD colors. Since these differences have not been widely discussed in the computer graphics literature, it will be helpful to describe them here.

Figure 3 tells part of the story. This figure, adapted from Pointer (1980), uses CIE Uniform Chromaticity Space to show three gamuts: (1) the gamut derived by Wintringham in 1951 from pigment samples (short dashes), (2) the gamut derived by Pointer in 1980 from the Munsell Color Limit Cascade (solid line), and (3) the gamut of a Barco Calibrator CRT purchased in 1991 (long dashes). Chromaticities inside a gamut contour are achievable in that medium; chromaticities outside

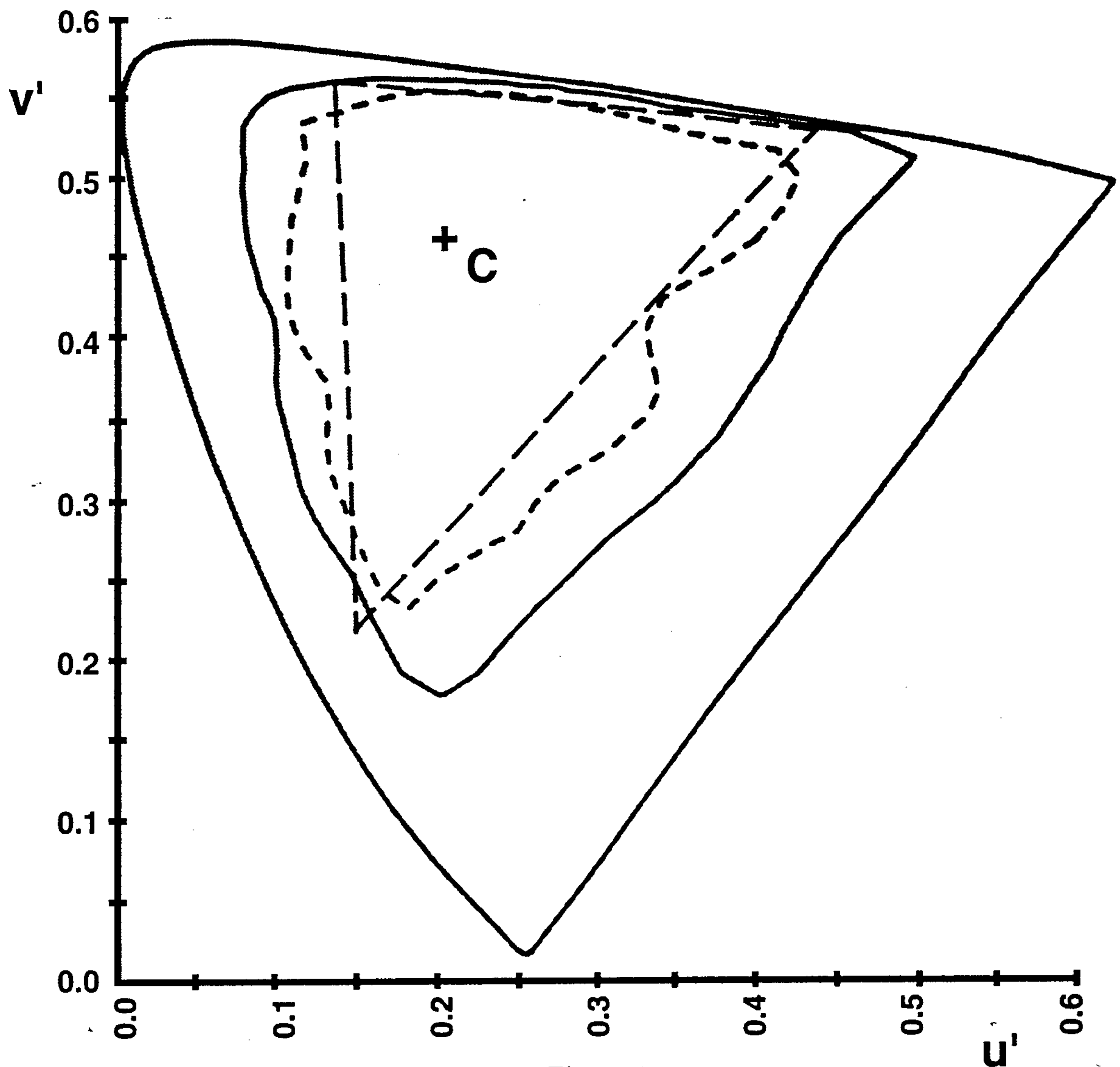


Figure 3
Maximum chromaticity gamuts in CIE 1976 Uniform Chromaticity Space for (a) real colors as determined by Wintringham in 1951 (short dashes), (b) real colors as computed by Pointer (1980, solid line), and (c) a Barco Calibrator CRT (long dashes). Adapted from Pointer (1980), p. 153.

the contour are not realizable. Pointer comments that the difference between his and Wintringham's pigment gamuts represents improvement in printing technology during the intervening three decades. Figure 3 shows that the CRT's gamut extends outside the pigment gamut in the blue region but lies well inside the pigment gamut for greens, blue-greens, reds and purples. This figure alone provides part of the reason why a CRT can excel in presentation of highly chromatic blue patches.

Figure 4, from Wyszecki & Stiles (1982), draws attention to the fact that the full extent of any color gamut is really available only at low relative luminance levels (low lightness). This figure, called the Rösch color solid, shows the theoretical maximum relative luminance (Y) and chromaticity (in x,y space) of all realizable colors. Because this figure is calculated from physical and psychophysical principles, its boundaries contain all possible colors, and the colors located at its outer surface are called *optimal colors*. The figure can be interpreted as applying either to reflective or transmissive media; reflective surfaces will be considered here. Any surface whose color is described by x,y-coordinates close to the spectrum locus will reflect only a limited portion of the daylight (D65) illuminant, and its luminance will therefore be less than 10% of the luminance of a perfectly reflecting surface. Those surfaces achieving at least 20% relative luminance occupy a more limited gamut, and the gamut continues to shrink toward the position of daylight white at successively higher relative luminances. Figure 4 forces a realization that highly chromatic reflective samples — whether theoretical (as in this figure) or actual (as in Figure 3) — are necessarily limited in relative luminance.

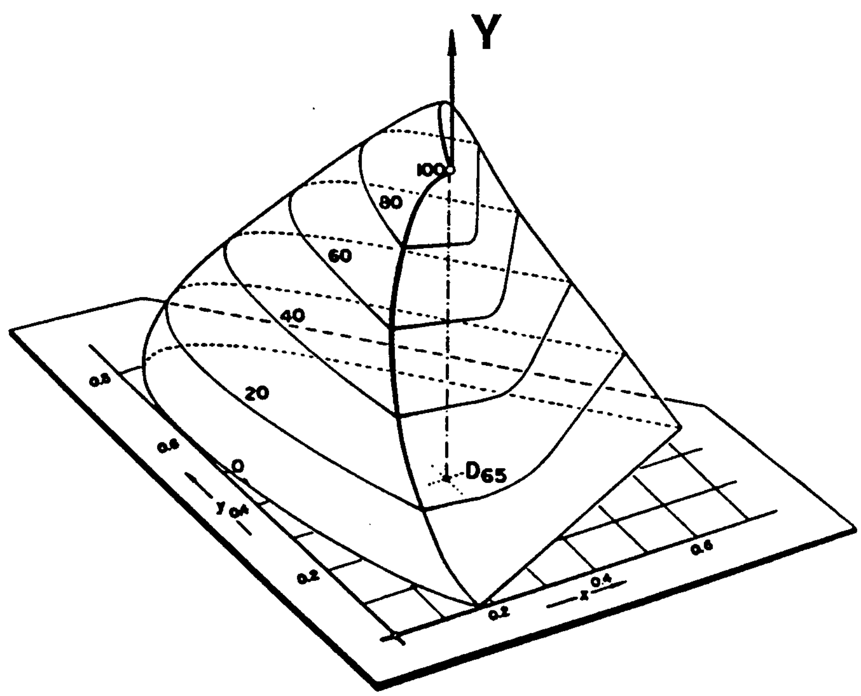


Figure 4

Oblique projection of the x,y,Y object-color solid showing the boundary surface representing the optimal color stimuli (Rosch color solid). Reproduced with permission from Wyszecki and Stiles (1982), p. 184.

Figure 5, also from Wyszecki & Stiles (1982), shows that this limitation is more severe for blue and red than for green. As relative luminance increases, the gamut shrinks away from the spectrum locus for blue (380-480 nm), but it continues to lie quite close to the spectrum in the region from green to red (520-600 nm). The x,y-coordinates of the Barco Calibrator have been superimposed on Figure 5. Notice that the blue phosphor's coordinates lie inside the 10% band, the red's inside the 30% band, and the green's inside the 80% band.

Now imagine a display containing a background of the Barco's maximum white with three patches of color, all the same size, each showing one of the CRT's primary colors at its maximum luminance. Since we know the chromaticity coordinates of these three colors, we can look in a table of Munsell x,y,Y for a Munsell sample close to the chromaticity of each color. If we placed these

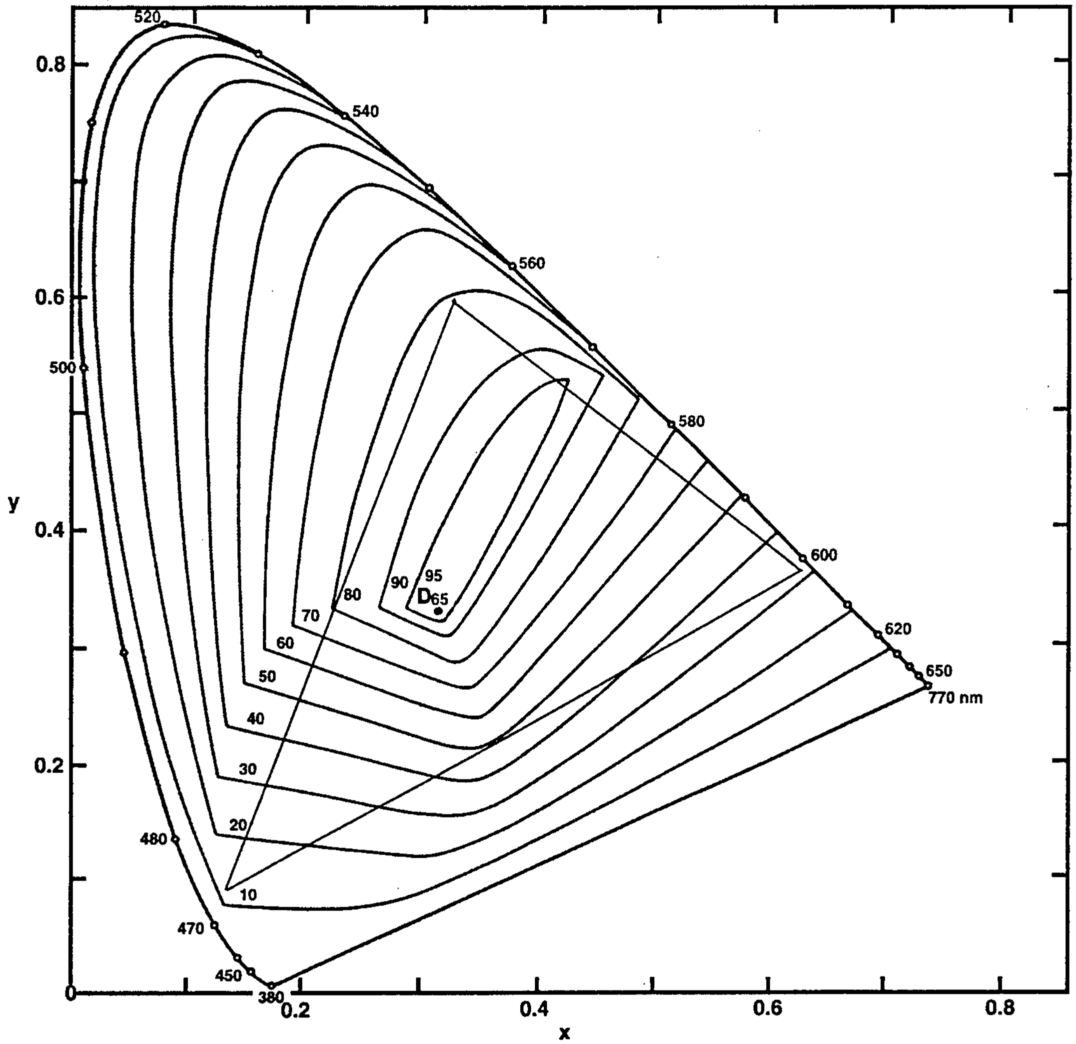


Figure 5

Chromaticity loci of optimal color stimuli as a function of Y (reflectance), on the basis of the CIE 1931 chromaticity diagram and for incident radiant power from CIE standard illuminant D65. Gamut of the Barco Calibrator appears as a triangle connecting the x,y-coordinates of its red, green, and blue primaries. Adapted from Wyszecki and Styles (1982), p. 183.

three Munsell samples on a standard white background, the CRT display and the reflective display would have the relative luminances and Munsell values shown in Table 2.

Table 2. CRT Display Using Maximum Luminances of Red, Green, Blue and White

| Color | Y ($cd/m^2$) | Y (reflectance) | Equivalent Munsell V | Matching Munsell Sample |
|---|---|---|---|---|
| White | **129** | **.961** | **9.75** | **N 9.75/** |
| Green | **83.6** | **.632** | **8.35 *** | **10 GY 8/18** |
| Red | **31.9** | **.241** | **5.6 *** | **10 R 4/15** |
| Blue | **15.0** | **.113** | **4.0 *** | **5 PB 2/13** |

*Equivalent Munsell V computed by equation provided in McCamy (1992)

For this table, the background white is assumed to have a Munsell value of 9.75/ with a corresponding reflectance of 0.961. Therefore, the background white of 129 $cd/m^2$, the maximum white of the display, is taken as representing 0.961 of a perfect reflector at 132.3 $cd/m^2$, and the reflectances of red, green, and blue patches are computed in relation to this value. These reflectances (Y values) are converted to Munsell Value by McCamy's equation (McCamy, 1992). The resulting Vs should be compared with the Vs for the Munsell samples closest to the CRT samples in chromaticity (shown in the last column). The green CRT sample has a V of 8.35/, only slightly higher than that of the nearest Munsell chromaticity match. However, the red CRT sample has a luminance that would represent a V of 5.6/, compared with only 4/ for its Munsell chromaticity equivalent, and the blue CRT sample's luminance is high enough to simulate a V of 4/, two steps higher than its Munsell chromaticity equivalent at 2/.

Consequently, anyone using the full energy of red, green, or blue available on this CRT display would produce a "simulation" of colors that are not realizable with reflective colors viewed in a common illumination with a white background of this luminance. The display would not be a valid simulation of any reflective display, and the three color patches (especially the two red and blue patches) should appear in this context to be *glowing*, as if they were either self-luminous or illuminated by a hidden source. The appearance of glowing or *fluorence* (Evans, 1974) does in fact occur under such conditions, and it is responsible for the unrealistic appearance of some parts of CRT-simulated scenes. To avoid fluorence and make the simulation valid, it is necessary to use less than the full luminance available from the CRT's primary phosphors so that the three samples have luminances converting to 8/, 4/ and 2/, respectively.

Table 3 shows how the CRT display could be modified to bring the color patch luminances into line with their approximately matching reflective samples. Luminance of the green patch would have to be reduced only 7% (from 83.6 to 78.2 cd/m$^2$), but the red and blue patches would have to be reduced to 50% and 28% of the available luminance, respectively.

Table 3. Revision of CRT Display in Table 2 to Simulate Reflective Samples

| Color | Y (cd/m$^2$) of CRT Patch | Y (reflectance) of CRT Patch | Equivalent Munsell V * | Matching Munsell Sample |
|---|---|---|---|---|
| White | **129** | **.961** | **9.75** | **N 9.75/** |
| Green | **78.2** | **.591** | **8** | **10 GY 8/18** |
| Red | **15.9** | **.120** | **4** | **10 R 4/15** |
| Blue | **4.14** | **.0313** | **2** | **5 PB 2/13** |

*Equivalent Munsell V taken from matching Munsell sample

These facts arise because of differences in the gamut of CRTs and reflective samples. It is instructive to consider how these gamuts compare in CIELUV space. The six graphs in Figure 6 are plots of C* versus L* for hue angles 20, 120, 260 (the positions in CIELUV for the CRT's red, green, and blue primaries), 70, 190, and 320 (midway between the primaries). In each graph the solid line represents the maximum gamut for a typical color monitor, and the dashed line represents the maximum gamut for real reflective samples (from Table 1 in Pointer, 1980). On all the graphs, C* increases with L*, reaches a maximum, then decreases. For real colors the relation tends to be curvilinear; it is sharply linear for the CRT because only three components contribute to the variation. At hue angles near the primaries, part or all of the CRT curve goes beyond the real color gamut. This occurs at low lightnesses near red, at high lightnesses near green, and throughout the lightness range near blue. While the gamuts of individual CRTs will differ in some details, it can be concluded that SLDs, *at low lightnesses,* can achieve reds and blues that are more highly chromatic than the most saturated reflective samples. At high lightnesses, they can achieve some greens and blues (but not reds) that exceed the gamut of reflective samples.

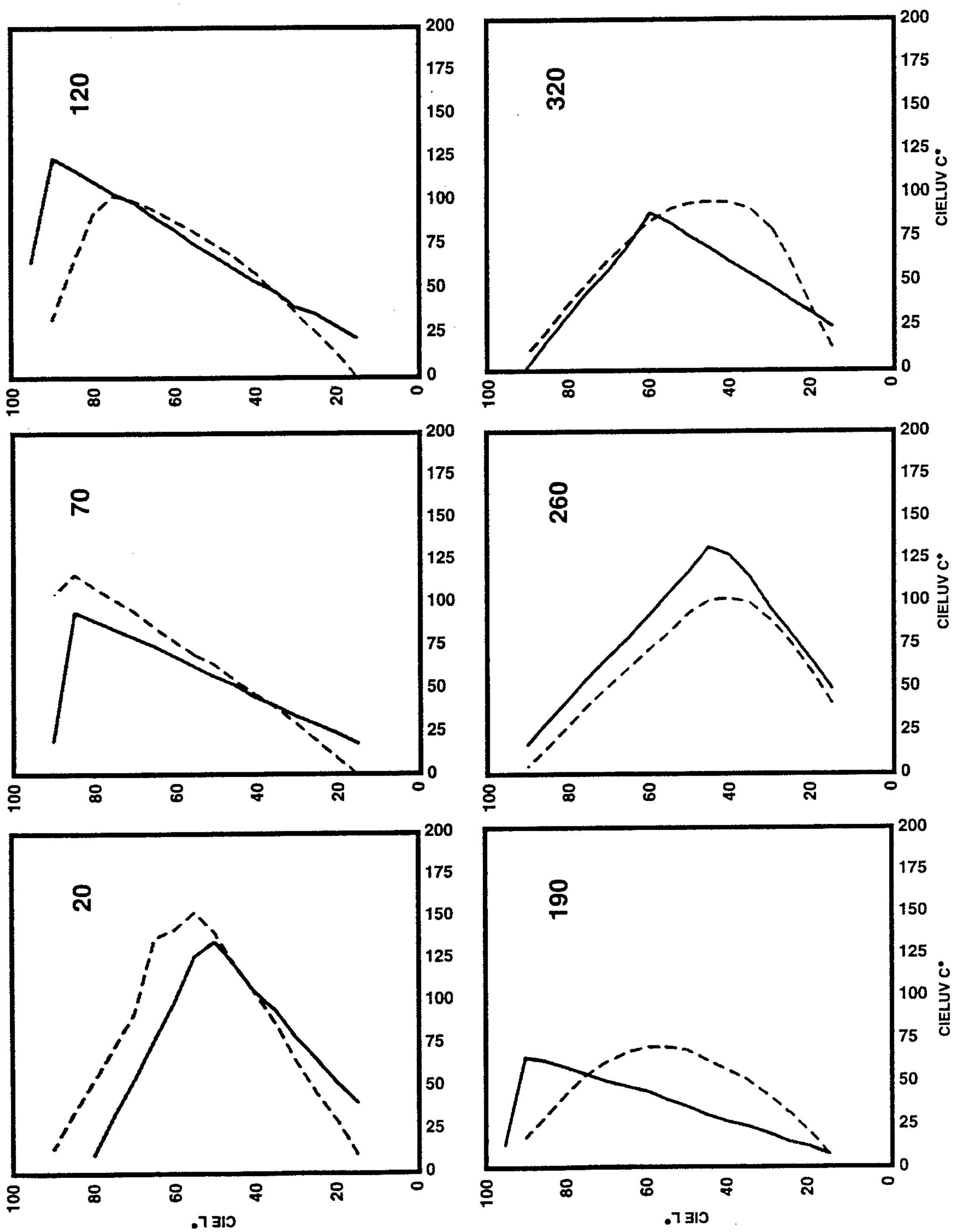


Figure 6
Hue-leaf gamuts in CIELUV space for real colors (dashed lines) and a typical CRT, showing maximum achievable chromaticity C* as a function of lightness L*. Hue angles shown are 20, 70, 120, 190, 260, and 320 (indicated by numbers on the graphs).

Figure 7a shows the maximum C* achievable at each hue angle for Pointer's real colors (filled diamonds) and for the CRT (open squares). Hue angles are represented by numbers 0 through 35; hues progress counterclockwise from red at 2 through yellow-green at 12, blue at 26, and purple around 32. For real colors, the shape of this gamut is roughly circular but elongated toward red; the CRT gamut is triangular, with peak values of C* near the red, green, and blue primaries. Both gamuts have high C* values in the red and relatively low C* between blue and green. Maximum C* is higher for the CRT than for real colors *only in the regions near its green and blue primaries.*

Each of the maximum C* points in Figure 7a occurs at a particular L*; these L* values are shown in Figure 7b. Throughout most of the range from yellow through green to purple, the CRT achieves its maximum C* at lightness levels well beyond those of the most saturated real colors. Clearly the chromaticities and lightnesses achievable by SLDs differ in important ways from the gamut of "real colors" represented by reflective samples. At the present time, there is no color appearance system that deals adequately with these differences.

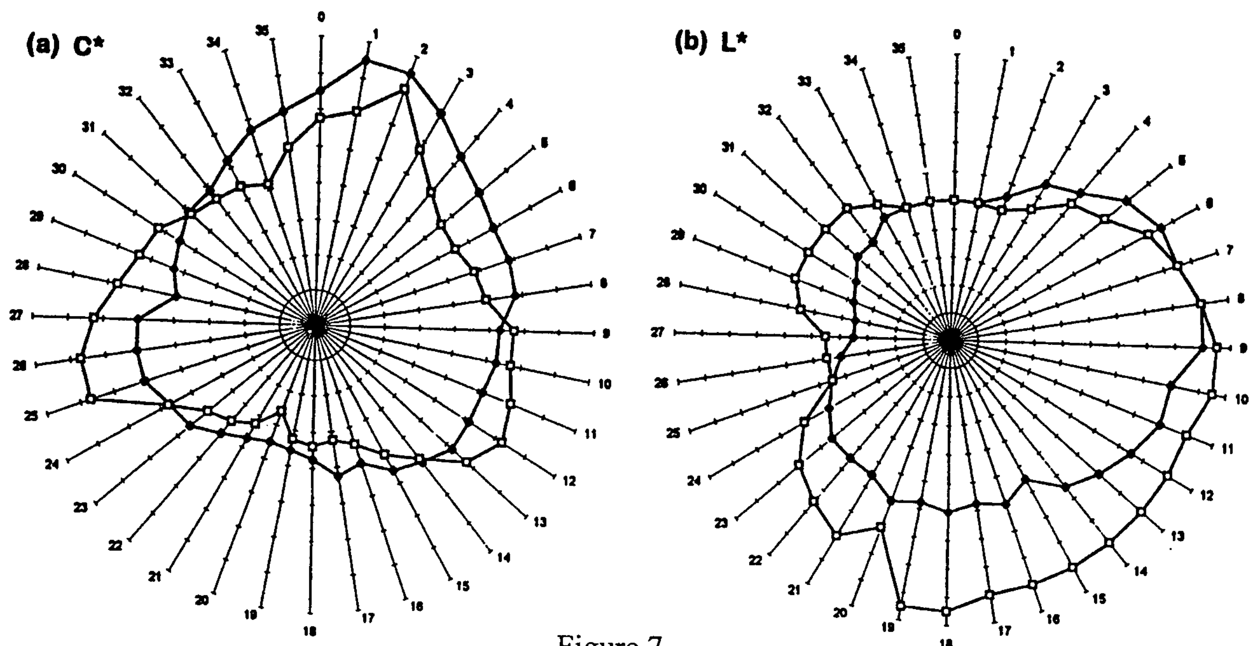


Figure 7

Maximum C* at every tenth hue angle for real colors (dashed lines) and a typical CRT. Hue angles are represented clockwise from 0 (hue angle 0 and 360) through 35 (hue angle 350); the CRT primaries are located near 2 (red), 12 (green), and 26 (blue). (a) Maximum chromaticity C* for each he leaf (scale marked in units of C* - 20); (b) L* for the point of maximum C* (scale marked in units of L* 10).

Whiteness/Blackness and Grayness. In addition to brightness and lightness, related colors have an additional perceptual dimension varying along the continuum blackness-grayness-whiteness (Evans, 1974). The Munsell system makes no explicit reference to this dimension; neither does the OSA system. However, whiteness/blackness is a central concept for the Swedish NCS, and it also has a place in the DIN system.

Samples in the NCS color atlas have been selected by a method of *absolute judgment*, based on the Hering opponent colors theory. Observers made numerical judgments of painted samples on a standard white background, using four numbers that summed to 100 for (a) red or green, (b) blue or yellow, (c) white, and (d) black content. No comparison samples were provided; judgments were made in relation to concepts of unique colors. (Unique red contains no yellow, blue, white, or black content; unique green, yellow, blue, white, and black are described similarly.) Consider a color judged to contain 30% yellowness, 40% greenness, 10% whiteness, and 20% blackness. Chromaticness $c$ is defined as the sum (yellowness + greenness) = 30 + 40; $c = 70$. Hue is written as G43Y for this color, that is, green with 43% yellow (30/70, times 100). Blackness $s$ (Swedish *svarthet*) and whiteness $w$ for such a color must sum to 30; only $s$ appears in the notation G43Y 2070.

Samples of different hues that have the same $s$ and $c$ values are said to have the same *nuance*. These are colors with equal *gray content*, a concept that is absent from other color order systems. Evans (1974) has shown that gray content will be seen even in a monochromatic test stimulus when it is embedded in a white surround of constant luminance (Figure 8). Pokorny *et al.* (1991, p. 47) describe Evans' findings clearly. "When the test stimulus is much less luminant than the surround, it appears black. As its luminance is raised, it appears blackish but tinged with color, then grayish. At a given luminance below that of the surround, the color appears to have no gray content. Evans called this the $G_0$ (zero gray) point. Above $G_0$ the color appears fluorent. Finally, when the color is more luminant than the surround, it appears in illuminant mode and has brightness." I have already commented that conditions giving rise to the appearance of fluorence are particularly common with SLDs.

Figure 8 indicates that there is also a level of relative luminance at which the color and the surround appear to have equal *lightness*. The luminance for equal lightness, as well as the luminance for zero gray, differs depending on wavelength according to a function that is similar in shape and form to the function describing saturation discrimination (Figure 9). These functions quantify the concept of *color strength*.. Color strength appears to be related to the *optimal colors*; blues and reds, which have greater color strength than yellows, also have optimal colors with lower relative luminance. Differences in color strength may explain differences between hues in the amount of chromatic contribution to brightness and lightness.

In the NCS color atlas, gray content and nuance are illustrated by samples with known x,y,Y coordinates. They can be simulated on SLDs by following the same rules described earlier for Munsell samples. Since colors with the same nuance are considered "harmonious" by many decorators, the NCS atlas is a valuable reference for SLD users working on interior or exterior design problems. But again it must be remembered that the atlas notations do not inhere in the samples or in their x,y,Y coordinates; they depend on faithfulness to the context. As the Evans (1974) studies demonstrate, gray content is strongly dependent on the relative luminance of sample and surround. Accurate simulation of an NCS sample requires careful attention to its context. The atlas notation for hue, chromaticness, and nuance of that sample will apply only if the sample is viewed on a white background of the right relative luminance and chromaticity.

Derefeldt (1991) regards the DIN system's D (darkness degree) as "a whiteness-blackness dimension rather than a lightness dimension." However, in the DIN system, samples of the same hue and saturation, but differing only in D, actually have the same x,y-chromaticity coordinates;

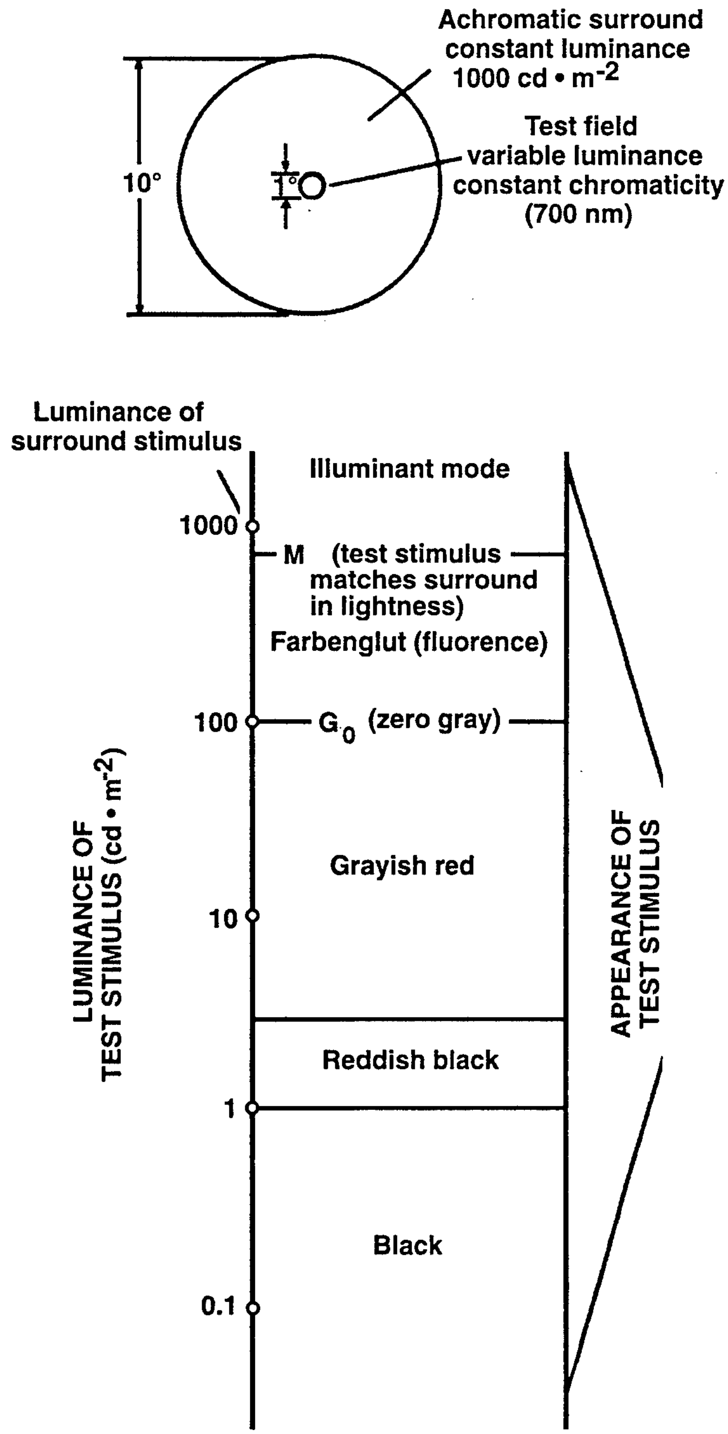


Figure 8

Diagram showing the appearance of a monochromatic (700 nm) test stimulus of 1∞ angular subtense surrounded by an achromatic (white stimulus of 10∞ angular subtense. The luminance of the test stimulus changes from 0.1 to over 1,000 cd/m$^2$ while the luminance of the surrounding stimulus is kept constant at 1000 cd/m$^2$. Reproduced with permission from Pokorny et al. (1991), p. 47.

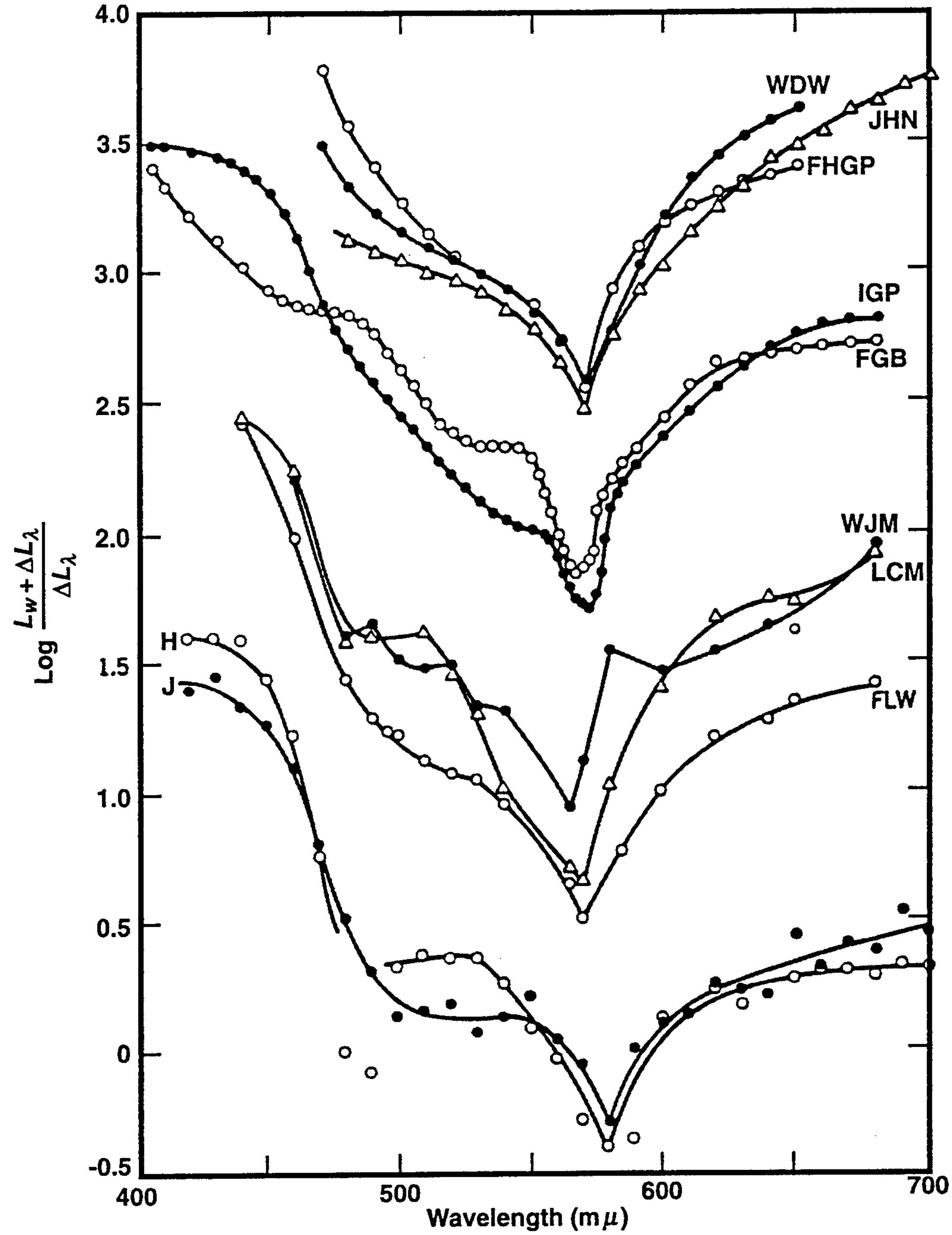


Figure 9

Saturation discrimination curves obtained in five major studies reported between 1933 and 1955. Reproduced with permission from Graham (1965), p. 361.

such samples differ only in Y. This feature is not present in either the NCS (for colors of the same hue and *c* but different *s*) or the Munsell system (for colors of the same hue and chroma but different lightness). In those systems shifting *s* or lightness entails shifting the x,y-coordinates as well as the reflectance Y. D is thus useful as defining a *shadow series*, a set of colors occurring naturally when different parts of the same surface (or different surfaces with the same reflectance profile) are illuminated by varying amounts of the same kind of light.

Texture algorithms in computer image generators commonly operate on the principle of a shadow series. A hue, described numerically as a digital RGB code, is varied in luminance by multipliers between 0 and 1 (for "shadow" effects) and/or above 1 (for "illumination" effects). Although proportional changes in R, G, and B do not actually result in constant chromaticity throughout the display's luminance range, human vision is forgiving of small chromaticity differences (especially at low luminances), and the textured surface is perceived as a surface of uniform color under different levels of illumination due to sun angle and shadowing.

**Advantages of Using Different Color Order Systems**

It is apparent that each color order system has something important to offer and that no system offers everything an SLD user might want. Since all the systems have tables and/or equations for converting to CIE x,y,Y coordinates, all are equally accessible to simulation, following the principles outlined previously for the Munsell system. In choosing one of the system atlases as a starting point for color selection, SLD users should think carefully about the color dimensions important in their particular applications.

Users concerned with the measurement (or management) of small color differences are likely to prefer the Munsell or OSA systems. Both these systems feature approximately equal perceptual distances between adjacent samples. Munsell's geometry is traditional, using common color names red, yellow, green, blue, and purple for its 50 hue steps. Achromatic colors from black to white occupy the center pole, and each hue is represented at 9 value levels and with steps of increasing chromatic content (chroma) along a radius. The geometry of the OSA system is more complex, and its three dimensions (*g* for red to green, *j* for yellow to blue, and *l* for lightness) do not explicitly refer to anything resembling the traditional "chroma" or "saturation" concept. But either system is clearly preferable to NCS or DIN for applications that require equal perceptual spacing of samples.

Munsell value is tied to luminous reflectance. As a scale of lightness, value is most satisfactory for achromatic colors; it represents lightness less well for highly chromatic colors, and the amount of error varies with the *chromatic strength* of the hue in a manner approximately described in Figure 9. OSA lightness *l* has been adjusted for chromatic strength; samples at the same OSA *l* therefore do *not* have the same luminance. The OSA adjustment is only approximate; there is evidence (Ikeda, Huang, & Ashizawa, 1989) that the chromatic contribution to lightness and brightness increases with increasing photopic luminance. However, in the limited luminance range available to SLDs, the OSA system should be relied on for choosing display colors of approximately *equal lightness*.

Neither Munsell nor OSA will be helpful in selecting colors according to gray content. For this purpose NCS is preeminent, and the published tables of x,y,Y values are actually more accurate than their realizations as painted samples in the NCS Color Atlas (Smith, Whitfield, & Wiltshire, 1990a,b; 1991). A simulated array of 16 major NCS hues at the same nuance (4050), displayed on a standard white background, looks like a credible set of surface colors; although there are differences in lightness among the samples, these differences do not appear extreme. A similar array of 16 different Munsell hues at the same value and chroma (5/12) is not a credible set of surface colors; although all samples have the same luminance, their lightness differences are profound, and some samples actually appear fluorent.

NCS colors at $s = 0$ are suitable examples of what Evans (1974) called zero gray; in NCS terminology, these colors are said to be "clear" colors. A series of such colors gives a satisfactory approximation to colors seen as color-contingent aftereffects (McCollough 1965, 1995). Aftereffect colors of different strengths will differ in NCS chromaticness $c$, but they have no gray content; they are clear colors.

Although none of the NCS color appearance dimensions were originally defined by reference to psychophysical luminance or chromaticity, blackness $s$ has been found to correspond to luminous reflectance *at chromaticity 0* (that is, for achromatic colors). Here the NCS scale $s$ is identical with the Munsell scale V. In the most recent edition of the NCS Color Atlas, lines of constant luminous reflectance (constant V) have been superimposed on each hue page, enabling a user to choose NCS samples according to (approximate) V. For hues of greater color strength and lower optimal-color luminance (blues and reds), these lines slope generally upward with increasing chromaticness. For yellow hues, they slope generally downward as $c$ increases. This complex relation between V and $s,c$ reflects the differences between whiteness/blackness, lightness, and luminous reflectance.

Except for relations suggested by the constant V lines, differences in chromatic strength of hues are not well represented in the NCS; the relation to optimal colors is also obscured. For all hues, the most chromatic example imaginable has the designation $s = 0$, $c = 100$ and occupies the same position on an NCS diagram. What is *achievable* with reflective samples (i.e., limitations of the real color gamut) can be roughly judged from the atlas pages. No examples beyond 0090 are found, and for many hues the sample having minimum $s$ and maximum $c$ is much lower (for example, 3060 for a purple with equal red and blue content). However, diagrams of the Munsell system (such as the ones found on pages 508 and 510 of Wyszecki & Stiles, 1982) give a much better idea of the gamut of optimal colors for reflective samples.

The DIN system not only facilitates the choice of colors forming a shadow series; it also relates the scaling of D (darkness degree) to the gamut of optimal colors. Having first established an equal interval scale for hue through judgments of reflective samples, the developers of DIN tied the 24 steps of this scale to dominant wavelengths in a 1931 CIE chromaticity diagram with D65 as reference white. They then determined a "closed line of equal saturation" (but constant lightness) for 8 of these 24 hues and designated the 8 pairs of x,y coordinates lying on this line as saturation S = 6. The distance from these points to S = 0 (at the white reference) was scaled psychophysically into 6 equal steps, and additional saturation steps were extrapolated beyond S = 6 (and interpolated for the 16 other hue radii).

Then, for the 24 points at which S = 6, D was determined as the luminance at that point divided by the luminance of the optimal color at the same dominant wavelength. The optimal color is assigned D = 0; ideal black is D = 10. The value of D is defined according to the equation

$$D = 10 - 6.1723 \log\left(40.7 \frac{Y}{Y_0} + 1\right) \tag{3}$$

where $Y_0$ is the luminance of the optimal color at the same dominant wavelength. Thus, for a yellow-green with x,y-coordinates 0.425, 0.484 at S = 6, the optimal color's luminance is about 96% of white luminance. If white luminance is 60, the yellow-green at luminance 57.6 will be assigned D = 1. A blue with x,y 0.184, 0.152 at S = 6 has an optimal color with luminance only about 31% of white luminance. To be assigned D = 1, this blue need only have a luminance of 18.6 $cd/m^2$. Use of the DIN system's x,y coordinates, therefore, enables SLD users to bring their simulation into line with the gamut of optimal colors.

**Surround Effects on Lightness, Whiteness/Blackness, and Chromaticness**

Pokorny *et al.* (1991, p. 46) have pointed out the unsatisfactoriness of existing CIE definitions of "lightness" and "chroma." "Lightness refers to the apparent amount of light in a patch in relation to a patch that is perceived as white....Chroma refers to the saturation of a colour with respect to an achromatic colour of the same lightness. It is related to the relative achromatic content of the colour....An unsatisfactory aspect of both these definitions is that they come primarily from consideration of the simple situation of pigment colours viewed in a neutral grey surround. In practice, colours are viewed in complex situations. Observers have difficulty in abstracting the concepts of lightness and chroma in a complex scene. Lightness is determined by the properties of surrounding colours....Chroma is an even more difficult and non-intuitive concept. The definition is unsatisfactory since *darkness can be induced by the presence of surrounds, and is interpreted as greyness* (Evans, 1974)."

Furthermore, a light surround is necessary for the production of dark colors. "Most dark colours, e.g., navy blue, maroon or forest green appear to be dark versions of hues associated with unrelated colours." However, brown is different. "Brown is...the colour name used to describe non-luminous related colours of yellowish, orange, or reddish hue that have an appreciable grey content....Orange appearing lights assume the appearance of brown when surrounded by a white appearing border only *one sixteenth* the width of the colour sample (Uchikawa, Uchikawa, & Boynton, 1989). Brown is typically not perceived as dark yellow." (Pokorny *et al.,* 1991, p. 48)

The problems pointed out by these authors are problems of color appearance generally, but they have special relevance for SLD users because the medium is luminous rather than reflective patches. Artists working with opaque paints find it easy to create dark colors; it is much more difficult to produce the appearance of bright illumination (such as moonlight reflected from ocean waves). Artists working with SLDs have the inverse problem: bright spots are easily created, but it can be hard to make dark colors convincing. The solution in both cases lies in the appropriate use of very dark or very light surrounds.

<u>Surround effects in color management systems</u>. Software for manipulating SLD color is available from many sources and varies greatly in quality. Originally such software was designed to help designers or modelers select appropriate display colors by enabling them to visualize the achievable possibilities in some orderly way. Many different sorts of three-dimensional arrangements were chosen and exhibited as available palettes. More recently, color management software has been augmented by methods of device-independent color rendering so that the image, once prepared on an SLD, can be faithfully reproduced as hard copy by a color printer. Hard copy reproduction is a special technology that will not be discussed here.

Palette displays produced by software typically show a set of colors from one region of color space, all arrayed against the same uniform background. The Armstrong Laboratory's Color Modeling Workstation (CMW) provides an example. The CMW was designed to compute the gamut of a device from characterization data and display one hue-leaf region at a time in CIELUV space. Those individual colors already chosen for a geographical database were displayed as small rectangular patches located at their L* and C* positions, provided their hue angles were within 5 or 10 degrees of the chosen hue-leaf position. Since the CMW was intended to assist color-matching between two or more different displays, the screen also contained a great deal of additional information. But the palette display, with its uniform whitish background, did not give the user any means of knowing *how these colors would really look in the actual scene.* For that purpose, users need to place potential color choices into the context of the scene for which they are being chosen. Color editing software for computer-generated images should provide this opportunity, but many versions do not.

Measuring the brightness of chromatic colors. The dependence of brightness and lightness upon chromatic content has already been mentioned, and the relation between this chromatic contribution to brightness and color strength (as defined by Evans' experiment) has been pointed out. Moreover, it has been demonstrated, in different ways, that SLDs can produce luminances for blues that exceed what is possible with reflective samples.

SLDs are increasingly used for vision research, yet there have been few studies using SLDs to measure the chromatic contribution to brightness. The ten observers in Mandra's (1989) experiment varied the luminance of an achromatic field to match the lightness of an adjacent chromatic test field at luminance 12 cd/m$^2$. The achromatic luminances chosen to match 10 simulated Munsell hues at the same V/C (5/6) did not differ significantly, indicating that the hues did not differ in lightness at this C level and in the presence of a white-appearing surround. However, matching achromatic luminances increased with increasing C (from /4 to /10, /12, or /16) for samples of constant hue and value. This experiment shows the expected increase in lightness due to increasing colorfulness for samples of the same objective luminance. It fails to give evidence for a hue effect on lightness.

Following a very similar matching procedure, Howard (1990) reported strong effects of both hue and colorfulness for 72 test colors at this same luminance level (12 cd/m$^2$), presented in a dark instead of white surround. Size of these effects differed markedly among the six observers; such individual differences were also observed and reported in detail by Sanders & Wyszecki (1963) using the MacAdam binocular colorimeter for matches to 20 cd/m$^2$ test colors in a surround of that same luminance. Analysis of these three experiments, each with a different background level, indicated a need for systematic study of the role played by surround in heterochromatic brightness matching studies.

A series of pilot studies was therefore initiated, using a set of 36 colors chosen systematically from the NCS (Howard, 1995). Although the procedure followed was similar to Mandra (1989) and Howard (1990), the new test colors were not all at the same luminance, as the test colors were in the previous experiments. Instead, their luminances were chosen to simulate the NCS samples appropriately when the luminance of a white perfect reflector is 39.7 cd/m$^2$. Since the sample luminances ranged from 5.33 to 29.1 cd/m$^2$, their relative luminances with respect to this reference range from 0.134 to 0.733 (equivalent Munsell values above 4/ and below 9/). In separate sessions, brightness matches were made in the presence of black, N3/ gray, N10/ white, and a brighter (60 cd/m$^2$) white surround.

Statistical analysis of 432 observations shows that white surrounds suppress the effect of color strength on lightness. Matches made in the presence of gray and black surrounds do not differ, as long as the gray surround luminance does not exceed the luminance of the test colors. Luo and his co-workers (Luo, Clarke, Rhodes, Scrivener, Schappo, & Tait, 1991a,b; Luo, Gao, Rhodes, Xin, Clarke, & Scrivener, 1993a,b; Luo, Gao, & Scrivener, 1995) have used SLDs in extensive studies of lightness and colorfulness; their data, obtained by the method of magnitude estimation, are in general agreement with the conclusion that chromatic effects on lightness vary with the level of surround luminance.

It thus becomes clear why Mandra (1989) reported no substantial hue effect on lightness, while Howard (1990) and Sanders & Wyszecki (1963) found strong evidence for such an effect. In Mandra's experiment the test and matching fields were presented on a simulated white background. In Howard's study, the background was black (as it has been in the numerous studies that have used Maxwellian view); Sanders & Wyszecki used an illuminated surround, but its luminance did not exceed the test color luminance.

## Conclusion

Hunt (1985, p. 19) comments that existing color order systems are not adequate for describing color appearance in SLDs, whether the displays present unrelated colors or luminous related colors. "The effect of the dark surround on the appearance of unrelated colours is very large, and implies that they may require colour order systems designed specifically for them. Luminous related colours are now an important class of colours, because of their widespread use in VDUs [video display units], and colour order systems applicable to them are required. Non-luminous related colours are the colours for which most colour order systems have, so far, been designed."

Ten years later the situation has not changed. The color science community has continued to treat SLDs as if they were indistinguishable from the reflective displays they often seek to simulate, and it has largely ignored the special problems presented by displays designed without simulation in mind. This report documents for the first time the important differences in reflective and luminous display gamuts, and it provides some guidance for SLD users who wish to apply the wide range of resources that have been developed for use with reflective materials. Context plays the key role in color appearance for both reflective displays and SLDs, but more explicit attention to context is required in managing the color appearance of self-luminous images.

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