Managing Color Appearance in Self-Luminous Displays

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Abstract

Electro-optical displays challenge color appearance systems based on the study of surface colors because these displays provide complex arrays of additive color. CRTs already enable us to present some colors beyond the gamut of surface colors at both high and low lightnesses. Laser-based devices will carry this potential much farther, resulting in dark colors as well as light ones with a colorfulness that in some cases lies even beyond the maximum theoretically achievable with illuminated objects. The work of Evans, who regarded surface colors as a special case of aperture colors, deserves renewed attention for its applicability to additive color displays. Users of self-luminous displays need to be aware that brightness is not adequately measured by photopic light meters and that lightness and chroma of display elements will be affected by their context, including not only the near background but also the far surround. Keywords: aperture and surface colors, optimal colors, additive color, heterochromatic brightness, lightness, chroma, fluorence, grayness, background and surround effects.

1. Additive Color in Computer-Generated Displays

We began referring to self-luminous displays (SLDs) some years ago when technology broadened to include not only cathode-ray tubes (CRTs) but also various other kinds of electro-optical displays. Leading authors on color appearance such as Wyszecki[1] and Hunt[2] have recognized that such displays present special problems. This paper focuses on the special problems that emerge when the electro-optical display produces *additive color* from a set of red, green, and blue primary light sources.

Color appearance systems as they exist today were devised to deal with *subtractive color*. These systems assume a standard broadband illuminant (usually Illuminant C or D65 daylight) falling on pigmented surfaces which *absorb and reflect* light from the illuminant in varying proportions, depending on wavelength. As the history of color photography shows, these systems have also been applied successfully to photographic transparencies, such as color slides, where the illuminant is located inside the projector and the transparency *filters* light from this source in varying proportions, depending on wavelength.

The CRT is an additive color device. In this sense it performs somewhat like the laboratory colorimeters employed in those classical color-matching experiments of the 1920s on which so much of modern color science rests. Like those instruments, it provides three primary light sources, but instead of extracting them from white light by filters or monochromators, it produces them by stimulating red-, green-, and blue-emitting phosphors. In the future we may also expect to see electro-optical displays based on monochromatic primaries derived from lasers. Such devices will combine the color capability of laboratory colorimeters with the temporal and spatial complexity of modern information displays.

Additive color has been extensively employed in color vision research, and until recently most of this research has employed quite simple spatial arrangements of one or two colors in a dark field. The bipartite field characteristic of colormatching experiments is an example, as well as the disk-annulus arrangement typical of experiments on contrast. Simple arrays on a dark field are called "aperture colors," to distinguish them from real or simulated arrays of reflective surfaces under illumination, called "surface colors." Most of us were taught that color appearance terms apply in different ways to colors in the aperture or surface "modes."

Now that we can produce complex, rapidly changing spatial arrays of additive color using electro-optical displays, perhaps we ought to expect that some unresolved color appearance issues will begin to catch up with us. We are being liberated from two restrictions imposed by reflective displays that may actually have served to protect our cozy color appearance ideas. First, in some areas of color space we are no longer restricted to the gamut of real surface colors. Second, no illuminant is present to perform its usual normalizing functions, setting limits on the range of lightness contrast and governing the lightness and colorfulness of objects and background. Absence of the illuminant results in a *decoupling of stimulus variables* with consequences I shall discuss in a later section. In the following section, I examine the gamut expansion already available with CRTs, and I describe the still greater expansion that will become available with laser-based devices.

In this discussion I use the term 'brightness' for the amount of light an area appears to emit, and I use 'lightness' for judgments of brightness that are relative to the brightness of a white area in the same array. Luminance is radiant energy evaluated for its effectiveness as a visual stimulus. Brightness is correlated with luminance, and lightness is correlated with relative luminance; but luminance is not the only factor influencing the brightness or lightness of an area. All color appearance systems deal with lightness, but they do so in different ways; I will be careful to point these out as we go along. I use 'hue' for the sort of difference designated by basic color names and 'chroma' for the amount of hue perceived in an area.

2. Gamut Differences

It is customary to describe display gamuts in a two-dimensional chromaticity space, ignoring the role of luminance. I will look first at these *chromaticity gamuts*, then expand them into a three-dimensional color appearance space, creating what can truly be called *color gamuts*.

2.1 Chromaticity Gamuts

Figure 1, adapted from Pointer,[3] is drawn in CIE 1976 Uniform Chromaticity Space (UCS). A linear transformation from x,y-coordinates into u′,v′-coordinates brings UCS closer to the goal of a perceptually uniform chromaticity space. The solid line in Figure 1 describes the chromaticity gamut of reflective surfaces derived by Pointer in 1980 from the Munsell Color Limit Cascade; this line approximates the range of chromaticities realizable with reflective pigment samples displayed in illuminant C. The line drawn with short dashes connects the chromaticity coordinates for the red, green, and blue phosphors of a Barco Calibrator CRT; it therefore represents the chromaticity gamut of that CRT. The CRT's gamut extends outside the pigment gamut in the blue region, touches it at the red edge, and lies well inside the pigment gamut for greens, blue-greens, and purples. Gamut comparisons of this sort are common, and many SPIE papers have offered proposals about how to deal with the limitations of an SLD gamut. The figure also includes a triangle outlined by long dashes, indicating the potential chromaticity gamut of a laser projector which I have imagined as having monochromatic primaries at 460, 530, and 660 nm.

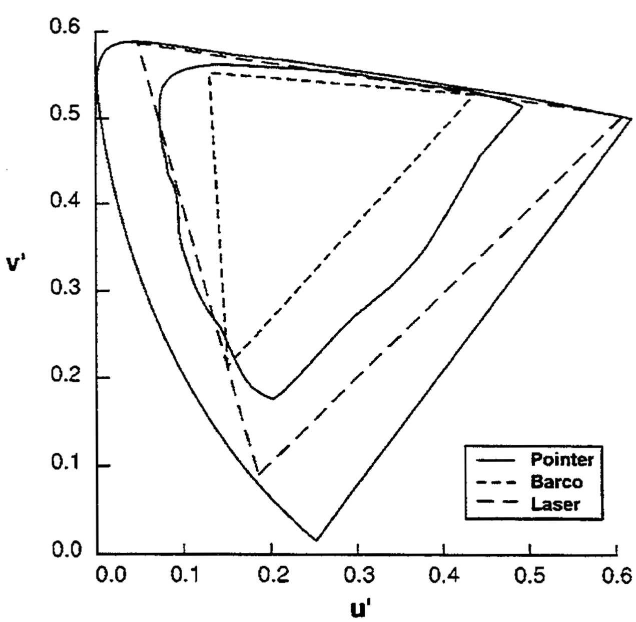

Figure 1. Chromaticity gamuts in CIE 1976 UCS

The full extent of any chromaticity gamut is really available only at low luminance levels relative to a maximum white luminance. Any surface whose chromaticity is described by chromaticity coordinates close to the spectrum locus will reflect only a limited portion of the daylight illuminant, and its luminance will therefore be less than 10% of the luminance of a perfectly reflecting white surface. Those surfaces achieving at least 20% relative luminance occupy a more limited gamut, and the gamut continues to shrink toward the position of the illuminant white at successively higher relative luminances. It is possible to calculate the set of colors that have the greatest luminance and chromaticity attainable by reflectance or transmission of radiant power with a given spectral power distribution. Colors at this theoretical maximum are called *optimal colors*. Representations of *optimal colors* for particular illuminants may be found in Wyszecki and Stiles.[4]

Highly chromatic areas of any display are necessarily limited in relative luminance. With electro-optical displays, however, the limitations imposed by the physics of reflected light do not apply. Instead, we have another set of limitations imposed by the physics of the lift source and the psychophysics of additive color-matching, represented by the chromaticity diagram. It will still be true that the maximum gamut is available only at low luminances. But since Figure l shows the Barco's blue primary lying outside the gamut for Pointer's surface colors, we may already expect to find that its luminance, relative to maximum white luminance, can sometitnes be greater than that of the most saturated similar color in Pointer's set.

2.2 Color Gamuts

To represent a three-dimensional color gamut, we need a solid shape similar to the Munsell color solid, often referred to as HVC color space. Value (V) is the Munsell variable related to lightness. V, tied to *relative luminance* by definition, is drawn on the vertical axis; hues (H) are arrayed around this axis in a circle; and chroma (C) increases with distance from the axis. Recall that the Munsell color solid is widest at middle levels of V and that the widest point is at higher V for yellow than for green, red, or blue.

The Munsell color solid can be represented in CIEL*u*v* (CIELUV) space. Pointer used CIELUV to represent the gamut of real surface colors in three dimensions, and I shall use it to compare that gamut with the color gamut of additive SLDs. In this space, the lightness-related variable is L*, a cube-root function of relative luminance. The chroma variable C* depends on the product of chromaticity (distance from white) and L*. Note that dark colors with chromaticity coordinates far from white will thus have lower C* values than more luminant colors located closer to white. The CIELUV equations were designed to reflect psychophysical data on the scaling of lightness and chroma.

The CIELUV color gamuts of additive SLDs can be computed by applying the same equations used in the study of reflective surface colors. These equations include a reference white with the chromaticity and luminance of a perfect reflector viewed in the designated illuminant. Since the brightest white normally available in an array of surface colors has a luminous reflectance of about 0.96, my calculations are based on a reference white slightly higher than the maximum white achievable by the display; the

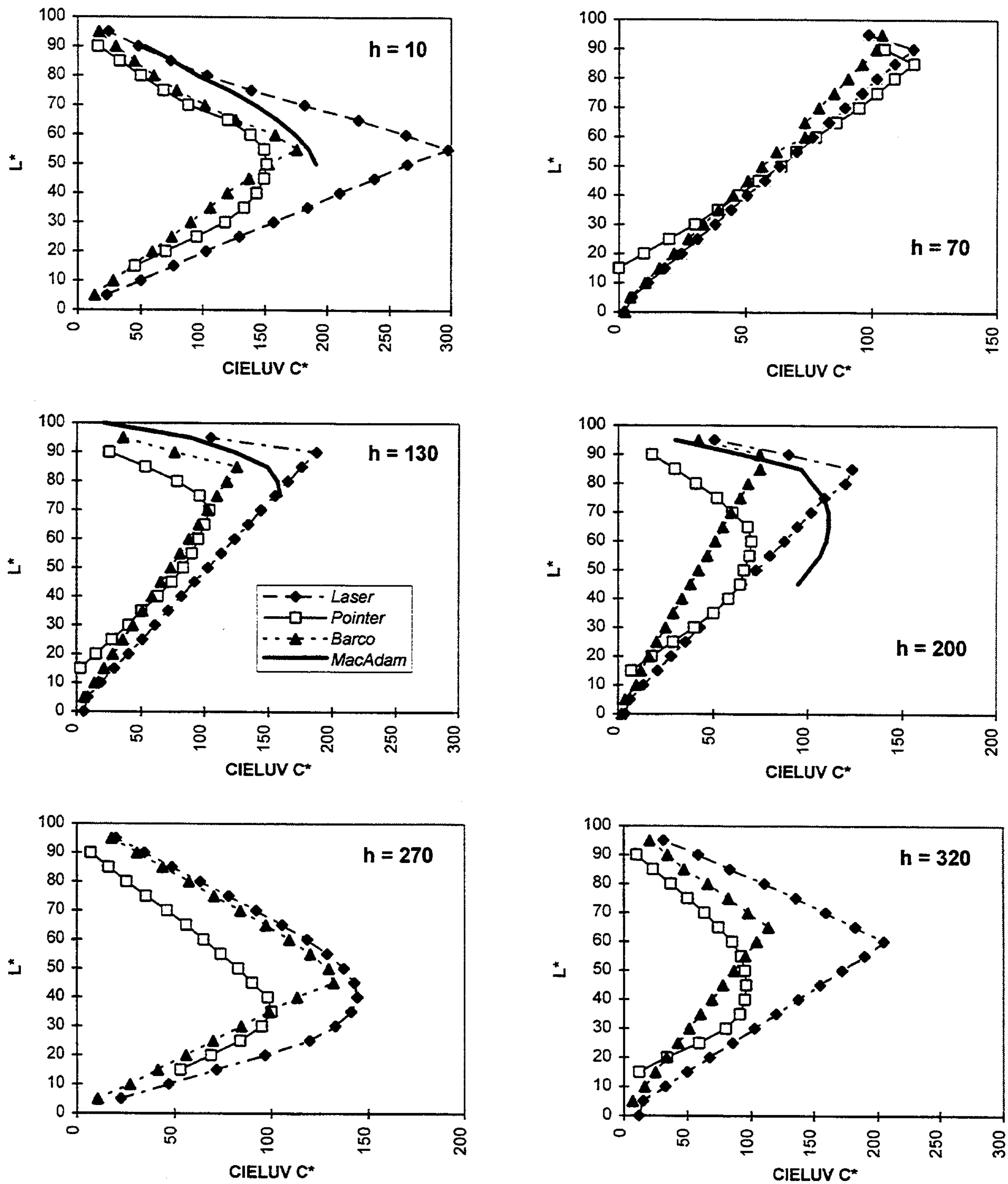

*Figure 2. Color gamuts in CIEL*u*v* space for Pointer's surface colors (squares), a Barco Calibrator CRT (triangles), and a hypothetical laser-based display (diamonds). Each graph shows maximum achievable C* as a function of L* for a hue-leaf. For hues at l0, 130, and 200 a heavy line represents optimal colors from MacAdam.*[4]

Calibrator's maximum white (124 cd/m^2) is 96.1 per cent of my reference white (129 cd/m^2), making it equivalent to a Munsell V of 9.75/.

I computed the color gamuts of the Calibrator CRT and my imaginary laser device from characterization data (voltage luminance functions for each primary) by calculating CIELUV statistics for every possible combination of RGB voltages and finding the maximum C* in each of 7200 L*C* bins (360 hue bins by 20 levels on L*). The characterization data for the CRT were obtained by radiometric measurement after the Calibrator was set for D65 white and maximum contrast. To create a characterization table for the imaginary laser, I first calculated the relative powers required to produce a D65 white from its 3 primaries, then converted these relative powers to luminances that, in combination, would give Calibrator's maximum white luminance. The voltage luminance functions from the Calibrator were then applied to these primary luminances.

Figure 2 presents C* as a function of L* for six hue angles: 10, 130, and 270 are the approximate positions in CIELUV for the devices' red, green, and blue primaries; 70, 200, and 320 are the intermediate positions near yellow, cyan, and magenta. In each graph triangles connected by short dashes represent the maximum gamut for the CRT, while a solid line connecting squares represents the maximum gamut for real reflective samples (from Table 1 in Pointer[3]). On all the graphs, C* increases with L*, reaches a maximum, then decreases. The well-known limitations of the CRT gamut are now seen to exist primarily at medium L* values. For L* values that are very high or very low, the CRT color gamut generally reaches beyond the gamut of surface colors. It can be seen that this CRT, *at low relative luminances*, achieves some colors (but not blues) that are more highly chromatic than the most saturated reflective samples. At *high relative luminances*, it achieves some greens and blues (but not reds) that exceed the gamut of reflective samples. Other CRTs whose gamuts I have examined can exceed the surface gamut in the blue region at both low and high L*.

Long dashes and diamonds represent the color gamut of my imaginary laser projector. Not surprisingly, the laser Gamut exceeds Pointer's surface color gamut almost everywhere; it is most limited in the yellow and cyan regions. (Even a laboratory colorimeter cannot obtain matches to all spectral colors through addition of primaries!) In some regions the laser gamut also exceeds that of optimal surface colors, shown in Figure 2 by a heavy line (based on MacAdam[5]). It will be possible with a laser device to get some very highly saturated colors at low relative luminances, as well as colors of increased chromaticity at high L*. *No color order system designed for reflective colors will be sufficient to describe such a gamut, and no reflective samples or photographic slide can adequately present it.*

Figure 3 is a way of summarizing the peak colorfulness of these devices in each region of the hue circle. This figure shows the maximum C* achievable at each hue angle for Pointer's surface colors (squares), for the CRT (triangles), and for the laser (diamonds). Hue angles are represented by numbers 0 through 350; hues progress counter-clockwise from red at 10 through yellow-green at 130, blue at 270, and purple around 320. For surface 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 surface colors only in the regions near its primaries. Clearly the chromas and lightnesses achievable by SLDs differ in important ways from the gamut of surface colors represented by reflective samples. I will now look at some implications of these differences for our understanding of color appearance.

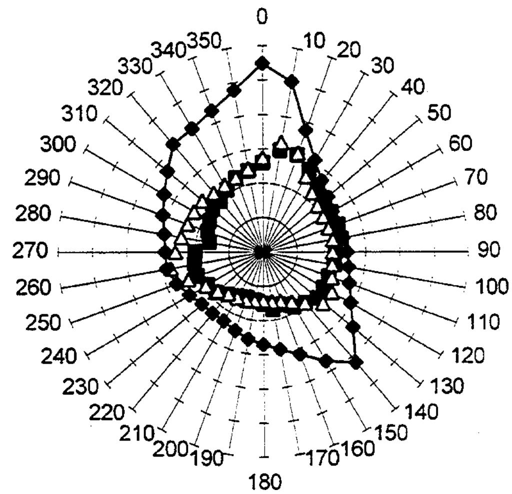

Figure. 3. Maximum C gamuts (scaled in units of C* = 50)*

Color Appearance Dimensions

Over twenty years ago Evans[6] argued that "there are five distinct and independently variable color perceptions, rather than the three usually assumed." To the three then commonly named (hue, brightness, and chroma) he added two more, lightness and brilliance. Wyszecki[1] and more recently Pokorny, Shevell, and Smith[7] have drawn attention to Evans' observations, which were nude in the laboratory using a simple disk-annulus display with aperture colors. For this discussion it is important to note that Evans considered the aperture mode as the general case that includes the surface mode. A decade after his death we began to have display devices that require this perspective. Many of the phenomena he described are not easy to see with illuminated arrays of reflective surfaces. We can see them better in additive SLDs because of gamut expansion and decoupled stimulus variables. I begin with the phenomenon for which Evans coined the term *fluorence*.

3.1 Fluorescence

Imagine a small area of red light embedded in a white-appearing background. Let the luminance of the background remain constant while the chromatic area is gradually raised from a low luminance, at which it appears black, to a luminance exceeding that of the background. The chromatic area first appears black, then blackish but tinged with color, then grayish-red. Its gray content gradually diminishes to a point at which the red appears to have no gray content; Evans called this the point of *zero gray*. As the red luminance increases above the zero gray point, it appears to *glow*. This is the appearance which Evans called "fluorence" and which was called *Farbenglut* in the early German literature.

Derefeldt[8] has remarked on the tendency of SLDs to produce the appearance of fluorence. She and her colleagues simulated pages from the Swedish Natural Color System (NCS) on a CRT, then shifted the background white to a lower luminance, one that might be considered to simulate a gray rather than a white background. Many of the simulated color samples then appeared to glow. The same effect can be achieved by lowering the background luminance of a simulated Munsell hue leaf. If one obtained absolute judgments of such samples on the NCS dimension of 'whiteness/blackness,' I believe even the samples that do not show fluorence would be found to have decreased gray content when displayed on a gray background.

It requires rather special circumstances to see fluorence with reflective samples. At the Colorado University vision laboratory, I have seen a uniformly illuminated hemisphere, about a meter in diameter, painted with a homogeneous medium gray. When fitted precisely into an opening in the center of this hemisphere, many small samples from the OSA Color System appear fluorent. Fluorence arises from the relative luminance of sample and background. We will see more of it with additive color displays because such displays remove the interdependence of sample and background luminance that is normally present in arrays of illuminated surfaces. Moreover, additive color displays provide us with expanded color gamuts, enabling us to achieve colors of great purity at higher relative luminances.

3.2 Brilliance

Fluorence and grayness are described by Evans as aspects of the perception of *brilliance*, a perception that can be experienced as similar to brightness. At 100 mL, Evans remarks, an isolated 430nm blue is "dazzling" and 574nm is "only comfortably bright." Brilliance needs to be distinguished from brightness when observers make heterochromatic brightness matches involving spectral colors. Helmholtz reported a similar view, which Evans found in the second edition of his great *Handbook of Physiological Optics*[9]; it is missing from the English translation of the third edition. Helmholtz wrote, "As far as my own senses are concerned I have the impression that in heterochromatic luminosity equations it is not a question of the comparison of one magnitude, but the combination of two, brightness and *Farbenglut*, for which I do not know how to form any simple sum, and which too I cannot further define in scientific terms." (Translation from Evans[6], Chapter 3)

As Pokorny *et al.* have recognized, Evans uses the 'fluorent' aspect of brilliance to designate a *chromatic contribution to brightness perception*. The size of this chromatic contribution varies systematically with wavelength composition, so that hues are said to have different *chromatic strengths*. Brightness judgments are correlated with luminance, but they are also affected by both hue and saturation. "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 *et al.*[7], p. 45) We should expect some anomalous brightness perceptions in additive displays, where blues, reds, and magentas can easily become fluorent.

CRT blues and reds do produce perceptions of unusual brightness. Taylor and Murch[10] offered some data on red, green and blue phosphor luminances required to match the brightness of a CRT white in adjacent 4.5° patches. Their 21 observers required an average blue luminance of only 2.7 cd/m^2 to match a white of 10 cd/m^2. The ratio of these brightness-matched luminances is almost 4, but not all of this effect should be ascribed to chromatic strength. Laboratory studies with 1° or 2° fields (such as Shaft and Werner[11]) obtain ratios around 2.5 to 3. The remainder of the effect is due to the presence of rod activity in the larger field at this luminance level. Retinal rods are active up to 100 cd/m^2. SLD users should not rely on readings from *photopic* photometers when they are adjusting the brightness of regions of different color. "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."[12]

Chromatic strength also affects the perception of lightness. At photopic levels blues appear lighter than reds or greens which have the same relative luminance, and the amount of difference depends on colorimetric purity. It is hard to demonstrate these effects with colored papers 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 luminance is in fact lower. With additive color displays larger effects of hue and saturation on lightness may be observed. Because the relative luminances of white and colored display areas can be independently adjusted, red, green, and blue patches at maximum chromaticity can all be displayed at a medium luminance relative to a white ground (such as Munsell V = 5, about 20 per cent of the maximum white luminance). Such a display would not be a valid simulation of any array of surfaces in a common illumination.

Part of Evans' message to us can be summarized here. Let us agree that we can speak of both 'brightness' and 'lightness' as dimensions of all colors, whether they are in the aperture mode or in the surface mode. Let us also agree that both are affected by the chromatic contribution to brightness perception, even though they are primarily dependent on luminance and relative luminance, respectively. Munsell V, explicitly tied to the photopic luminance of a sample, does not take into account the effects of hue and saturation on lightness. Neither does the L* variable in CIELUV. On the other hand, the lightness variable *l* in the OSA system has been adjusted for chromatic strength; samples of different hue at the same OSA *l* do not have the same luminous reflectance. The lightness-related variable *D* (darkness degree) in the DIN system is adjusted to fit the gamut of optimal colors for a D65 white; differently colored samples at the same D have different reflectances.

Brightness, lightness, hue, and chroma make four variables. Brilliance, in its fluorence aspect, seems to boil down to a chromatic strength factor affecting brightness and lightness. Is there a fifth variable?

3.3 Grayness

According to Evans, grayness is another aspect of brilliance. A single light area in a dark field can appear to be white, but it never appears to be gray or black; grayness and blackness arise only in the presence of a background of sufficient luminance. With such a background both aperture and surface colors have an added perceptual dimension, varying along a continuum from black to gray to white. In fact this dimension serves as a lightness-related variable in the NCS. It is called blackness *s* (svarthet), and samples of different hue but equal *s* do not have the same luminous reflectance. Lines of constant luminous reflectance (identical with Munsell V) have been drawn in a recent edition of the NCS atlas; their slope differs from hue to hue. NCS colors at *s* = 0 are suitable examples of what Evans called zero gray, colors with no gray content.

SLD uses have independent control of sample and background luminance. Raising background luminance induces darkness in the sample, which is interpreted as grayness. A light background is necessary for the production of dark colors such as maroon, navy blue, dark green, and brown. Brown is perceived in samples that would appear yellow, orange, or red without the gray content induced by a light background. A white border only one sixteenth the width of an orange sample is sufficient to induce the appearance of brown (Uchikawa *et al.*[13]).

I have not made up my mind whether grayness is a fifth color perception, but I am convinced that it is often useful to identify colors according to their gray content. Gray content varies with context, and additive displays permit us greater latitude in choosing a context for color samples. My final section recommends that SLD users pay careful attention to background and surround.

4. Background and Surround Effects

Several writers on color appearance draw a distinction between a test area's immediate environment (its background) and its more remote environment. Following Hunt,[14] Fairchild[15] thinks of the background as extending 10° in all directions from the edge of the sample; whatever lies beyond that region is the *surround* Although Fairchild's interest is primarily in cross-media color reproductions, his recent article summarizes the different effects of background and surround on both lightness and chroma. These effects are very important for the study of color appearance in additive displays.

4.1 Background

The availability of displays using digital color has inspired many of us to simulate surface colors on our displays, and frequently we take advantage of the CIE tristimulus values available for color order systems such as Munsell and the Swedish Natural Color System (NCS). A simulation of any set of reflective samples on an electro-optical display will be a true simulation *if and only if* the normalized Y values found in the tables are converted to display luminances by using the same assumed ordeal 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 color order system which is being simulated.

However, I believe it is not sufficiently recognized that presentation of Munsell or NCS 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 system's 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 reflective 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 "IR 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. In discussing fluorence, I have already noted that some colors shift their mode of color appearance from surface to fluorent when background luminance changes from white to gray. The background can also change the relative balance of chroma and gray content by inducing darkness, interpreted as grayness.

4.2 Surround

Fairchild[15] relates how the photographic industry came to recognize that color transparencies projected in a dark surround required greater luminance contrast and chroma than color prints viewed in an illuminated surround. To obtain an optimum reproduction on a transparency, the physically measured luminance contrast must be about 1.5 log units higher than that in the scene. With photographic systems, this increase in luminance contrast automatically increased chroma. Fairchild explains why: "In photographic systems...the system contrast for lightness is controlled by three color processes that must be balanced to properly reproduce the gray scale. If the gray-scale contrast is increased, all three processes must have increased contrast, resulting in an increase in chromatic contrast and, therefore, the chroma of colored image areas." Innovators in the photographic industry first discovered how to produce optimum transparencies, then carried out the experiments which measured what they had done. The role of the dark surround in producing these effects was then apparent.

Electro-optical displays projected in dark surrounds are subject to surround effects and will require similar corrections. Until recently, I have not myself appreciated the need for exaggerated contrast and chroma in some of my laboratory's flight simulator displays. I now see that the dark surround in which they are projected may require the enhancement of contrast and chroma in order to achieve optimum reproduction of real world scenes. But with digital color devices, increasing contrast will not automatically increase chroma; it will be necessary to make explicit changes in both variables. Fairchild has suggested a way in which this can be done by using the CIELAB (CIEL*a*b*) color space. CIELUV and CIELAB have identical equations for L* but differ in the way they define the two dimensions describing hue and chroma. CIELUV defines these dimensions in relation to u′v′-chromaticity space. CIELAB uses power functions of the X and Z tristimulus values (just as L* is a power function of tristimulus Y). Correcting for surround effects can be accomplished by converting design colors into CIELAB space, expanding their L*, a* and b* values appropriately, and converting back to digital color through XYZ space. Fairchild suggests some exponents to use in the expansion.

5. References

1. G. Wyszecki, "Color appearance," in *Handbook of Perception and Human Performance*, K. R Boff, L. Kaufman, and J.

P. Thomas (eds.), vol. **I**, 9-1 to 9-57, Wiley, New York, 1986.
2. R. W. G. Hunt, "Perceptual factors affecting colour order systems," *Color Research & Application* **10**, 19, 1985.
3. M. R. Pointer, "The gamut of real surface colors," *Color Research & Application* **5**/3, 145-155, 1980.
4. D. L. MacAdam, "Maximum visual efficiency of colored materials," *Journal of the Optical Society of America* **25**, 361-367, 1935.
5. G. Wyszecki & W. S. Stiles, *Color Science: Concepts and Methods, Quantitative Data and Formulae*, Wiley, New York, 1982.
6. R M. Evans, *The Perception of Color*, Wiley, New York, 1974.
7. J. Pokorny, S. K. Shevell, & V. C. Smith, "Color appearance and color constancy," in *The Perception of Color*, P. Gouras (ed.), 43-61, CRC Press, New York,1991.
8. G. Derefeldt, C.-E. Hedin, & C. Sahlin, "NCS colour space for VDU colours," *Displays* **11**, 8-29, 1990.
9. H. von Helmholtz, *Handbuch der physiologischen Optik,* 2nd ed, Voss, Hamburg, 1896.
10. J. M. Taylor & G. M. Murch, "The effective use of color in visual displays: Text and graphics applications," *Color Research & Application* **11**, S3-S10, 1986.
11. J. M. Kraft and J. S. Werner, "Spectral efficiency across the life span: flicker photometry and brightness matching," *Journal of the Optical Society of America*, **11A**, 1213-1221, 1991.
12. Mesopic Photometry: History, Special Problems, and Practical Solutions, *CIE Pub.* No. **81**, Central Bureau of the CIE, Vienna, 1989.
13. H. Uchikawa, K. Uchikawa, & R. M. Boynton, "Influence of achromatic surrounds on categorical perception of surface colors," *Vision Research* **29**, 881-890, 1989.
14. R W. G. Hunt, "Revised colour-appearance model for related and unrelated colours," *Color Research & Application* **16**, 146-165, 1991.
15. M. D. Fairchild, "Considering the surround in device-independent color imaging," *Color Research & Application* **20**, 352-363,1995.

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