

Color Spaces and Image Quality

John J. McCann and Michael Stokes
McCann Imaging and Hewlett Packard
Belmont, MA 02178 and Boise, ID 83714
mccanns@tiac.net and Michael_Stokes@HP.com

Abstract

When studying the quality of color reproductions we often turn to Color Spaces to help us quantify the difference between two colors. If we know the coordinates of two different samples, we can use the straight-line distance between their positions in three-space as a measure of the color difference or the color error.

There are many different spaces, each established with different criteria. Which of the many color spaces is the best? Which mimics human color vision the best? If we want to use a color space to quantify color appearance, the answer is easy. We must use an isotropic color space; that is, one that has the same appearance increments in all directions. Throughout this space a unit of chroma, a unit of lightness and a unit of hue must appear equally different.

In summary, this paper reviews a variety of color spaces, their criteria and properties. It plots isotropic, observation-based spaces in colorimetric spaces. It discusses which color spaces are consistent with quality issues in pictorial images.

Introduction

In 1978 the CIE[1] adopted a standard called L*a*b*. It uses X,Y,Z as inputs.[2] These values are linear transforms of the sensitivities of human cones. The X,Y,Z space has the valuable property that it can identify whether two adjacent patches on the retina will match. However, if one wants to represent colors as they appear in everyday life, then X,Y,Z, space is a very poor space. The spectral sensitivities overlap. That means that a single wavelength will generate a partial response on all three axes. All colors, with the exception of white and black, fall in the center of the color space.

The CIE L*a*b* space addresses this problem with X,Y,Z Space. First, it scales white to black using appearance data. Munsell and many others have made equally spaced white-to-black scales. These gray appearance scales are fit by the cube root functions of radiance of patches in the display. Stiehl et al.[3] worked with equally spaced displays and corrected them for intraocular scattered light. They showed that after scatter on the retina, a log radiance function fits the equal lightness data. In other words, the cube root function corrects for the effect of intraocular scatter.

L* is the cube root of Y normalized by maximum Y. which is not derived from the scene. It is a separate measurement of a known white. L* is scaled from 100 to 0.

CIE a* is an axis perpendicular to L* that represents a red-green axis. It is the difference of the cube root of normalized X and the cube root of normalized Y. The output a* stretches the red green axes by multiplying this difference by 500. CIE b* is an axis perpendicular to L* that represents a yellow-blue axis. It is the difference of the cube root of normalized Z and the cube root of normalized Y. It stretches this yellow-blue axis by multiplying this difference by 200. The selections of these coefficients is based on color difference data. This is formally called the CIE Uniform Color Space and Color Difference formula, and informally called L*a*b* uniform color space. It is almost universally used when scientists and engineers want an isotropic color space.

Viewing conditions influence appearance of colors. Each color space works best for the conditions used to define the space. Many of us need a uniform color space for real world viewing conditions. An extremely good example is the problem of mapping color on a computer monitor to colors on a reflection print. The question is whether L*a*b* is an isotropic color space in ordinary viewing conditions.

The Optical Society of America Uniform Color Space(OSA-UCS)[4] is a set of colors that have been selected to appear uniformly spaced. That is, the apparent distance in lightness of 2 is equal to the apparent difference of 2 in yellow j and 2 in green g.

We began by looking at OSA-UCS samples in a variety of viewing conditions (gray surround, white surround, wooden table) and illuminants (daylight and incandescent). We observed only even numbered planes: L=-4, -2, 0, 2, 4; j= -6, -4, -2, 0, 2, 4, 6, 8, 10, 12: g= -10, -8, -6, -4, -2, 0, 2, 4, 6. These colors formed a cubic

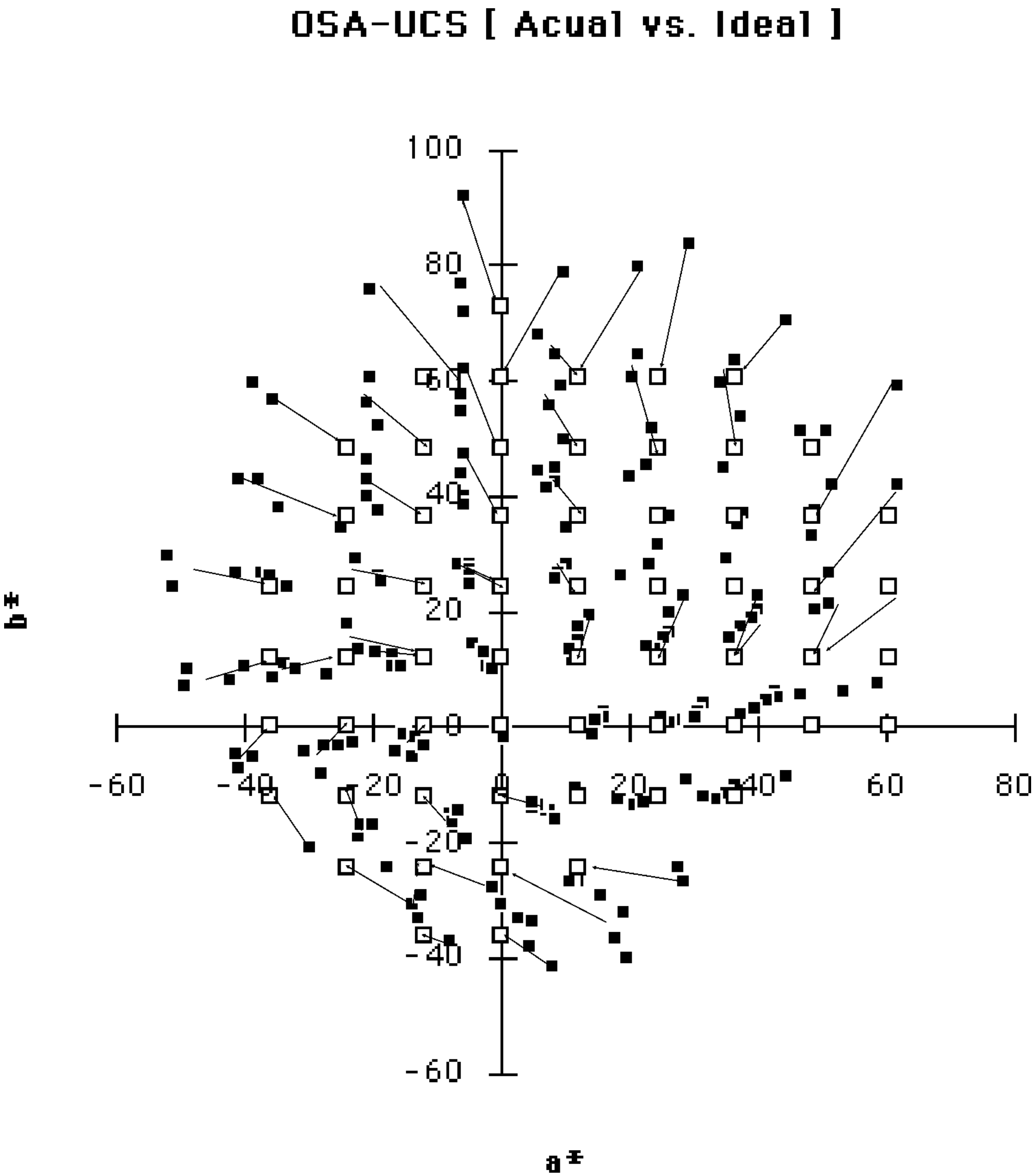

Figure 1. The plot of even integers of j, g (-8, -6, -4, -2, 0, 2, 4, 6, 8, 10 ,12) for L planes (-6, -4, -2, 0, 2, 4,). Open squares plot the expected values of a*, b*. Black squares plot the measured values for all 6 L* planes Lines traces the differences between selected actual and ideal values.

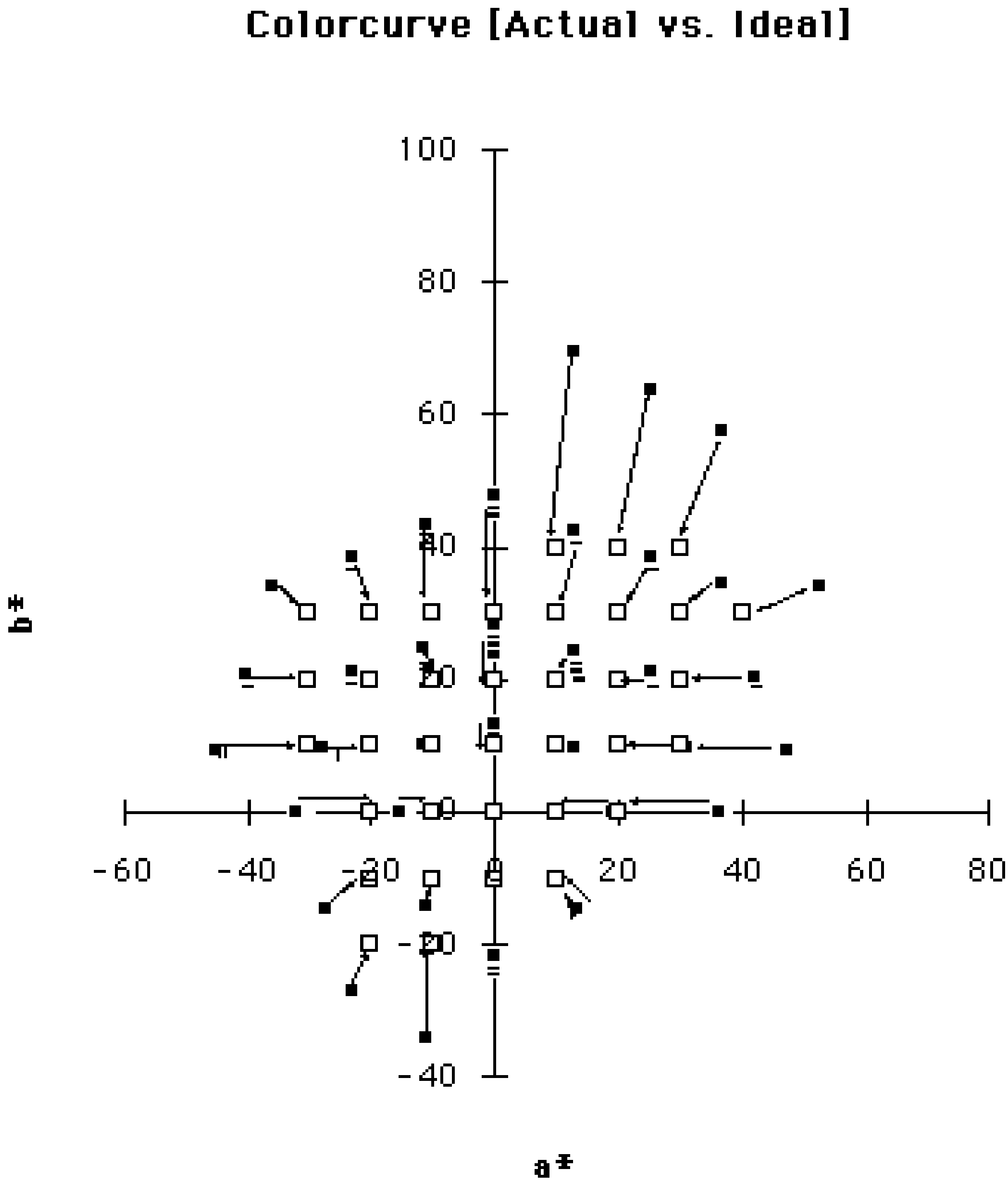

Figure 2. The plot of Colorcurve existing samples of R, Y (-6, -4, -2, 0, 2, 4, 6, 8) for L planes (30, 40, 50, 60, 70, 80, 90). Open squares plot the expected values of a*, b*. Black squares plot the measured values for all 7 L* planes. Lines traces the differences between selected actual and ideal values.

grid in OSA-UCS notation. We observed that these samples looked isotropic, that is they are visually a cubic grid. The appearance differences in hues and lightnesses appeared equal.

We wanted to see how L*a*b* portrays these isotropic, cubic-grid samples. We measured a set of OSA-UCS samples with a Greytag colorimeter to get L*a*b*. We plotted L*a*b* values expecting that they would represent the OSA-UCS colors as a cubic grid (Figure 1). In OSA-UCS the lightness planes are on average 12.1 L* units apart. The L* plot behaved as we expected. We also expected the colored samples to fall on a grid with 12.1 spacing in a* and b*. The isotropic colors did not fall on the predicted grid.

L*a*b* represents the OSA-UCS colors near gray (j=0, g=0) close to expected values. The brightest yellow (j=10, g=-6) has a measured L*a*b* value of (78.2 29.1, 83.8.) compared with an expected value of (76.9, 36.3, 60.5. That means L*a*b* has overestimated the color saturation of the yellow axis by 23 units or 39%. Most colors with j, or g values above 4 show exaggerated color saturation.

Colorcurve Color Space

Colorcurve[5] is another color space with arrays of color patches carefully chosen to fall on an isotropic color appearance array. Here the papers are mounted on a white surround. Again, we began by confirming that the color patches appeared isotropic with regard to hues and lightnesses.

We used the L*a*b* values provided with the book. We plotted them to see how L*a*b* portrayed these isotropic colors (Figure 2).

L*a*b* represents the Colorcurve colors near gray (R=0, Y=0) close to expected values. The brightest yellow (L= 80, R=2, Y=8) has a measured L*a*b* value of (80.0 13.0, 69.3) compared with an expected value of (80, 10, 40). That means L*a*b* has overestimated the color saturation of the yellow axis by 29.3 units or 73%. Most colors with R or Y values above 2 show exaggerated color saturation.

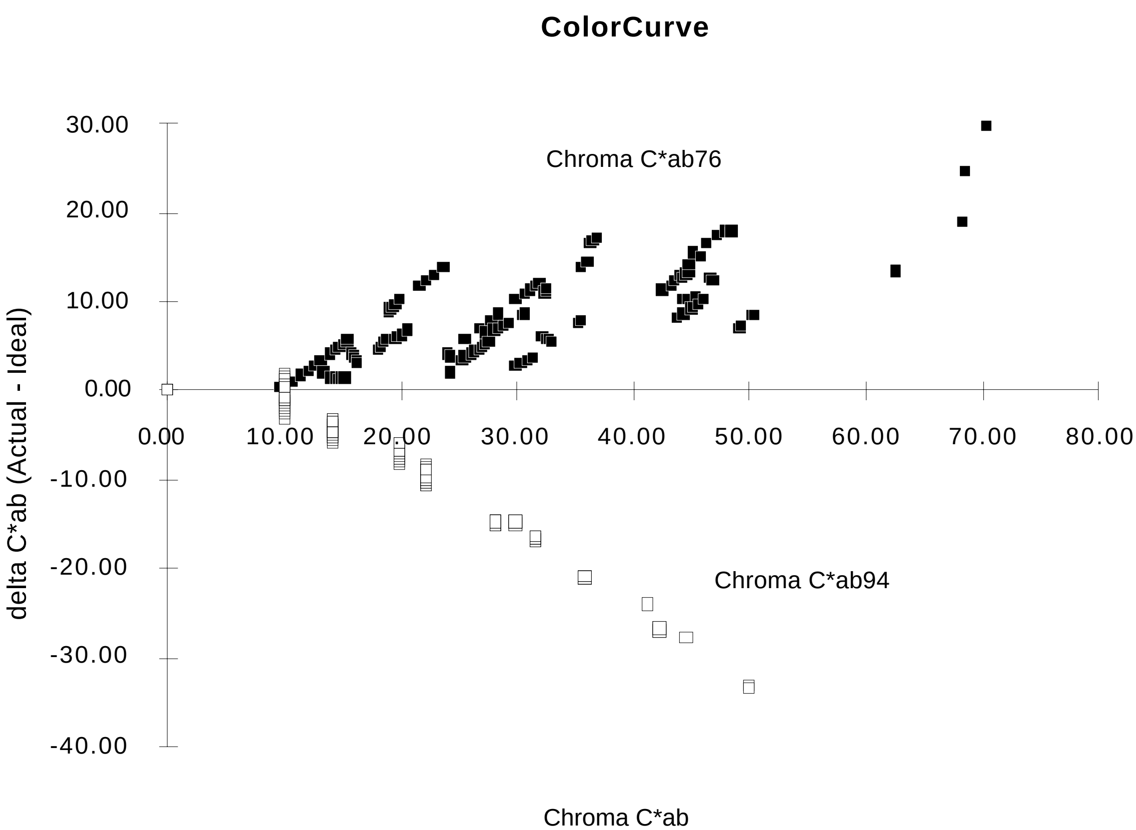

Figure 3 Plot of the distance in L*a*b* space between expected and actual values. The data above the horizontal line (ΔC*ab = 0) are L*a*b*(1976)values. They exaggerate chroma. The data below the horizontal line ΔC*ab = 0 are L*a*b*(1994) values. They underestimate chroma.

CIE 1994

The 1994 CIE ΔE equation[6] recognizes the problem that L*a*b* overstates Chroma and provides a new equation for ΔE. It is designed for small color differences (ΔE of 2 to 5). There are a number of very specific warnings about when ΔE(1994) should be used. They include the usual conditions of D65 illuminant simulator, 1000 lux illuminator, L* = 50 background. In addition, ΔE(1994) requires greater than 4 degrees of visual angle with direct edge contact and with no apparent pattern or non-uniformity. It is hard to imagining evaluating the entire OSA-UCS using such viewing conditions. Clearly, when we want to evaluate a color image and measure the color differences between objects in the image we are forced to make one of two poor choices. First we can ignore the specifications of ΔE(1994) and use it, or second, we can look for something else.

We ignored the viewing specifications and applied ΔE(1994) to our whole color space problem. ΔCab(1994) displays chroma distances smaller than lightness distances in Colorcurve space. Figure 3 plots the difference between ideal representation of the Colorcurve color samples and ΔC(1994) representation. All of the C values in the Colorcurve book are smaller than the ideal, isotropic values.

The OSA-UCS and Colorcurve spaces appear isotropic in normal viewing conditions. CIE L*a*b* spaces do not render these isotropic samples as equally spaced. The important conclusion here is that viewing conditions, or the psychophysical tasks for making and viewing OSA-UCS and Colorcurve space are different from those for used to define L*a*b*. They give very different results.

The tasks involved in finding the best compromise between monitor and printer are more like those used to define the isotopic appearance spaces. They involve viewing conditions in the world, with different illuminations. They are particularly sensitive problems with very saturated colors. Of particular interest are saturated yellows, because the yellow gamuts of monitors and prints are distinctly different. This is the region in which L*a*b* overstated OSA-UCS space by 39 % and Colorcurve space by 73%. This is the region of color space where L*a*b* has the greatest problems. We still need a numerical uniform color notation that can appropriately portray colors in the world that are isotropically spaced.

Summary

This paper compares the above observation based color spaces with colorimetric systems. We measured the L*a*b* of color samples from OSA Uniform Color Space and Colorcurve Space after careful visual inspections to confirm that these papers appear isotropic. We observed that OSA and Colorcurve are isotropic and that CIE L*a*b*[1976] is far from isotropic. The problem is that the 500 and 200 multiplication factors overstretch the saturated colors. In particular, differences between saturated yellows is exaggerated. What comes to mind is that for color conversions between monitors and prints this region of saturated colors is critical. This is the region of greatest mismatch in gamuts. This is the region in which L*a*b* fails to be isotropic compared to visual appearance. The 1994 CIE ΔE equation calculates chroma distances smaller than lightness distances in Colorcurve space.

References

1 CIE "Recommendations on Uniform Color Spaces, Color Difference Equations, Psychometric Color Terms, Supplement No. 2 of CIE Publ. No 15 (E-1.3.1) 1971, Bureau Central de la CIE, Paris, 1978.

2 CIE Proceedings 1931, p. 19, Cambridge University Press, Cambridge, 1932.

3 W. A. Stiehl, J. J. McCann and R. L. Savoy , "Influence of intraocular scattered light on lightness scaling experiments", J. Opt. Soc. Am. **73**, pp. 1143-1148, 1983.

4 D. L. MacAdam, Uniform Color Scales, J. Opt. Soc. Am., **64**, 1691,1702, 1974., D. L. MacAdam, Colorimetric Data for samples of the OSA uniform color scales", J. Opt. Soc. Am., **68**, 121,130, 1978.

5 R. Stanziola, "The Colorcurve System®" Color Res. Appl., **17**, 263-272, 1992.

6 CIE Proceedings, Industrial Colour Difference Evaluation, CIE Tech. Rep. 116, Vienna, 1995