Uniform Color Spaces: 3D LUTs vs. Algorithms

John J. McCann
McCann Imaging
Belmont, MA 02478 / USA
mccanns@tiac.net

Introduction

Until recently I have always used L*a*b* as a very convenient tool to transform color data into a sensible isotropic color space. Since isotropic spaces are uniform in all directions, the space performed the difficult task of making sure that differences in hue, lightness and chroma were all taken into account and that any pair of equal distances between two colors, regardless of their location in color space appeared equally different to observers. How this happened was left as a mystery, because I needed this property for the next step in my work. I was willing to sweep under the rug the messy issues of color surround, the complexity of the image and multiple illuminants because I was in a hurry. I also knew of reports of departures of L*a*b* from perfect uniformity, as well as great many papers suggesting clever variations in formulas that moved this or that part of the color space closer to ideal color uniformity.

L*a*b* vs. Ideal Uniform Color Space

Recently, I wanted to evaluate a new color gamut algorithm. Since I really liked the algorithm I decided to do a few experiments to make sure that the familiar L*a*b* color space did what I thought it would. I plotted OSA and Munsell color spaces in L*a*b*. The results were surprisingly bad.[1] In fact, there is a 30% average discrepancy between ideal behavior and L*a*b* behavior for all the chips in the Munsell Book.[2] Both Gabriel Marcu[3] and I independently started working on 3D LUTS as an alternative to algebraic formulae to position spectral measurements in an isotropic color space. We both chose Newhall, Nickerson and Judd's data for Munsell chips as the data for our Look Up Tables(LUT). We used the colorimetric description of each Munsell Chip at the position specified by Munsell notation. The LUT has zero error at any chip location. The distance between chips is small and interpolation errors between chips is presumably very small. We do not have any observer data measuring uniformity between Munsell chips.

The purpose of this paper is to evaluate the choice of Munsell Space as the LUT data to obtain an *Ideal* Uniform color space. How do we evaluate the results of the Munsell Committee?

Comparison with Other Spaces

Munsell defined his space by a considerable amount of work.[4] That was followed by decades of work to improve the space. In 1929 the Atlas of the Munsell Color System was superceded by the Munsell Color Atlas. In 1934, James Glenn and James Killian (later Eisenhower's science advisor and President of MIT) used Hardy's spectrophotometer (operated by David MacAdam) to measure the reflectance spectra of Munsell's Chips and calculate their Tristimulus Values.[5] David MacAdam used that data to analyze the spacing of chips in colorimetric space. MacAdam extrapolated Munsell Notations from the real chips out to the spectrum locus in CIE 1931 space.[6] More than a decade of work culminated in the "Final report of the O.S.A. Subcommittee in the Spacing of the Munsell Colors" by Newhall, Nickerson and Judd.[7] It incorporated ratio method observations by 40 observers totalling three million color judgements into a colorimetric space. It is difficult to see how to modify this mountain of work to improve an observation based uniform color space.

Figure 1 shows a diagram of Munsell space. The vertical axis through the center of the diagram is Lightness from White at the top to Black at the bottom. Each plane has the same color or Hue, but with different Lightnesses and Chromas.

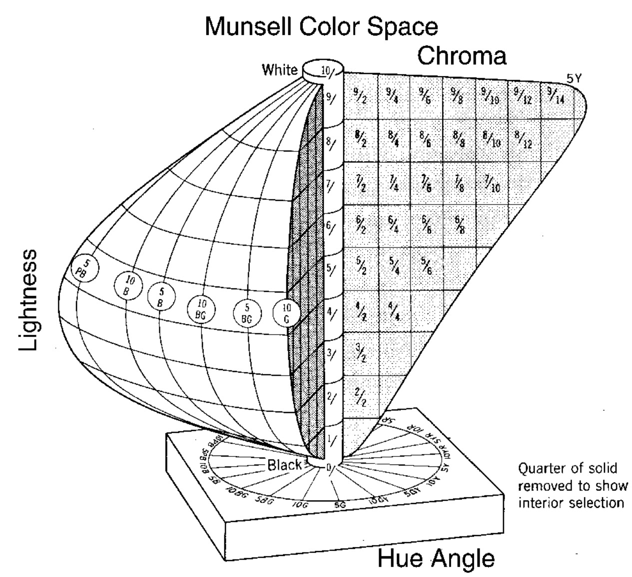

Figure 1 illustrates the munsell Space and its Color Notation.

Observer data has placed these real papers at the specified locations in this isotropic space. Two units of Chroma equal one unit of Lightness and the 40 color planes are equally spaced around the hue circle.

The plots of Munsell Space in L*a*b* space showed a number of interesting results:

- L* plots Lightness in discrete planes
  - -these planes are equally spaced.
  - -near perfect correlation with Munsell Lightness
- C* (a*,b*) spacing is highly variable
  - - both over- and under-estimates ideal values
  - - introduces significant errors
- H* (a*,b*) plots constant Hues as warped
  - - non vertical planes.
- H* (a*,b*) plots constant Hues as not equally spaced
  - - introduces errors up to 20° Hue angle

The 3D LUT solution corrects these problems by using the colorimetric values for each chip. The only errors are generated by interpolation or extrapolation. The error between internal chips is smaller than experimental measurements of uniform color spaces.

- Lightness is as good as L* - no loss in uniformity
- Chroma is corrected color by color
  - - based on observer data
- Hue planes are vertical and equally spaced

There can be no quarrel with Lightness axes because they are the same. There can be little quarrel with the Chroma axes because they are so close to observer data. Nevertheless, there might be quarrels with the spacing of the Hue planes. Local accuracy is assured again by experimental data, but there is the possibility that errors could accumulate around the circle, so that non-uniformities could occur. Short of redoing the decades of work that led to Munsell Space, what can we do to evaluate the placement of Hue planes?

Comparison of Hue Angles from Different Spaces

One technique is to compare Munsell with other color spaces such as Ostwald, NCS and OSA Uniform Color Space. First, we need to identify sources of colorimetric data for each space. The Munsell data is documented in Newhall, Nickerson and Judd[7], OSA data is documented in MacAdam et. al.[8] and both are reprinted in Wyszecki and Stiles[9]. Ostwald data was measured from the most colorful samples of book.[10] NCS data came from Derefeldt and Sahlin.[11]

The next step is to convert the data to a common colorimetic space (L*a*b*). From this we calculated Hue angle (H) and chroma (C). Next we need to rotate the different hue circles so that they are equal at one point in the circle. We decided to assign 90° to a*=0, for maximum +b* value. We took the (a*, b*)'s for the most saturated yellow papers and calculated H(a,b). We interpolated between papers to find the hue angle of the paper nearest 90°.

For each color space we can now assign an ideal hue angle. For example, when Hue plane 5.0 Y is placed at 93.2 degrees, the a*= 0 is at 90°. Since Munsell Space has 40 hue planes, then they should be 9° apart around the circle if they are uniform. 2.5Y falls at 84.2° and 7.5 Y falls at 102.2 Similarly, NCS has 40 hue planes and the Y Hue page fall at 85.6° when b*=90°. In this case, Y10R falls at 76.6° and G90Y falls at 95.6°. Ostwald has 24 planes, each 15° apart. Plane 2 falls at 90.2°, Plane 1 falls at 75.2° and Plane 3 falls at 105.2°.

Now each Uniform Color Space has a common *ideal* Hue angle assigned to it. We can compare the Hue angle estimated by L*a*b* with the ideal hue angle. We can also compare these Hue plane positions between different color spaces. If all the color spaces behave identically, then Munsell hue plane positioning is the same as the others. If the different spaces all behave differently, then there are inherent errors in some, or all of the color spaces.

Results: Munsell, NSC and Ostwald

Figure 2 plots the Difference in Hue Angle [H* (a*b*)-Ideal H(Ma,Mb] vs. Ideal Hue angle. The Hue Angle [H] is calculated from a*,b*. The ideal Hue Angle [MH] is calculated from Ma, Mb. These are the coordinates of the 3D LUT space. The values are calculated from the chip's Munsell Notation. It represents what it should be, rather than a colorimetric calculation from the reflectance spectrum. If Munsell notation for a chip is 8/12, then Lightness is 80 (8*10) and Chroma is 60 (12*5).

First, we plot all the real chips in the Munsell Book. Next we plot all the chips in NCS, and finally we plot the most saturated chips in Ostwald book. The results in Figure 2 show a general similarity between these spaces. All curves have 0 difference at 90°. We normalized the Hue angles for the most saturated yellows (b*=90°) .

Between 90° and 270° L*a*b* underestimates hue angle compared to ideal angles for all three color spaces (except for 3 pages in Ostwald). Between 90° and 180° Munsell and NCS are in close agreement. The average errors are between 10° and 15°.

Between 270° to 0° to 90° L*a*b* overestimates hue angle compared to ideal angles for all three color spaces. Munsell space has the smallest discrepancies, Oswald next and NCS has the largest differences.

We are left with the conclusion that Munsell position of Hue planes is consistent with other color systems, but not exactly the same. The spaces were defined in different illuminants and under different viewing conditions. The shapes of the spaces are different. Munsell has high Lightness yellows and low lightness blues. In both NCS and Ostwald the most saturated color is placed halfway between white and black. The hue plane placements in these three spaces are similar, but somewhat different.

Results: Munsell and OSA

Munsell, NCS and Ostwald are similar spaces because observers chose the relationship of papers by experiment. OSA is different from Munsell in two important ways.

- OSA is described in 10° observer CIE 1964 space, while Munsell is described in 2° CIE 1931 space.
- OSA hue angle is defined by formula, rather than by observer paper selection

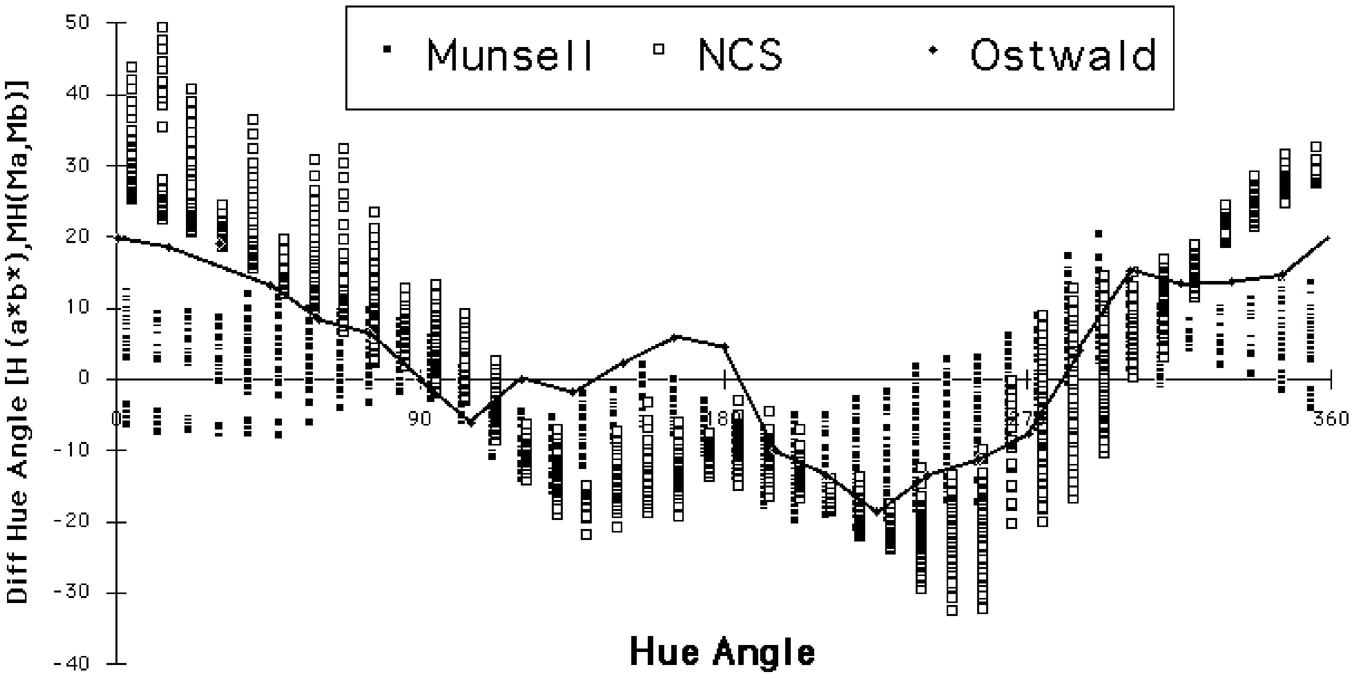

Figure 2 shows the plot of Difference of Hue Angle [H(a,b), MH(Ma,Mb)] vs. Ideal hue Angle. All the real chips in the Munsell book are plotted as solid squares. All of the chips in the NCS are plotted as open squares. The most saturated chips in the Ostwald book are plotted as diamonds, connected by a solid line. All data rotated so that a=0 at 90°. The graph shows that L*a*b* overestimates the hue anle between 90°-0°-270° and underesrimates it between 90°-270°. The comparison of different spaces is far from perfect agreement. Nevertheless the trends are the same for these three spaces. L*a*b* distorts all three color spaces in the same way, but not to the same extent. The differences are due to the inherent difference in Munsell, NCS and Ostwald color spaces, not L*a*b*.*

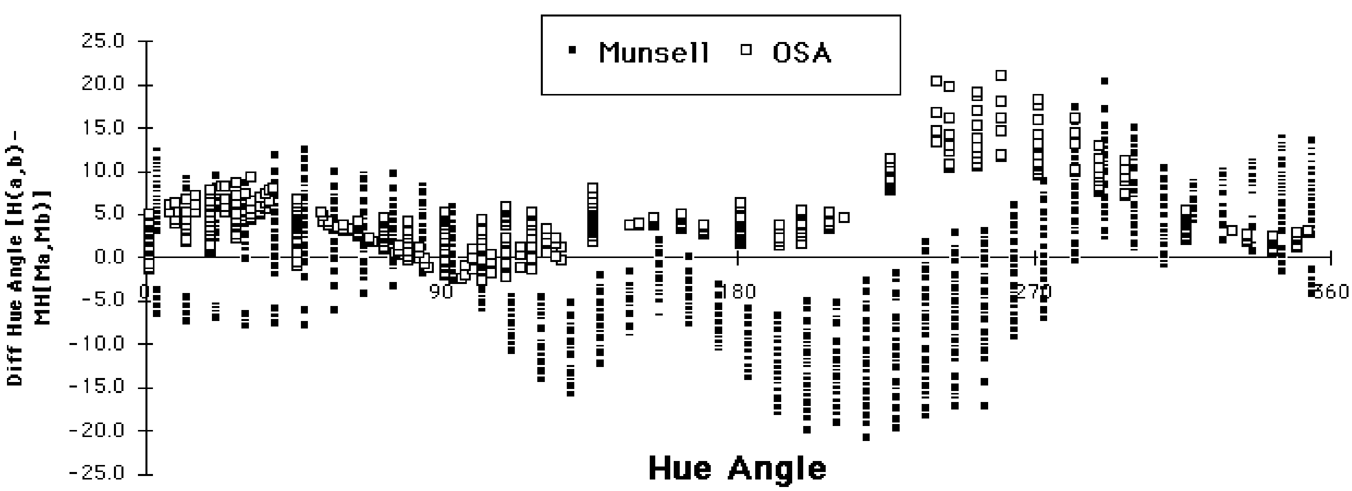

Figure 3 shows the plot of Difference of Hue Angle [H(a,b), MH(Ma,Mb)] vs. Ideal hue Angle. All data rotated so that a=0 at 90°. The graph shows that L*a*b* overestimates the hue angle between 0°- 90° for both OSA and Munsell spaces. Above 90° the curves are different. These differences are due to the inherent difference in color space, and to differences beween CIE1931 and CIE1964..*

Either or both of these differences can introduce different behavior in the color space.

Figure 3 plots the Difference in Hue Angle [H* (L*a*b*)-Ideal H(Ma,Mb] vs. Ideal Hue angle for Munsell and OSA spaces. The Hue Angle [H] is calculated from a*,b*. The ideal Hue Angle [MH] is calculated from Ma, Mb.

First, we plot all the real chips in the Munsell Book. Next, we plot all the chips in OSA Uniform Color Space. Figure 3 show a lack of similarity between these spaces. Although both sets of data are similar between 0° and 90°, above 90° the data sets are no longer similar.

Colorcurve Color space is another space that shows considerable discrepancy between ideal apparent Chroma and L*a*b* Chroma. Here the authors positioned the hues using a* and b*. We have another example of assigned hue angle and it cannot help to answer the current question.

We are left with the conclusion that Munsell position of Hue planes is consistent with other color systems, but not the same. We know that the average discrepancy between Ideal and L*a*b* is 30 % of MC.[2] It would also be interesting to know the relative contribution of H error and C error. Since there is negligible Lightness error in L*a*b* position, all the error is due to either discrepancy in hue or discrepancy in Chroma. Let us project all the Munsell data into the a*, b* plane. Figure 4 illustrates that each Munsell chip has two representations. One is the a*, b* represented by its colorimetric formula , the other is Ma,Mb representation, it's ideal position calculated from its Munsell notation or obtained from a 3D LUT. ΔC is the difference in Chroma and ΔH is [C*sin(ΔH)].

By decomposing the distance between (a,b) and (Ma,Mb) into ΔH and ΔC we can evaluate the size of the hue error as compared to the chroma error. If the Hue error is small compared to the Chroma error, we need not be concerned about the differences we see between different color spaces.

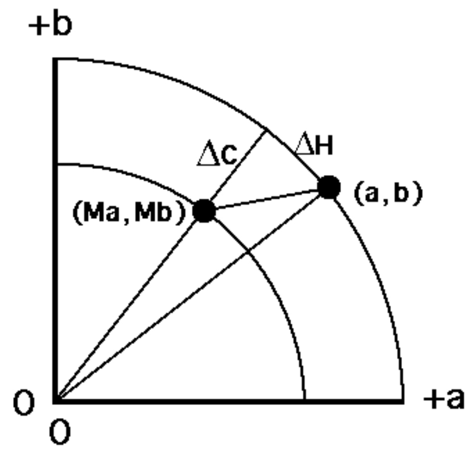

Figure 4 illustrates the spatial relationship between Lab spatial position (a,b) and Ideal position (Ma,Mb). ΔC is the Chroma difference in radial distance and DH is the distance across the Hue Angle. We will use ΔH and ΔC in analyzing the magnitude of the Hue and Chroma contributions to the distances between (a,b) and (Ma,Mb).

Figure 5 shows the breakdown of the Munsell Book distances into component vectors, ΔH and ΔC. The ΔH graph on the left shows that Hue discrepancies are significant. The middle ΔC graph shows that Chroma discrepancies are somewhat larger. The resultant ΔEr error is shown in the right graph.

Conclusions

The selection of Munsell space as the data for a 3D LUT is reviewed. The basis of evaluating Munsell by comparing it to other color spaces. Munsell space shares the same goals as Ostwald, NSC, OSA and ColorCurve spaces. They all

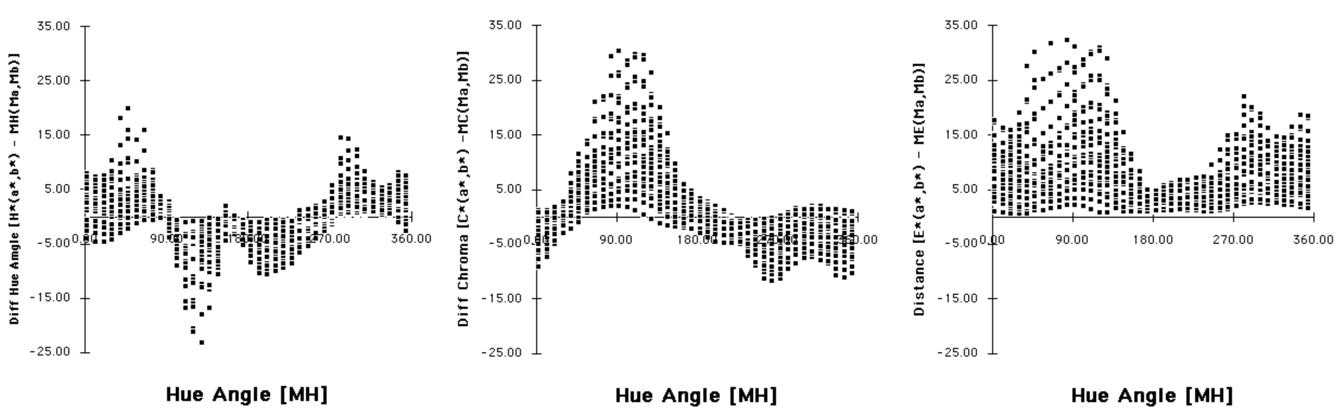

*Figure 5 compares the differences between L*a*b* spatial rendition of Munsell and the Ideal rendition. The three graphs break the distances into ΔH , DC and DE. The left graph shows the plot of Difference of Hue Angle [H(a,b), MH(Ma,Mb)] vs. Ideal hue Angle. The middle graph shows the plot of Difference of Chroma [C(a,b), MC(Ma,Mb)] vs. Ideal hue Angle. The right graph shows the plot of Distance DE between (a,b) and (Ma,Mb). Both DH and DC make substantial contributions to the the distance between (a,b) and (Ma,Mb).*

attemped to provide a set of colors that are uniformly spaced in hue, chroma and lightness. The experiments that defined these spaces were different and therefore the data are different. Nevertheless, Munsell, NCS and Ostwald show similar properties when compared in L*a*b* space. In OSA space, j and g have a specific relationship defined by equations and are described by CIE 1964 Tristimulus Values. These results are different from Munsell, NSC and Ostwald color spaces.

The decomposition of the distance between (a,b) and (Ma,Mb) into ΔH and ΔC shows that Hue distortions introduced by L*a*b* are substantial, but somewhat smaller than those introduced by Chroma. Lightness discrepancies are very small.

For color problems that require a truely isotropic space, observer based data is much more accurate than algebraic formulae. The LUT approach allows specific information about each portion of the color space to be preserved in the uniform color space. Problems such as mapping extra-gamut colors into smaller color spaces require this kind of local information based on observation. Marcu has shown that using such a LUT space has improved experimental results[3].

Munsell Space remains the prefered data for a uniform color 3D LUT. It is unique in that it provides data out to the spectrum locus. It is the compilation of 3 million observations, most highly relevent to the problem. There may be some errors in the hue plane placement, but it is not obvious how to improve the process.

Acknowledgements

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