Hue Constancy of RGB Spaces

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Abstract

A non-linear, sigmoidal transform is applied independently to each of the three channels in sRGB, e-sRGB, ROMM, Wide Gamut RGB and a prime color based RGB space. The input data are all of the chromatic samples of the MacBeth color checker. The resulting hue errors are compared in CIELAB, CIECAM97s, IPT and the OSA-UCS. ROMM has the best hue constancy based on the CIELAB results. However, ROMM does not have the best hue constancy based on the CIECAM97s, IPT and OSA-UCS results. This implies that the hue constancy optimization will be sensitive to the color space, specifically in the blues. Previous research has shown that the CIECAM97s and IPT spaces have significantly better blue hue constancy than CIELAB. Therefore, sRGB, e-sRGB, Wide Gamut RGB and prime color RGB may have better blue constancy than ROMM. This hypothesis is verified using a constant sum paired comparison psychophysics experiment.

Introduction

Standard RGB spaces, such as sRGB[1], e-sRGB[2], ROMM[3], Wide Gamut RGB[4] and others[5] are becoming increasingly common. There has also been recent investigation of prime color based RGB spaces.[6] It has been noted that one of the requirements of these spaces is that they have a high degree of hue constancy for simple non-linear channel editing operations. In fact, this is one of the proposed strengths of ROMM[3] and was one of the optimization criteria used during the development of the ROMM standard. However, this optimization was based on the CIELAB color space. There are known shortcomings in the blue constancy for CIELAB[7-10] and it has been shown that CIECAM97s[11] and IPT[12] have significantly improved blue hue constancy.[13]

As a result, it may be informative to compare the hue constancy of a subset of standard RGB spaces using color spaces other than CIELAB. While there is no universally agreed upon color space or metric for evaluating hue constancy, computing hue error statistics in multiple color spaces will provide a more complete assessment hue constancy. This paper uses CIECAM97s, IPT and OSA-UCS[14] as independent tests of hue constancy for the RGB spaces. The complexities of input data, white point differences, observer differences and nature of the selection of a suitable transformation will be used to select a test stimulus for a psychophysics experiment. Therefore, the results for the sigmoidal tranform should be treated as initial results to be verified by psychophyiscs.

Numeric Calculations

The input data consisted of the 18 chromatic MacBeth ColorChecker 1931 XYZ values with the corresponding white point. The neutral ramp of the MacBeth chart was not used. These input values were then converted to a given RGB space and modified using a sigmoidal function applied to each of the individual channels independently. The sigmoid used is shown plotted in Figure 1 were the input value is shown on the x-axis and the output value is shown on the y-axis. Higher bit depth curves were created by linearly scaling the sigmoidal curve shown in Figure 1.

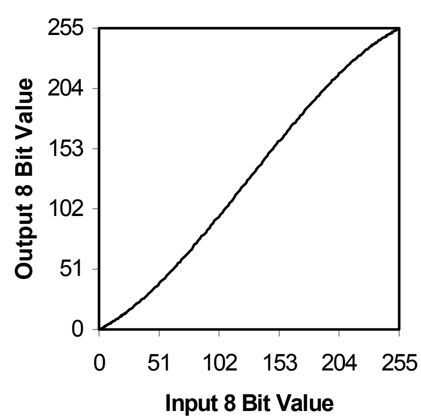

Figure 1. Eight-bit sigmoidal transfer function used for each channel independently.

The data for ROMM and Wide Gamut RGB were converted to D65 using a simple Von Kries transform using the Bradford cone fundamentals. This same transform was used for the D50 balanced prime color RGB matrix. The exact matrix used for converting prime color RGBs to D50 XYZ values was:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.592036 & 0.218759 & 0.153580 \\ 0.263989 & 0.718652 & 0.017359 \\ 0.000132 & 0.015292 & 0.809521 \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (1)$$

The 16 bit versions of ROMM and e-sRGB were used for the calculations. The input XYZ values for the OSA-UCS calculations were simply assumed to be 10 degree, even though they were presumably appropriate only for the 2 degree observer. For this reason the OSA-UCS data is provided with the caveat that the 10 degree observer was not actually used for the calcuations.

Table. 1. ΔH*ab values for 18 sRGB constrained MacBeth ColorChecker values

RGB Space	Maximum ΔH*ab	Mean ΔH*ab	RMS ΔH*ab
sRGB	11.2	4.1	5.2
e-sRGB	15.2	4.1	5.8
ROMM	5.1	1.6	2.1
Wide Gamut	21.4	4.0	6.6
Prime Color	5.9	2.1	2.7

Table. 2. ΔH*c97 values for 18 sRGB constrained MacBeth ColorChecker values

RGB Space	Maximum ΔH*c97	Mean ΔH*c97	RMS ΔH*c97
sRGB	10.3	4.0	4.7
e-sRGB	10.0	3.8	4.3
ROMM	22.1	4.3	6.8
Wide Gamut	10.2	3.1	4.2
Prime Color	13.1	4.3	5.6

Table 3. ΔH*IPT values for 18 sRGB constrained MacBeth ColorChecker values.

RGB Space	Maximum ΔH*IPT	Mean ΔH*IPT	RMS ΔH*IPT
sRGB	0.058	0.020	0.025
e-sRGB	0.078	0.021	0.027
ROMM	0.224	0.033	0.062
Wide Gamut	0.048	0.012	0.018
Prime Color	0.042	0.015	0.019

Table 4. ΔH*OSA-USC values for 18 sRGB constrained MacBeth ColorChecker values.

RGB Space	Maximum ΔH*OSA	Mean ΔH*OSA	RMS ΔH*OSA
sRGB	1.5	0.5	0.6
e-sRGB	1.9	0.5	0.7
ROMM	8.3	0.9	2.1
Wide Gamut	1.0	0.3	0.5
Prime Color	1.5	0.5	0.6

Calculation Results

The CIELAB and CIECAM97s hue errors are shown in table form in Tables 1 and 2, respectively. These tables show the maximum, average and RMS ΔH[15] errors for sRGB, e-sRGB, ROMM and Wide Gamut RGB. The IPT and OSA-UCS hue errors are shown in Table 3 and 4.

Note that the IPT axes are scaled roughly 0 to 1 and therefore the absolute magnitude of the ΔH values is smaller than the CIELAB or CIECAM97s ΔH values. A similar reduction in scale is also evident in the OSA-UCS results. However, the relative order of the IPT and OSA-UCS ΔH values can be used to rank the relative hue errors. In fact given that it is difficult to normalize the magnitude of the sigmoidal transform for the different spaces the most important result is the relative rankings for the different spaces using the different hue error metrics. In all cases the ΔH value was computed:

$$\Delta H = \left[\Delta E^2 - \Delta L^2 - \Delta C^2\right]^{\frac{1}{2}} \quad (2)$$

Where the ΔE corresponds to the Euclidean distance for the given space, the ΔL is either the L*, J or I differencesand the ΔC is the difference in the chroma as computed using the a* and b*, a_{c97} and b_{c97}, P and T or j and g axes. CIECAM97s, IPT and OSA-UCS do not have formally defined ΔH metrics but the geometric interpretation of the quantities is the same regardless. Specifically, the ΔH value is a distance that corresponds only to hue difference between two colors. It is not an angular quanitity and will tend to be larger for more chromatic colors. Given that ΔH*ab is a color difference and not an angular quantity, values greater than 1 will be perceptible.

Graphical plotting of the color differences in CIELAB show that for ROMM, the hue errors are small for all the hue angles. However, the hue errors for ROMM are considerably larger for the CIECAM97s and IPT color spaces. This is especially true for the blue patch. In comparison, sRGB has larger errors for CIELAB but smaller hue errors for CIECAM97s and IPT. The same trend is similar for e-sRGB, Wide Gamut RGB and prime color RGB. A sub-set of these plots is shown in figures 2 through 5. Figures 2 and 3 are the CIELAB and CIECAM97s color differences for ROMM while Figures 4 and 5 are for Wide Gamut RGB. The plots are shown looking down the lightness axis and the red-green axis is horizontal and the yellow-blue axis is vertical. Note the changes in the maximum errors near the blue samples.

ROMM is the best based on CIELAB but worst based on the other three hue error metrics. Wide Gamut RGB is worst based on CIELAB but is the best or close to the best for the other hue error metrics. The results for sRGB, e-sRGB and prime color RGB also show a change in relative ranking based on which color space is used to compute the ΔH values. The results for the prime color RGB space however show considerable errors in the red regions while ROMM shows considerable errors in the blue regions.

There is general agrrement in the results for CIECAM97s, IPT and OSA-UCS and also if the maximum, mean or RMS hue error is used. This is based on the assumption that differences in a few decimal places may not be statistically significant. However, the size and location of the maximum errors may be significant and therefore a specific psychophysics experiment was conducted.

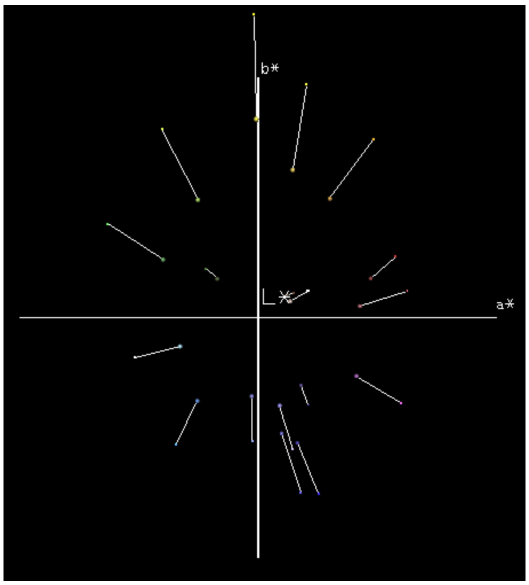

Figure 2. ROMM CIELAB color differences.

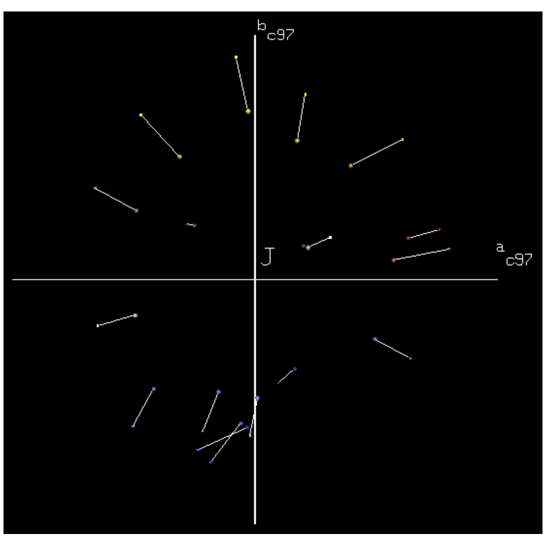

Figure 3. ROMM CIECAM97s color differences.

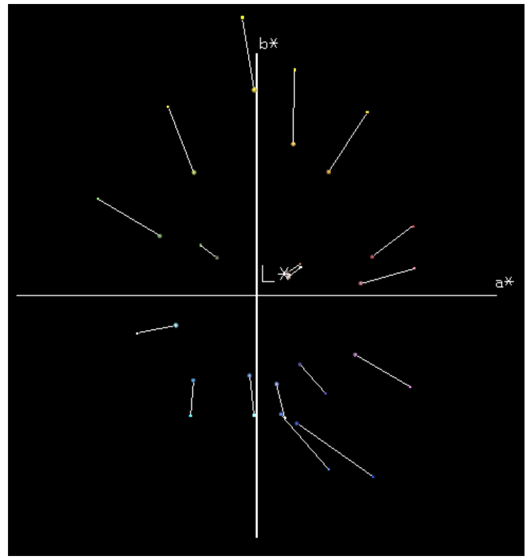

Figure 4. Wide Gamut CIELAB color differences

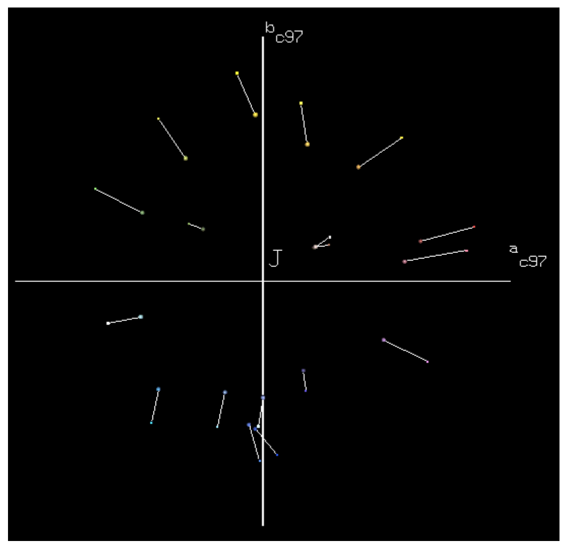

Figure 5. Wide Gamut CIECAM97s color differences.

Psychophysics Experiment

Given the importance of the shortcoming of CIELAB in the blue region and the absence of a definitive metric for hue constancy, a constant sum paired comparison of blue gradients was conducted. This blue gradient consisted of sRGB anchors of a full blue and a light gray. The blue anchor had sRGB values of 0, 0, and 255 while the light gray had sRGB values of 192, 192, and 192. Each RGB space was then used to connect the anchors using simple linear interpolation. The gradients were then converted back to sRGB for display on an sRGB display. A CIELAB based gradient was also included for reference. The user interface was programmed using TCl/Tk and the gradients were computed directly using the latest available specifications.

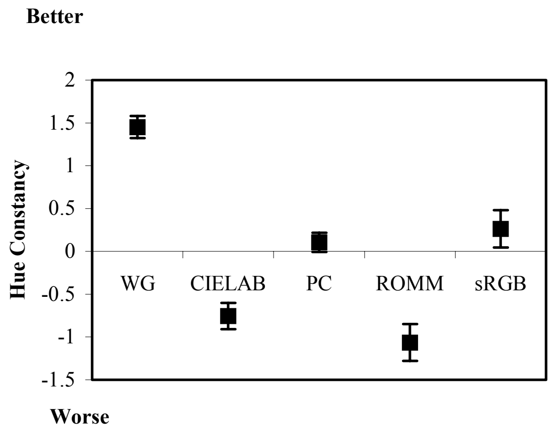

Figure 6. Constant sum paired comparison of blue gradient hue uniformity. Error bars are plus or minus two standard errors.

Seven observers were then instructed to compare the hue constancy of each gradient and assign a score to each gradient. The higher the score the better the hue constancy and the two scores were required to sum to 100. Individual observer results were standardized and then combined to yield the results shown in Figure 6. The x-axis is the color space and the y-axis is the hue constancy where the larger value corresponds to better hue constancy. Wide gamut RGB, shown on the left, is the best. SRGB and Prime color are next and the worst are CIELAB and ROMM. The overlap in the error bars clearly shows three statistically significant levels of hue constancy. The two standard errors plotted for the error bars are larger for sRGB and ROMM. This is likely due to differences in chroma gradation that observers scaled less consistently than they did for the other color spaces.

These results are for the maximum hue error but additional testing should be conducted for other hue angles. For example, there are secondary differences for the yellows and reds for some of the spaces. However, priority was given to testing the maximum error for the majority of spaces, especially since this tended occur for the blue hue angle.

Discussion

Assessing perceptual uniformity of color spaces is a complex task. Even for more uniform color spaces, such as CIELAB, CIELUV, CIECAM97s, IPT, and OSA-UCS there are differences between the spaces. This paper has attempted to account for possible differences by using hue error in multiple spaces. It is encouraging that for CIECAM97s, IPT and OSA-UCS there was some degree of consistency for the maximum hue errors. Less encouraging but consistent with previous results, is the opposite relative ranking of blue hue errors for CIELAB.

It is important to note that for the psychophysics experiment, no gamut mapping or cross-rendering was performed. The gradients were designed to be within gamut of the test display. Furthermore, the hue of the primaries was not a consideration. The task was to test the inherent hue constancy of the space given the same blue and gray anchors. Stated another way, the hues for the primaries were not compared but the hue of a constant blue stimulus was, regardless of its location in the RGB space. It may be appropriate to require the primaries to have specific hue characteristics, but this is not necessarily the same as ensuring that the space is hue constant. For instance, an RGB space could be derived such that the red, green and blue primaries corresponded to the unique hues[16] but that hue constancy was poor. The opposite case, where a space has good hue constancy but the red, green and blue primaries do line up exactly with the unique hues, is also possible. Explicit requirements should be provided for both the hue constancy and the hue properties of the primaries.

This may account for contradictory results reported for other workflows.[17] For example, assessing how close the gamut-mapped primaries of a given extended RGB space are to unique hues is not the same as testing only the inherent hue constancy of that space. Furthermore, when testing extended bit RGB spaces it will be important to consider confounding factors, such as gamut mapping. It may be that hue constancy for a specific simplified processing scheme is appropriate but once again the assumed processing should be made explicit.

Conclusion

The color space used for hue constancy optimization will impact the resulting optimization results. CIELAB has known shortcomings in the blues, while CIECAM97s and IPT are significantly better in this region. Consequently, ROMM may have a worse degree of blue constancy than initial results indicated. This was confirmed by computing hue error statistics in CIECAM97s, IPT and OSA-UCS. These results showed ROMM to have significant errors in the blue region. There was a rough equivalence for the other RGB spaces tested although additional testing may be useful at other hue angles. The results of the numeric calculations were confirmed using a constant sum paired comparison of gradients. The CIELAB and ROMM gradients were ranked worst while the Wide Gamut RGB gradient was ranked best. The sRGB and prime color RGB gradients had intermediate hue constancy.

References

1. International Electrotechnical Commission, “Part 2-1: Colour Management - Default RGB Color Space- sRGB*”,First edition, IEC 61966-2-1*, (1999).
2. Photographic and Imgaing Manufacturers Association, Inc, Photography – Electronic still picture imaging – Extended sRGB color encoding – e-sRGB, PIMA 7667, Working Draft 1.0, (2000).

3. Kevin E. Spaulding, Geoffrey J. Woolfe and Edward J. Giorgianni, "Reference Input/Output Medium Metric RGB Color Encodings (RIMM/ROMM RGB)", *Proc. PICS 2000 Conference*, 155-163, (2000).
4. Adobe Systems Incorporated, *PhotoShop*, version 5.0, Color Preferences, CRT Setup, Primaries of 700 nm, 525nm and 450 nm, D50 white point and γ of 2.2.
5. M. H. Brill, G. D. Finlayson, P. M. Hubel and W. A. Thornton, "Prime colors and color imaging", *Proc. IS&T/SID 6th Color Imaging Conference*, 33-42 (1999).
6. Sabine Susstrunk, Robert Buckley, Steve Swen, "Standard RGB Color Spaces", *Proc. IS&T/SID Seventh Color Imaging Conference*, 127-134 (1999).
7. Po-Chieh Hung and Roy S. Berns, "Determination of Constant Hue Loci for a CRT Gamut and their Predictions Using Color Appearance Spaces", *Color Res. and App.,* **20**, 285-295 (1995).
8. Fritz Ebner and Mark D. Fairchild, "Finding Constant Hue Surfaces in Color Space", *Proc. SPIE Color Imaging: Device Independent Color, Color Hardcopy, and Graphic Arts III*, 3300-16 (1998).
9. Gustav J. Braun and Mark D. Fairchild, "Color Gamut Mapping in a Hue-Linearized CIELAB space", *Proc. IS&T/SID Sixth Color Imaging Conference*, 163-168 (1998).
10. Gabriel Marcu, "Gamut Mapping in Munsell Constant Hue Sections", *Proc. IS&T/SID Sixth Color Imaging Conference*, 159-162 (1998).
11. M.R. Luo and R.W.G. Hunt, "The Structure of the CIE 1997 Colour Appearance Model (CIECAM97s)", *Color Res. App.* **23** 138-146 (1998).
12. Fritz Ebner and Mark Fairchild, "Development and Testing of a Color Space (IPT) with Improved Hue Uniformity", *Proc. IS&T/SID Sixth Color Imaging Conference*, 8-13 (1998).
13. Nathan Moroney, "Assessing hue constancy using gradients", in *Color Imaging: Device Independent Color, Color Hardcopy, and Graphic Arts V*, Reiner Eschbach, Gabriel Marcu Editors, Proceedings of SPIE Vol. 3963, 294-300 (2000).
14. Fred W. Billmeyer, "Survey of Color Order Systems", *Col. Res. Appl*. **12**, 4, 173-186 (1987).
15. CIE Publication 15.2. *Colorimetry*, Second Edition Central Bureau of the CIE, Vienna, Austria, (1986).
16. Rolf G. Kuehni, "Determination of unique hues using Munsell color chips", *Col. Res. Appl*., **26**, 1, 61-66 (2001).
17. Bruce Fraser, "Out of Gamut: Exploring Wide, Open (Color) Spaces", www.creativepro.com, "Wide Gamut RGB, which is built into PhotoShop is pretty wide but has weak blues that tend to shift purple, and hues tend to shift when you edit tone. This happens to some extent in any RGB space, but it's much more pronounced in wide-gamut spaces in general, and even more so in Wide Gamut RGB." (2000)