Hue Preservation in Rendering Operations – An Evaluation of RGB Color Encodings

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Abstract

Nonlinear tone scale operations applied to RGB image data are important in many image processing applications. While such operations are intended to produce desirable changes in image luminance contrast and colorfulness, they may also introduce unwanted hue shifts of image colors. The magnitudes and distributions of these hue shifts in color space are affected significantly by the selection of the RGB primaries for the color encoding. This work has systematically investigated such hue shifts resulting from the application of typical nonlinear image processing transformations. Tests were performed using a highlight-to-shadow series for 18 different starting colors, representative of color transitions that occur in real scenes and images. Hue-shift metrics were calculated in four "perceptually uniform" color spaces: CIELAB, CIECAM97s, IPT, and OSA_UCS. Three sets of primaries were evaluated in this study, corresponding to those defined for the ROMM RGB, sRGB, and Adobe Photoshop Wide Gamut RGB color encodings. Of these, it was found that the ROMM RGB primaries introduced the smallest overall hue shifts, while the Wide Gamut RGB primaries introduced the largest overall hue shifts. These results were consistent across all of the uniform color spaces in which the hue shifts were evaluated.

Introduction

One of the important requirements of color encodings based on additive RGB color spaces is that they be well suited for application of common image processing manipulations. Many such manipulations include the step of applying nonlinear transformations to each of the channels of an RGB image (e.g. rendering transforms, tone scale modifications, color balance adjustments etc.). Although such transformations are often used to enhance the appearance of images, one potential pitfall is that image hues can be undesirably altered by the nonlinear transformation. Hue shifts arise because the nonlinearity re-scales the RGB values of the colors differentially. The extent of the hue rotation is a function of the starting color, the chromaticities of the primaries of the RGB color encoding, and characteristics of the nonlinearity.

During the development of the (E)RIMM and ROMM RGB color encodings, minimization of such hue rotations was one of the criteria used in the optimization of the chromaticities of the primaries.[1] In that optimization, hue rotations were evaluated for a highlight-to-shadow series of eight test colors (corresponding to the red, green, blue, cyan, magenta, yellow, and skin tone patches from the Macbeth Color Checker). A rendering model typical of that used to render scene-referred images to output-referred images was used in that optimization, and hue rotations were evaluated in the CIE 1976 $L^*a^*b^*$ (CIELAB) color space. Subsequent to that original work, Nathan Moroney has undertaken a further investigation of hue rotations.[2] Moroney, aware of the limitations of CIELAB with regard to hue constancy in the blue region,[3] extended the basic analysis technique to other color spaces including CIECAM97s,[4] IPT,[5] and the OSA_UCS color space.[6] Moroney based his analysis on the 18 chromatic color patches of the Macbeth Color Checker. However, he did not generate a highlight-to-shadow series for the patches. As a result, his analysis did not provide a complete picture of the relative performances of the different sets of primaries. Following the example of Moroney, this paper extends our original analysis of hue rotations using full highlight-to-shadow series and incorporating additional hue error metrics evaluated in four "perceptually uniform" color spaces (CIELAB, CIECAM97s, IPT, and OSA UCS). Three sets of RGB color primaries are tested for two different modes of rendering. The three sets of color primaries considered are those defined for (E)RIMM/ROMM RGB,[1] sRGB,[7] and Adobe Photoshop Wide Gamut RGB.[8]

Test Procedures

To quantitatively evaluate the hue constancy of various sets of primaries upon application of a nonlinear transformation, highlight-to-shadow series were created for a series of test colors. The test colors were represented in terms of the appropriate primaries, and a nonlinear transformation was applied to each channel of the RGB representation. The input color values and the resulting modified output color values were transformed into various "perceptually uniform" color spaces for evaluation of the hue shifts induced by the nonlinearity.

Test Colors

A sampling of test colors was created based on the non-neutral patches of the Macbeth Color Checker. This sampling provides a sufficiently diverse and representative set of colors appropriate for this study. The chromaticities for these test colors are shown in Figure 1, in comparison to the chromaticity gamuts of the various primary sets that were evaluated in this experiment.

The spectral reflectance data for each of the test colors was the starting point for the calculations used in this evaluation. To simulate an extensive highlight-to-shadow series for each test color, each reflectance spectrum was first peak-normalized to a reflectance of 1.0. A range of scaling factors was then applied to the normalized reflectance spectra. Twenty scaling factors were used, to simulate a surface color under a range of illumination levels from deep-shadow to bright-highlight. Each resulting series of colors has a constant chromaticity, with varying lightness and chroma. The highlight-to-shadow series fall on approximately straight lines in CIELAB space, as is shown in Figure 2 and Figure 3.

These figures also demonstrate that the straight-line relationships begin to deviate for very dark colors. This is a consequence of the breakpoint between the nonlinear and linear functions in the CIELAB calculations.

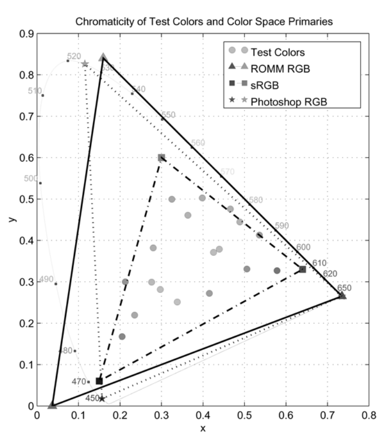

Figure 1. Chromaticities of test colors shown in relation to the chromaticity gamuts of the RGB primaries.

Application of Nonlinear Tone Scale

To apply the nonlinear tone scale transformation to the test colors, it was first necessary to express the scaled reflectance spectra in terms of the particular sets of primaries. To accomplish this, the scaled spectra were converted to CIE XYZ tristimulus values (using CIE Standard Illuminant D_{50} and the CIE 1931 Standard Colorimetric Observer). Linear RGB values were calculated from the XYZ tristimulus values using a 3×3 matrix calculated for the particular set of primaries. (As can be seen from Figure 1, some test colors were out-of-gamut for the sRGB primaries. In such cases, negative RGB values were clipped to zero.) The linear RGB values next were mapped through the appropriate nonlinear tone scale. The resulting output RGB values were then converted to CIE XYZ tristimulus values using the appropriate inverse matrix for the set of primaries being tested.

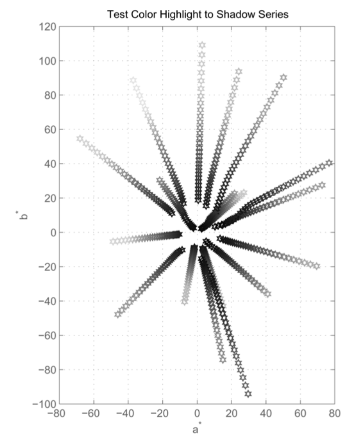

Figure 2. Highlight-to-shadow series for the test colors plotted in CIELAB b vs. a*.*

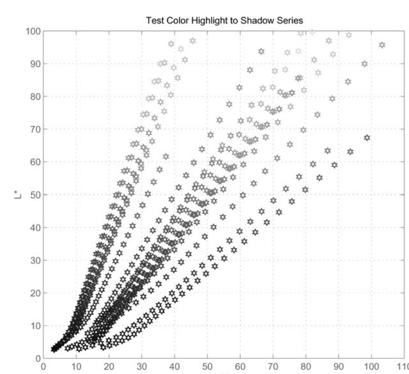

Figure 3. Highlight-to-shadow series for the test colors plotted in CIELAB L vs. C*.*

Analysis of Hue Constancy

The hue error metrics used in this work are equivalent to those adopted in previous work in this area.[2] The input and output CIE XYZ tristimulus values were converted to several "perceptually uniform" color spaces for evaluation of the hue shifts. Hue shifts were calculated using the ΔH^*_{ab} metric for CIELAB color difference calculations, and analogous metrics for CIECAM97s, IPT and OSA UCS.[a] For the CIELAB color space, ΔH^*_{ab} is computed as follows:

[a] It should be noted that these are not true "hue-angle" shifts. These hue-difference metrics scale with perceptibility of the hue differences, whereas the perceptibility of hue-angle shifts increases with chroma.

$$\left(\Delta E^*\right)^2 = \left(\Delta L^*\right)^2 + \left(\Delta a^*\right)^2 + \left(\Delta b^*\right)^2 \quad , \tag{1}$$

$$\begin{aligned}\left(\Delta H_{ab}{}^*\right)^2 &= \left(\Delta E^*\right)^2 - \left(\Delta L^*\right)^2 - \left(\Delta C_{ab}{}^*\right)^2 \\ &= \left(\Delta a^*\right)^2 + \left(\Delta b^*\right)^2 - \left(\Delta C_{ab}{}^*\right)^2 \quad ,\end{aligned} \tag{2}$$

$$\Delta H_{ab}{}^* = \left[\left(a_2^* - a_1^*\right)^2 + \left(b_2^* - b_1^*\right)^2 - \left(\sqrt{\left[\left(a_2^*\right)^2 + \left(b_2^*\right)^2\right]} - \sqrt{\left[\left(a_1^*\right)^2 + \left(b_1^*\right)^2\right]}\right)^2\right]^{1/2} \tag{3}$$

where the subscripts 1 and 2 represent the initial color and the modified color respectively. The corresponding hue shift calculations for CIECAM97s are:

$$\Delta H_{c97}{}^* = \left[\begin{array}{l}\left(a_{c97_2}{}^* - a_{c97_1}{}^*\right)^2 + \left(b_{c97_2}{}^* - b_{c97_1}{}^*\right)^2 - \\ \left(\sqrt{\left[\left(a_{c97_2}{}^*\right)^2 + \left(b_{c97_2}{}^*\right)^2\right]} - \sqrt{\left[\left(a_{c97_1}{}^*\right)^2 + \left(b_{c97_1}{}^*\right)^2\right]}\right)^2\end{array}\right]^{1/2} \tag{4}$$

for IPT are:[b]

$$\Delta H_{pt}{}^* = \left[(p_2 - p_1)^2 + (t_2 - t_1)^2 - \left(\sqrt{\left[(p_2)^2 + (t_2)^2\right]} - \sqrt{\left[(p_1)^2 + (t_1)^2\right]}\right)^2\right]^{1/2} \tag{5}$$

and for OSA UCS are:[c]

$$\Delta H_{gj}{}^* = \left[(g_2 - g_1)^2 + (j_2 - j_1)^2 - \left(\sqrt{\left[(g_2)^2 + (j_2)^2\right]} - \sqrt{\left[(g_1)^2 + (j_1)^2\right]}\right)^2\right]^{1/2} \tag{6}$$

b The IPT color space was developed for use with a D65 adaptive white point. A von Kries transform was used to determine D65 corresponding colorimetric values when the viewing illuminant was other than CIE Standard Illuminant D65.

c Conversion between colorimetry and OSA UCS color coordinates is based on use of the CIE 1964 Supplementary Standard Observer (10°) color matching functions and a D65 illuminant. This work was carried out using the CIE 1931 Standard Colorimetric Observer (2°)and tristimulus values for this observer were used in the conversion to OSA UCS A von Kries transform was used to determine D65 corresponding colorimetric values when the viewing illuminant was other than D65. Conversion between CIE XYZ and OSA UCS involves an intermediate step of representing colors in a new set of additive RGB primaries. Some colors are out of gamut for this set of primaries and result in computational errors in the conversion. Such colors were omitted from the OSA UCS analysis. The conversion also involves calculation of a factor that applies Semmelroth's crispening to color differences. The calculation of this factor is straightforward for colors within the OSA color samples but the range of colors used in the current work extended to very low luminous reflectances where the calculation of this factor breaks down, resulting in non-real results. Colors for which this problem applied were eliminated from the OSA UCS analysis.

Modes of Rendering

Two different nonlinearities were used in this study, corresponding to two types of rendering transforms that are particularly important in many image-processing workflows.

Rendering Scene-Referred Images to Output-Referred Images

The process of forming a rendered image from a scene is one important application of nonlinear tone scales. Among other things, the tone/color reproduction process that "renders" the colors of a scene to the desired colors of the rendered image must compensate for differences between the scene and rendered image viewing conditions.[9,10] For example, rendered images generally are viewed at luminance levels much lower than those of typical outdoor scenes. As a consequence, an increase in the overall contrast of the rendered image usually is required in order to compensate for perceived losses in reproduced luminance and chrominance. Additionally, the rendering process should compensate for viewing flare associated with rendered-image viewing conditions.

In addition, psychological factors such as color memory and color preference must be considered in image rendering. For example, observers generally remember colors as being of higher purity than they really were, and they typically prefer skies and grass to be more colorful than they were in the original scene. The tone/color reproduction aims of well-designed imaging systems will account for such factors.

Finally, the tone/color reproduction process also must account for the fact that the luminance dynamic range of a rendered image typically is substantially less than that of an original scene. It is, therefore, necessary to discard and/or compress some of the highlight and shadow information of the scene to fit within the limited dynamic range of the rendered image.

In applications where scene-referred and output-referred color encodings are defined based on a common set of RGB primaries, simple nonlinear tone scale transformations can be applied to the individual channels of an image in the scene-referred color encoding to produce an image in the corresponding output-referred color encoding. (This was one of the objectives in defining the (E)RIMM/ROMM RGB family of color encodings.[1]) In many cases, these simple tone scale transformations are quite successful in achieving all of the rendering objectives in a visually pleasing way, while maintaining the simplicity of the image processing chain. However, depending on the primaries, the scene colors and the rendering tone scale, the application of the nonlinearity can give rise to hue shifts between the original scene colors and the resulting rendered output colors. These hue shifts can result in image quality degradations, particularly when the hue of an object is perceived to change through a highlight-to-shadow transition. Such hue shifts can be particularly problematic for important memory colors such as human skin tones, sky, and foliage.

A representative nonlinear scene-to-print tone scale transformation was used to evaluate the different sets of primaries. The tone scale that was used is shown in Figure 4. For this rendering mode, the test color spectra were scaled by 20 logarithmically-spaced scale factors ranging from 0.0632 ($2 \times 10^{-1.5}$) to 2.0 (2×10^{0}). The scaling factors greater than 1.0 allow for simulation of the large dynamic range typical of many scenes.

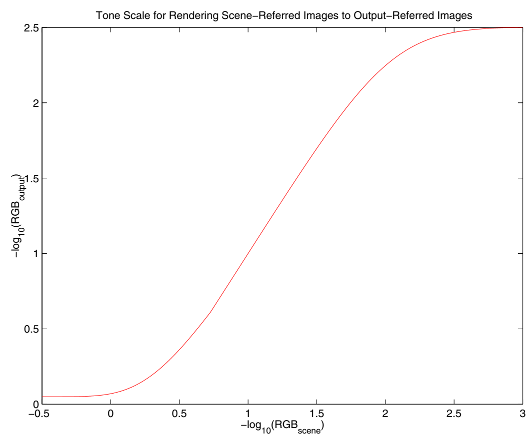

Figure 4. Tone scale used for rendering scene-referred to output-referred image

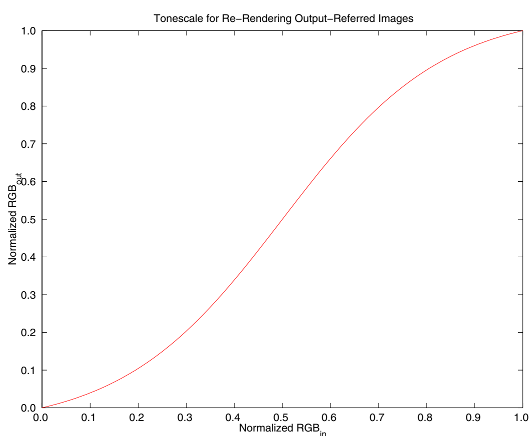

Figure 5. Re-rendering tone scale.

Re-Rendering Output-Referred Images to Adjust Image Appearance

A second commonly used application of nonlinear tone scales is the adjustment of already rendered images. This is sometimes referred to as "re-rendering" an image. Often such re-rendering operations are performed using interactive image editing tools, such as the "Adjust Curves" option available in Adobe Photoshop software. Because these nonlinearities are generally used to make finer adjustments than those associated with the rendering transforms discussed in the last section, the resulting hue shifts are often less objectionable, although they may be significant in certain cases. A typical s-shaped contrast-boosting nonlinearity, shown in Figure 5, was used to evaluate the hue shifts resulting from re-rendering operations. (Nathan Moroney of Hewlett Packard kindly supplied the tone scale transform used in his previously reported work.[2]) For purposes of this experiment, the 8-bit RGB values used to define the re-rendering tone scale were converted to linear RGB values using the sRGB nonlinearity. This allowed evaluation of the primaries independent of the encoding functions with which they are typically associated. For this rendering mode, the test color spectra were scaled by 20 logarithmically spaced scale factors ranging from 0.0316 ($10^{-1.5}$) to 1.0 (10^{0}).

Results

Scene-Referred to Output Referred Rendering

The hue errors for rendering scene-referred to output-referred images, calculated in CIELAB, CIECAM97s, IPT, and OSA UCS are shown in Table 1 - Table 4. In every case, the ROMM RGB primaries gave considerably smaller average and maximum hue errors than did sRGB, which in turn gave slightly smaller errors than did Photoshop Wide Gamut RGB primaries. The absolute values of the hue errors are difficult to compare across the four tables because of the different scalings used in the various color spaces, but relative differences among the three sets of primaries examined are quite consistent within each table. The data for all of the test colors are plotted in Figure 6 - Figure 11 for the CIELAB and CIECAM97s color spaces. In these figures, the original test colors are shown as circles, and are connected to the corresponding output colors using arrows. Arrows not directed along radial paths relative to the origin are indicative of hue shifts induced during the rendering operation. These figures clearly illustrate that ROMM RGB primaries produce the smallest hue errors when averaged over all the colors, regardless of the color space upon which the hue error metric was based. (Similar results were found for IPT and OSA UCS but figures are not included here due to space limitations.)

In the blue region, where CIELAB is known to have problems with hue constancy,[3] it can be seen that the ROMM RGB hue errors are somewhat larger in CIECAM97s than in CIELAB, whereas the reverse is true for both the sRGB and Photoshop Wide Gamut RGB primaries. Figure 12 illustrates the dependence of the hue shift on the color space in which it is calculated for the Macbeth blue patch highlight-to-shadow series. For this blue series, it can be seen that the ROMM RGB primaries produce the smallest hue shifts when the CIELAB color space is used, whereas the sRGB primaries perform slightly better when the other color spaces are used. A possibly more significant difference between the primaries is the direction of the hue shift. The Macbeth blue colors move toward purple when rendered using ROMM RGB primaries, but shift toward cyan when rendered using the sRGB or Photoshop Wide Gamut primaries.

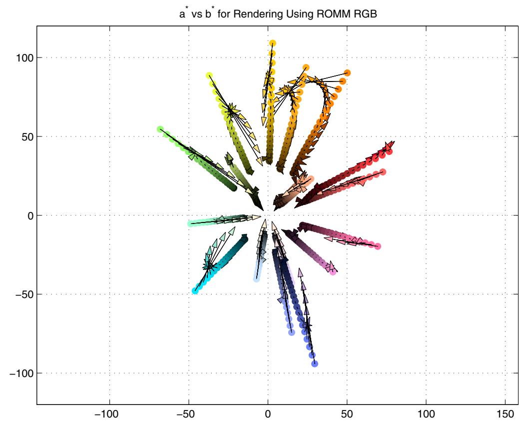

Figure 6. CIELAB hue constancy plots for ROMM RGB when rendering scene-referred images to output -referred images.

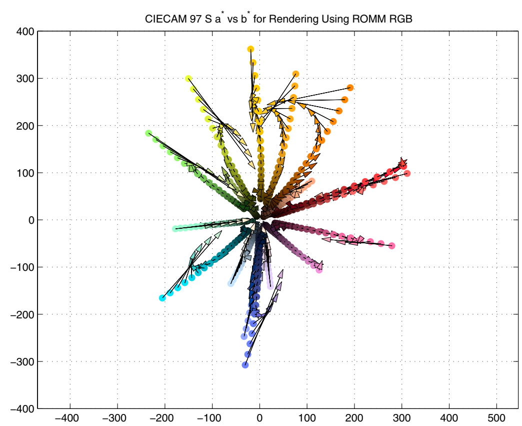

Figure 7. CIECAM97s hue constancy plots for ROMM RGB when rendering scene-referred images to output-referred images.

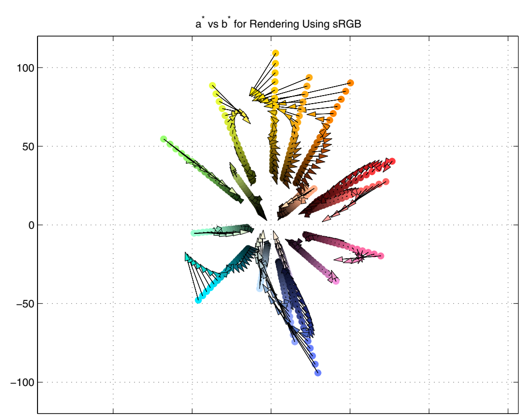

Figure 8. CIELAB hue constancy plots for sRGB when rendering scene-referred images to output-referred images.

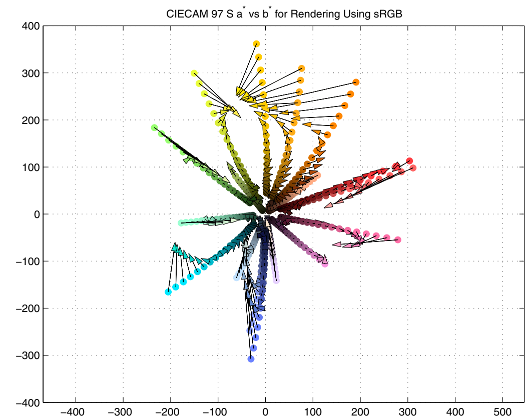

Figure 9. CIECAM97s hue constancy plots for sRGB when rendering scene-referred images to output-referred images.

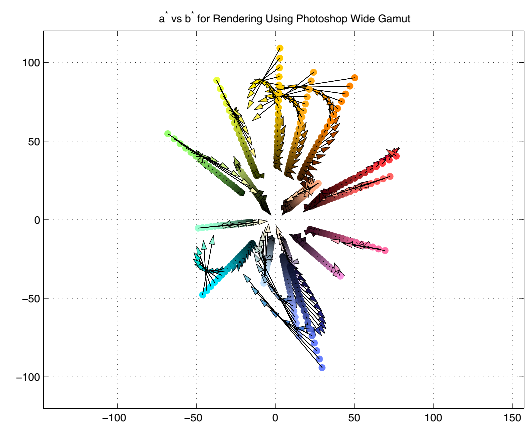

Figure 10. CIELAB hue-constancy plots for Wide Gamut RGB when rendering scene-referred images to output-referred images

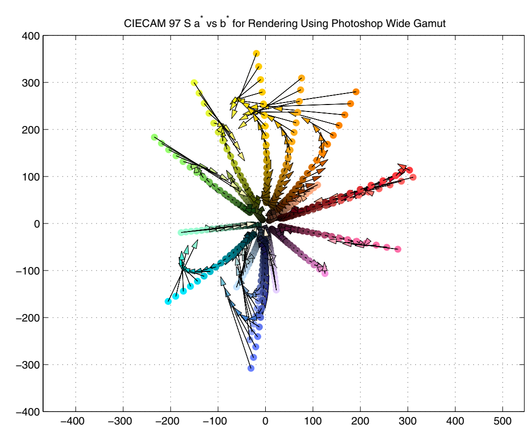

Figure 11. CIELAB hue constancy plots for Wide Gamut RGB when rendering scene-referred images to output-referred images.

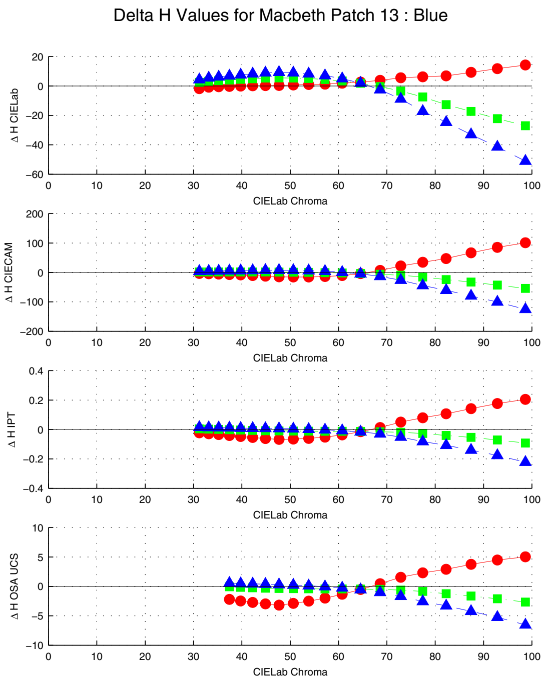

Figure 12. Hue shift plots for Macbeth blue patch highlight-to-shadow series for (top to bottom) CIELAB, CIECAM97s, IPT and OSA UCS (ROMM RGB: red circles, sRGB: green squares, Wide Gamut RGB: blue triangles).

Table 1. CIELAB Hue Errors For Rendering.

Primaries	RMS ΔH	Mean |ΔH|	Max ΔH
ROMM RGB	5.56	2.98	38.0
sRGB	8.20	4.80	46.9
Wide Gamut	9.68	5.13	53.1

Table 2. CIECAM97s Hue Errors For Rendering.

Primaries	RMS ΔH	Mean |ΔH|	Max ΔH
ROMM RGB	22.1	10.9	152
sRGB	26.5	13.1	183
Wide Gamut	31.4	14.8	210

Table 3. IPT Hue Errors For Rendering.

Primaries	RMS ΔH	Mean |ΔH|	Max ΔH
ROMM RGB	0.0440	0.0234	0.282
sRGB	0.0518	0.0280	0.344
Wide Gamut	0.0591	0.0290	0.389

Table 4. OSA UCS Hue Errors For Rendering.

Primaries	RMS ΔH	Mean |ΔH|	Max ΔH
ROMM RGB	1.19	0.673	6.97
sRGB	1.37	0.799	8.43
Wide Gamut	1.58	0.836	9.44

Hue shifts are largest for all sets of primaries in the orange-yellow hues, but the ROMM RGB primaries deliver the best result for these colors. ROMM RGB primaries also produce smaller hue shifts in the cyan region, while the sRGB primaries perform slightly better for greens. There is little significant difference between the three sets of primaries for the other test colors.

A similar hue error analysis was also performed using CIE Standard Illuminant D65 as the viewing illuminant. In this case, the results were very similar to those shown here for CIE Standard Illuminant D50, with the ROMM RGB primaries producing significantly smaller average and maximum hue errors relative to both the sRGB and Photoshop Wide Gamut RGB primaries.

Output Referred Image Re-Rendering Operations

The hue errors for re-rendering output-referred images calculated in CIELAB, CIECAM97s, IPT and OSA UCS are shown in Table 5 -Table 8. Using either the ROMM RGB or sRGB primaries resulted in significantly smaller hue shifts than using Wide Gamut RGB primaries, with the ROMM RGB primaries generally being slightly advantaged relative to the sRGB primaries. However, sRGB primaries produced slightly smaller RMS hue shifts when evaluated using OSA UCS, even though the mean absolute ΔH values were still smaller for the ROMM RGB primaries. The reason for this apparent discrepancy is that ROMM RGB primaries produced a few moderately large hue errors in the highly chromatic light blue region when evaluated using the OSA UCS color space. These larger errors made a more significant contribution to the RMS ΔH metric than they did to the mean absolute ΔH metric. Close examination of the calculations for these particular data points indicates that the OSA UCS color space conversion function may be poorly behaved in this region of color space. Probably this region of color space falls outside the gamut of color patches used in formulating the conversion function, and it is therefore unreliable. The data for all of the highlight-to-shadow series are plotted in Figure 13 - Figure 18 for the CIELAB and CIECAM97s color spaces. Once again, these figures clearly illustrate the well-known problems of non-constant perceived hue in the blue region for CIELAB compared to CIECAM97s. Similar results are found for IPT and OSA UCS but figures are not included here due to space limitations. A complete hue error analysis was also performed using CIE Standard Illuminant D65 and the results were found to be very similar to those obtained for CIE Standard Illuminant D50.

The general trends observed for re-rendering operations closely parallel those noted earlier for the case of rendering scene-referred images to output-referred images, although the magnitudes of the hue shifts are generally smaller in the re-rendering case. The ROMM RGB primaries resulted in smaller hue shifts for red, orange, yellow, cyan, and magenta colors while sRGB primaries produced slightly smaller shifts for blues. Greens appeared to give similar results using either ROMM RGB primaries or sRGB primaries. The Wide Gamut RGB primaries produced quite large hue shifts for most of the test colors.

Table 5. CIELAB Hue Errors For Re-Rendering.

Primaries	RMS ΔH	Mean |ΔH|	Max ΔH
ROMM RGB	3.00	1.85	16.7
sRGB	4.70	3.36	18.2
Wide Gamut	7.68	5.71	26.5

Table 6. CIECAM97s Hue Errors For Re-Rendering.

Primaries	RMS ΔH	Mean |ΔH|	Max ΔH
ROMM RGB	9.85	5.13	66.0
sRGB	11.1	6.42	72.6
Wide Gamut	18.1	11.0	100

Table 7. IPT Hue Errors For Re-Rendering.

Primaries	RMS ΔH	Mean |ΔH|	Max ΔH
ROMM RGB	0.0238	0.0130	0.132
sRGB	0.0259	0.0171	0.134
Wide Gamut	0.0396	0.0277	0.182

Table 8. OSA UCS Hue Errors For Re-Rendering.

Primaries	RMS ΔH	Mean |ΔH|	Max ΔH
ROMM RGB	0.959	0.500	4.86
sRGB	0.950	0.711	3.14
Wide Gamut	1.33	1.03	4.41

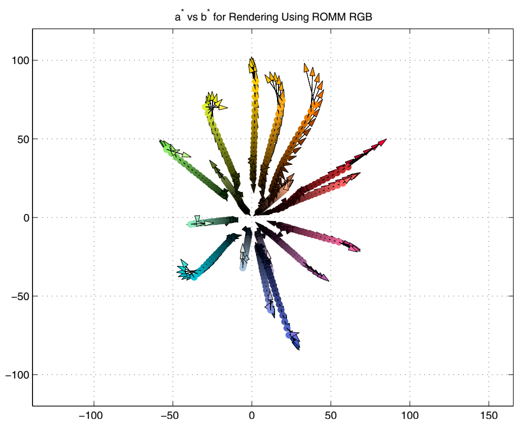

Figure 13. CIELAB hue constancy plots for ROMM RGB when re-rendering output-referred images.

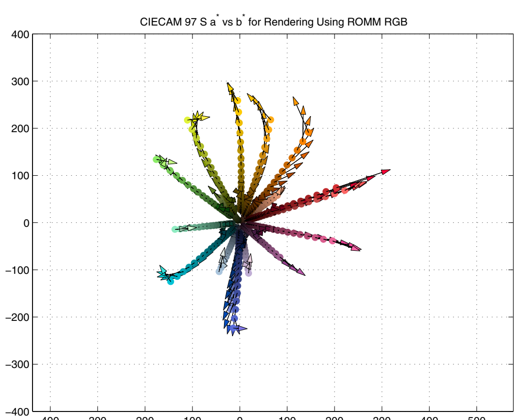

Figure 14. CIECAM97s hue constancy plots for ROMM RGB when re-rendering output-referred images.

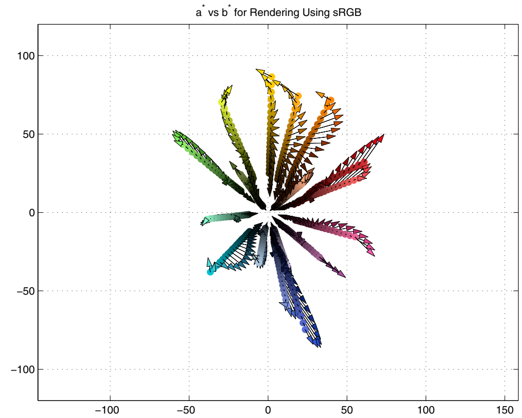

Figure 15. CIELAB hue constancy plots for sRGB when re-rendering output-referred images

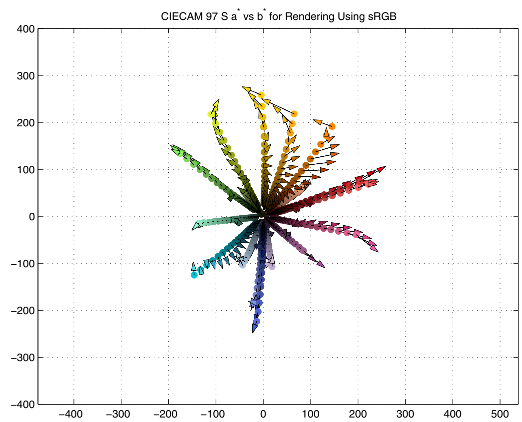

Figure 16. CIECAM97s hue constancy plots for sRGB when re-rendering output-referred images.

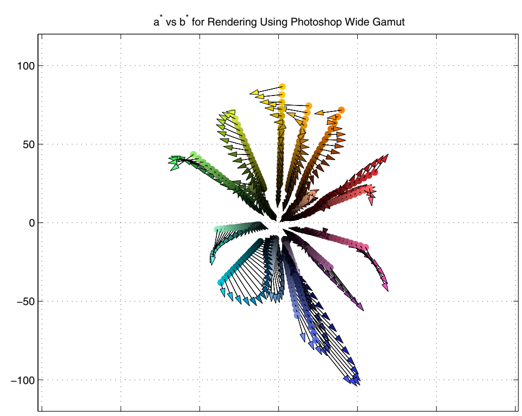

Figure 17. CIELAB hue constancy plots for Wide Gamut RGB when re-rendering output-referred images.

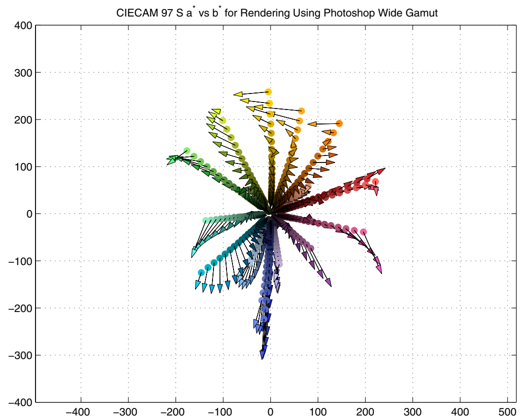

Figure 18. CIECAM97s hue constancy plots for Wide Gamut RGB when re-rendering output-referred images.

Conclusions

Color image data are frequently represented in color encodings based on RGB additive primaries. Such RGB image data is commonly mapped through nonlinear tone scales to effect a rendering or re-rendering of the image. While such operations often produce desirable changes in the contrast and colorfulness of the image, they frequently introduce unwanted hue shifts in image colors. The magnitudes and distributions of these hue shifts are affected significantly by the colorimetric properties of the RGB primaries used in the color encoding. This work has systematically investigated such hue shifts produced when rendering scene-referred images to output-referred images, and when re-rendering output-referred images. Tests were performed using a highlight-to-shadow series for 18 different starting colors. These highlight-to-shadow series have important diagnostic value in that they closely match the type of color transitions that occur in real images. Hue-shift results were evaluated in four "perceptually uniform" color spaces. The evaluation spaces yielded similar interpretations of the hue shifts. However, as expected, the results in the blue region when using CIELAB differed slightly from those obtained using the other color spaces due to the well-known deficiencies of CIELAB in that part of color space.

Of the sets of primaries that were studied, it was found that the ROMM RGB primaries introduced the smallest overall hue shifts, which is consistent with the stated design goals of the (E)RIMM/ROMM RGB family of color encodings. This conclusion is independent of the uniform color space in which the hue shifts were evaluated.

References

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Biography

Geoff Woolfe holds BS (honors) and PhD degrees in physical chemistry from the University of Melbourne and an MS degree in imaging science from Rochester Institute of Technology. His early scientific career was spent researching the field of time-resolved spectroscopy at the Technische Universitaet Muenchen (Munich, Germany) and later at the University of Melbourne (Australia).

He is currently a Senior Principal Research Scientist in the Imaging Science Division of the Eastman Kodak Research Laboratories in Rochester NY. His research interests include hardcopy/softcopy appearance matching of images, digital simulation and modeling of imaging systems, development of color imaging algorithms, preferred color image reproduction, color restoration of faded and degraded images, gamut mapping, computational color science and development of color control tools and color management systems.

Geoff Woolfe has authored numerous scientific papers and US and international patents in the fields of chemical physics and color imaging.