Color Gamut Mapping in a Hue-Linearized CIELAB Color Space

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Abstract

Color gamut mapping plays a crucial role in color management. Depending on the application, it is sometimes desirable to perform color gamut mapping by shifting the lightness and compressing the chroma of an out-of-gamut color while preserving the perceived hue of the color. The term "perceived hue" is used to distinguish between the visual sensation of hue and metric hue angle (e.g., CIELAB hue angle (h_{ab})). If a gamut-mapping task constrains CIELAB metric hue angle in the "blue"† region of CIELAB, a perceived-hue shift will result. Due to these non-linearities, two hue-linearized versions of the CIELAB color space were generated, one from the Hung and Berns visual data (1995) and one from the Ebner and Fairchild data set (1998). Both data sets consist of visually mapped hue data to planes of constant visual hue. These modified versions of the CIELAB color space were psychophysically tested for their hue-linearity characteristics against the CIELAB color space. The results of these experiments show that, in the "blue" region of CIELAB, the hue-corrected color spaces are more visually uniform and perform better than CIELAB in gamut mapping situations with respect to perceived hue. However, the CIELAB color space performed as good as or better than either hue-corrected spaces outside of the blue region.

KEYWORDS: Gamut Mapping, Color Appearance

Introduction

The hue linearity of a reference color space is critical in color gamut mapping. The reason for this is that when a color is reduced in chroma to fit within a destination gamut, following a line of constant metric hue angle (e.g., CIELAB h_{ab}), the perceived hue of that color will change if the reference color space is non-linear with respect to hue. This has been shown for the CIELAB color space (Hung and Berns (1995), Ebner and Fairchild (1998)). Thus, lines/planes of constant metric hue angle do not correspond to lines/planes of constant perceived hue in the CIELAB color space, Figure 1. Some of the strongest non-linearities occur in the red and blue regions of the color space.

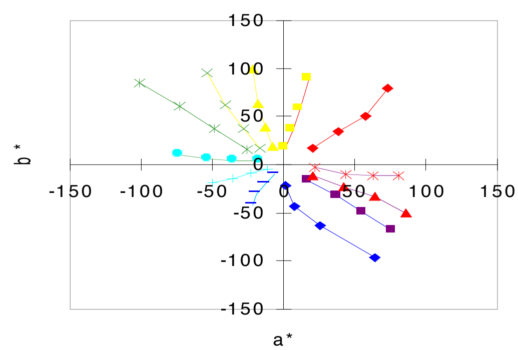

Figure 1. Hung and Berns lines of constant perceived hue plotted in CIELAB.

Recently, the CIE has recommended the CIECAM97s color space for describing color appearance and for generating corresponding color matches across changes in viewing conditions. Unfortunately, the CIECAM97s color space is also non-linear with respect to lines of constant hue. This can be illustrated by plotting the Hung and Berns data set in the CIECAM97s color space, Figure 2.

† The "blue" region of CIELAB refers to hue angles between approximately 260˚ and 320˚.

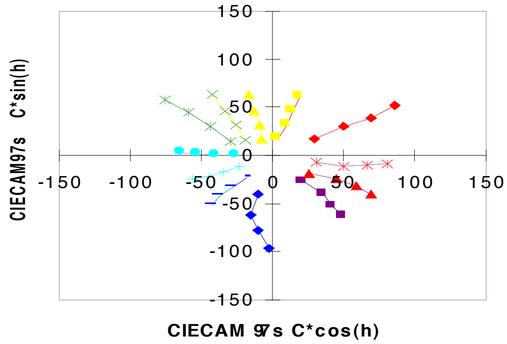

Figure 2. Hung and Berns (1995) lines of constant perceived hue in the CIECAM97s color space.

Based on the widespread use and acceptance of the CIELAB color space in color imaging, two attempts were made to generate hue-linearized versions of CIELAB for color gamut mapping. The first was based on the constant hue line data from Hung and Berns and the second was based on a set of constant hue planes from Ebner and Fairchild. The following details how these visual data were used to create multi-dimensional look-up-tables (LUTs) that linearized the CIELAB color space with respect to perceived hue and provided a sound basis for color gamut mapping. A visual experiment that used these LUTs for a color gamut mapping application is presented.

Generation of Hue-Correcting Look-Up-Tables

Hung and Berns Data Set

The Hung and Berns data set used to create the LUTs used in this experiment consisted of 12 lines of constant perceived hue that uniformly spanned the CIELAB hue circle, Figure 1. For a given hue angle, each hue line consisted of 4 points at constant lightness and constant perceived hue. The points varied in chroma by 25, 50, 75, and 100 percent of the maximum chroma that the CRT gamut would allow. Thus, in order to get the maximum range of possible chroma these lines occurred at lightness levels at or near the lightness of the CRT primaries and secondaries.

These data were used to create a two-dimensional LUT where the departure from linear hue lines was assumed to be invariant with lightness. This assumption was predicated on the fact that the Hung and Berns data set did not contain complete lines of constant hue at multiple lightness levels. It was also believed that, while a lightness dependency certainly may exist, the benefit of doing some amount of correction may take care of the obvious hue errors that were obtained when using CIELAB.

The Hung and Berns data set were converted into a LUT using the following sequential linear interpolation process:

1. Complete the Hung and Berns data set so that each of the 12 hue lines were defined from the neutral axis [a*=0, b*=0] out to a C^*_{ab} of 150. Extrapolation of the data to the neutral axis consisted of a simple linear fit between the first point in the data series to the neutral axis. Extrapolation out to a C^*_{ab} =150 was done by determining the intersection point between the line formed by the last 2 points in the data series and a chroma circle at a radius of 150 chroma units, centered on the neutral axis - Figure 3.
2. Convert the complete data set into CIELAB LCh coordinates.
3. Determine the base hue angle for each of the 12 hue lines. Base hue angle is defined by the CIELAB hue angle of the first point in the hue line series.
4. Generate a gridline for each of the 12 base hue angles by linearly interpolating the departure in hue angle, as a function of C^*_{ab}, from the base hue angle, Figure 4. The gridlines represent the departure from the base hue angle as a function of chroma. (Note: If the color space was linear with respect to hue, then as the chroma increased the gridline would have the same numerical hue angle for all chromas.) The 12 gridlines are shown as the solid lines in Figure 5.
5. Generate a complete set of gridpoints (i.e., filling in the LUT) by linearly interpolating between the 12 gridlines at fixed chroma intervals on the range of {0,150}, every one degree in hue angle from {0,360}. This process results in a 150x360 element matrix (LUT). This LUT defines the transformation from a hue-linearized space into CIELAB (i.e., the inverse hue-correction transformation).

The process involved in generating the forward hue correction transformation (i.e., CIELAB to hue-corrected CIELAB) involved switching the input and output when generating the gridlines defined in Step 4. The final LUTs are visualized in Figures 6 and 7.

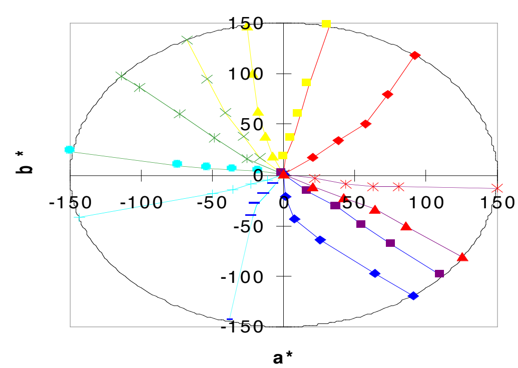

Figure 3. Extrapolation of Hung and Berns data out to C^*_{ab} =150.

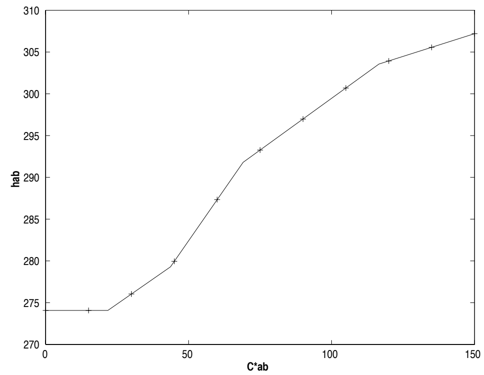

Figure 4. Example gridline calculation for the constant hue line at base-hue angle = 274.1 degrees. The figure shows that as the chroma increases along this hue line that the CIELAB hue angle increases. By linear interpolation between the Hung and Berns points it is possible to estimate the departure of hue (+), from the base-hue angle, as a function of chroma).

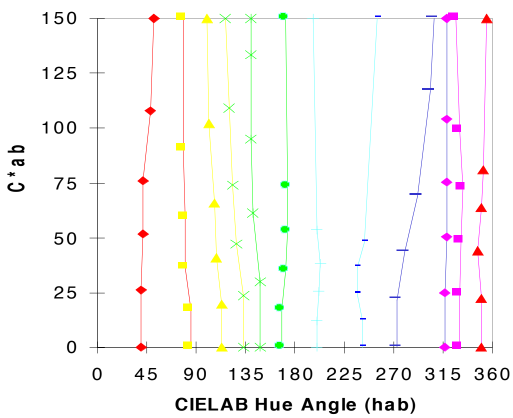

Figure 5. Twelve gridlines generated from the Hung and Berns data set. These gridlines are used to populate the 2D LUT.

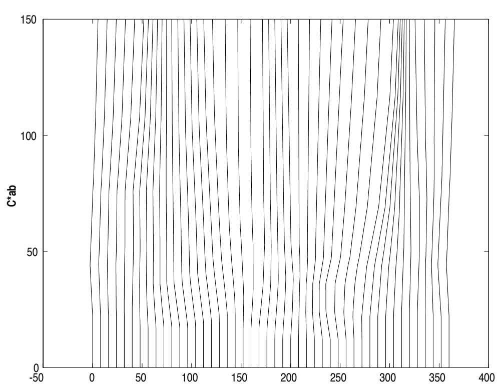

Figure 6. Samplings from the Inverse hue-correction transformation every 8 degrees. Defines the transformation from hue-corrected CIELAB to CIELAB.

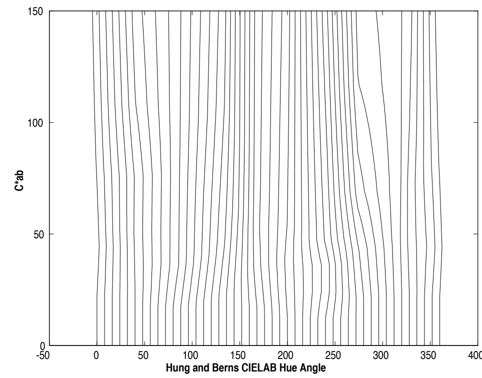

Figure 7. Samplings from the forward hue-correction transformation every 8 degrees in hue angle. Defines the transformation from CIELAB to hue-corrected CIELAB.

Ebner and Fairchild Data Set

A neutral network was used to create a three-dimensional forward transform LUT from CIELAB to hue-corrected CIELAB space. The neural network was trained using methods from Masters (1993). A 10 node, one hidden layer neural network was trained on 366 data points. Of these 366 data points 306 points were from the Ebner and Fairchild constant hue data set. The additional 60 points were data that were extrapolated, by hand, to fill the space out to a C^*_{ab} of 127. The neural network was trained and used to create a LUT that defined the transformation from CIELAB to hue-corrected CIELAB. The forward LUT was inverted using methods similar to Rolleston (1994). The average and maximum ΔE^*_{ab} errors for the forward LUT were 0.31 and 1.79 respectively. The average ad maximum ΔE^*_{ab} errors for the inverse LUT were 0.29 and 1.29 respectively. Thus, the average and maximum ΔE^*_{ab} errors for the forward and inverse transforms combined were 0.06 and 0.61 respectively. The set of 366 points was used both to train the neural network and to test the LUTs.

Experimental Testing

Testing the hue linearity properties of CIELAB and the two hue-corrected spaces consisted of two paired-comparison psychophysical experiments. The first was performed by comparing pairs of hue leaves on a CRT, similar in form to pages from the Munsell Book of Color, derived from the three color spaces. The second experiment consisted of viewing pairs of pictorial images that were gamut mapped in CIELAB and the hue-corrected color spaces. In both experiments, the colorimetrically controlled CRT white point was set to chromaticities near CIE Illuminant D65 with a peak luminance near 70 cd/m^2. Device-dependent image pixel data (digital counts) were converted to and from CIELAB using a gain-offset-gamma CRT characterization model (Berns, Motta, and Gorzynski (1993)).

Image Processing Path

For this experiment the viewing conditions were set to chromaticities near D65. This was done so that the viewing conditions would be optimized for CIELAB. The CIELAB color space was defined for a reference illuminant of D65. If the current viewing conditions were specified for a different source then it would have been necessary to convert the reference tristimulus values to corresponding D65 matches. This could be accomplished by using a color appearance model such as RLAB, LLAB, or CIECAM97s to perform the chromatic adaptation transformations necessary to calculate D65 corresponding color matches to the tristimulus values in the reference viewing conditions.

Once the corresponding tristimulus values have been defined for the D65 illuminant, then the CIELAB hue-correction LUTs would be applied to the image pixel data. At this point all gamut-mapping operations are applied. The image data are then processed through the inverse LUTs, back into CIELAB. As with the input stage, corresponding output tristimulus values can be calculated for the output viewing conditions, using a color appearance model such as RLAB, LLAB, or CIECAM97s. This process has the benefit of using the chromatic adaptation properties of the color appearance models as well as providing a hue-linearized color space for gamut mapping. An alternative approach would be to use the techniques described in this study to construct hue-correcting LUTs in the color appearance space of interest, using the constant-hue visual data cited.

Hue Leaf Experiment

The hue leaf experiment consisted of converting 15 metric hue angle planes, uniformly sampled in lightness and chroma, into CIELAB from the two hue-corrected color spaces. In addition, CIELAB constant metric hue planes were generated for the same 15 hue angles. CIELAB points outside the CRT gamut were converted to a neutral gray (CIELAB coordinates L*a*b* = [50,0,0]). Only same-base-hue images were compared to each other. Thirty observations of the entire data set were made. Nine observers took part in the experiment. All observers had experience with color, and were familiar with the terminology and the concept of hue uniformity. The task given to the observers was as follows:

"You will be shown pairs of images. For each pair of images shown, pick the image that has the best hue uniformity. The maximum chroma color for each image is the same color. Compare the colors in each image separately; don't compare colors between images."

Pictorial Gamut-Mapping Experiment

The gamut mapping experiment consisted of gamut mapping 5 full-gamut CRT images to an inkjet printer gamut scaled to completely fit within the full CRT gamut. Both images were displayed on the CRT. Three gamut-mapping algorithms were used: 1.) Chroma clipping with lightness and hue preservation, 2.) Minimum ΔE^*_{ab} clipping with hue preservation, and 3.) Centroid clipping toward L*a*b* = [50,0,0] with hue preservation. These algorithms were selected to represent popular gamut mapping transformations. They were picked for their ease of computation and their representative lightness and chroma shifts that may typically occur in other gamut mapping algorithms. This experiment was designed to test the hue uniformity characteristics of the color spaces, and not the "goodness" of the gamut mapping algorithms used. Images were selected to test several different hue regions.

The gamut-mapped images were shown to 22 observers in sets of three images. These images were an original full gamut image and two reproductions, mapped using the same gamut mapping algorithm but using different hue-corrected spaces. A paired-comparison technique was used, and the gamut-mapped reproductions consisted of all possible pairs of the three color spaces. The interface was such that observers could only view one image at a time, and allowed them to freely toggle among the three images. They were asked to pick the reproduction that was closest in hue to the original full gamut image.

The data from the two visual experiments were used to generate interval scales using Thurstone's law of comparative judgment (version V) (Bartleson and Grum (1984)).

Experimental Results

Hue Leaf Experiment Results

The results of the hue leaf experiment were somewhat surprising. Essentially, the results indicate that CIELAB was as uniform as, or more uniform than, either hue-corrected space, with the exception of the "blue" region of the color space (approximately h_{ab} = 260 – 300). For the hue-leaves at 48 and 72 degrees, CIELAB was judged to be more uniform than either hue-corrected space. This was indicated by the interval scale results shown in Figure 8. At a given base CIELAB hue angle, a significant difference between the various color spaces exists when the 95 percent error bars of the spaces do not bound the interval scale value for a given space. For example, at the h_{ab}=0 leaf it was not possible to say that one of the color spaces produced a leaf that was more uniform than either of the other spaces. However, at the h_{ab}=288 leaf it was possible to say that both of the hue-corrected color spaces produce significantly more uniform leaves than CIELAB. It was not possible, however, to say which of the hue-corrected spaces was more uniform. Overall, when the hue-corrected spaces were deemed significantly more uniform than CIELAB they were judged to be equally uniform.

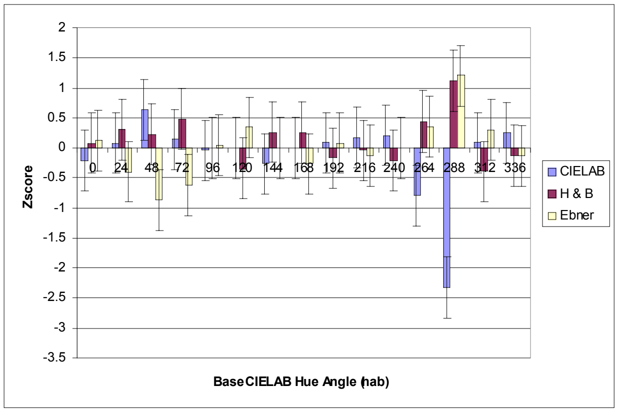

Figure 8. Interval scales for the 15 hue leaves. In order for one space to be significantly better than another the mean of one space has to be outside the error bars of the other.

Pictorial Gamut-Mapping Experiment Results

The results of the pictorial gamut mapping experiment showed that, over all of the images and routines tested, the hue-linearized versions of CIELAB maintained the perceived hue of the gamut mapped images better than CIELAB, Figure 9. In addition, these scales tend to indicate that, overall, the Hung and Berns hue-corrected CIELAB space slightly out-performs the Ebner and Fairchild hue-corrected CIELAB space.

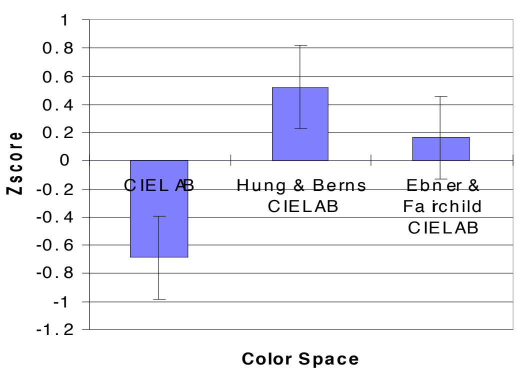

Figure 9. Interval scale pooled over all images and gamut mapping routines tested. Results show that Hung and Berns hue-corrected CIELAB outperforms the Ebner and Fairchild hue-corrected CIELAB and CIELAB.

Based on the fact that the hue-leaf experiment found that the hue-linearization performed by the Hung and Berns and Ebner and Fairchild LUTs was not universally better than CIELAB for all hue angles, the analysis of the pictorial gamut mapping experiment was broken up by dominant image color. In doing this, the results of the pictorial gamut mapping experiment were very similar in nature to those found in the hue leaf experiment. While the images selected contained colors that spanned CIELAB, there were definite dominant features that were most sensitive to hue shifts. The images were broken down into three categories; dominant red images, dominant blue images, and mixed images.

When the observer data were analyzed in this manner, the following conclusions were made. For the images that were classified as having predominantly red features that were gamut-mapped, the data supports using CIELAB as the color space for gamut mapping, Figure 10. Images that contained predominantly blue features that were gamut-mapped were mapped better using the hue-corrected CIELAB space generated by the Hung and Berns data set, Figure 11. Finally, for the image that contained a mixture of red, green, blue, and yellow features that were gamut mapped the results indicate that the hue-corrected spaces were selected as the most hue preserving, Figure 12. This is most likely due to the fact that there was a fair amount of high chroma blue features that were gamut-mapped.

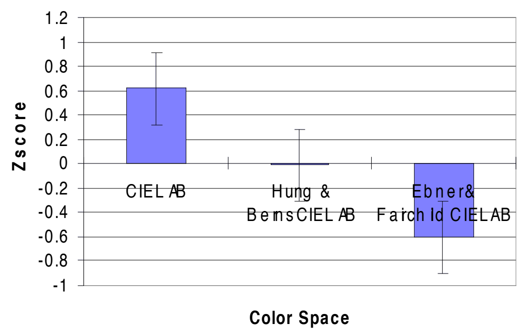

Figure 10. Interval scale for images that had predominantly red features that were gamut mapped. Results show that performing the gamut mapping in the CIELAB space maintained the hue of the original image better than either hue-corrected space.

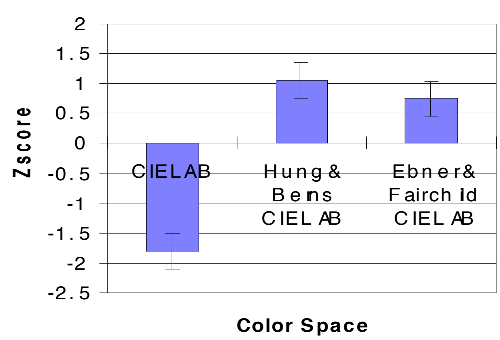

Figure 11. Interval scale results for the images that contained predominatly blue features. Results indicate that the hue-corrected versions of CIELAB more accurately preserved the original hue of the image after gamut mapping.

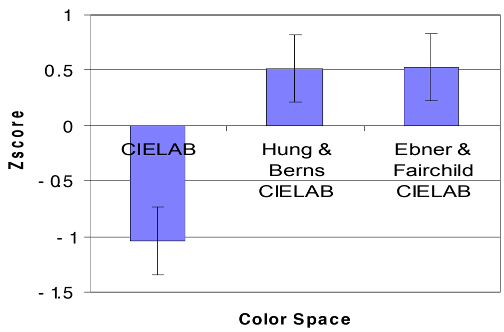

Figure 12. Interval scale results for the image that contained mixed colored features that were gamut mapped.

Conclusions

The experiments performed were designed to test the utility of using constant hue visual data to generate LUTs to linearize the CIELAB space with respect to hue. These hue-corrected CIELAB spaces were then used in a gamut mapping experiment to evaluate whether the hue-corrected spaces preserve the hue of the original scene better than CIELAB. The results of these experiments showed the benefit of using the hue-corrected CIELAB space for blue features. The hue of image features that were outside the blue region of color space (h_{ab} = 260 – 300) were not preserved better using the hue-correction LUTs tested in these experiments. These results suggest that a new set of LUTs be generated that provide only hue-correction in the "blue" region of CIELAB where the strongest hue-nonlinearity exists. An example of these types of LUTs is given in Figure 13 and 14. It is hoped that, these results can be used as a benchmark to future studies designed to develop a color space with uniform perceived hue.

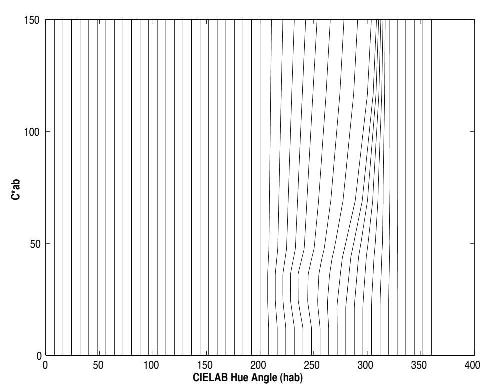

Figure 13. Inverse hue-correction LUT with only correction in the "blue" region generated from the Berns and Hung (1995) data set.

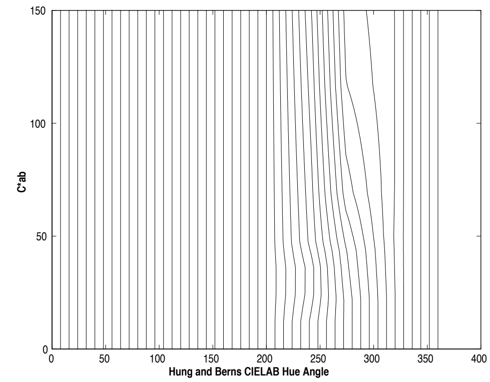

Figure 14. Forward hue-correctioin LUT with only correction in the "blue" region generated from the Berns and Hung (1995) data set.

Acknowledgements

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