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SIMG-503

Senior Research

Development of a Linear Version of the CIECAM97s Chromatic Adaptation Transform

Final Report

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Development of a Linear Version of the CIECAM97s Chromatic Adaptation Transform

Matthew J. Ochs

Abstract

Color appearance models are used to predict the perceived color of a source. Within these models are chromatic-adaptation transforms that predict matches only across different viewing conditions. They ignore many of the factors that are used later on in a model. This project was performed to create a simpler and easier to use chromatic-adaptation transform that was also a linear transform. This was based on the previously known CIECAM97s color appearance model and the non-linear chromatic-adaptation transform that it utilized. The research specifically attempted to create a new transform that will go from XYZ to RGB coordinates that will allow a chromatic adaptation model to perform as well as the Bradford model in CIECAM97s, but while using the linear von Kries rules. A new transform was found, but it can be concluded that it did not perform as well as the CIECAM97s transform.

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This report is accepted in partial fulfillment of the requirements of the course SIMG-503 Senior Research.

Title: Development of a Linear Version of the CIECAM97s Chromatic Adaptation Transform

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Development of a Linear Version of the CIECAM97s Color Appearance Model

Matthew J. Ochs

Introduction & Background

Chromatic adaptation is the human visual system's capability to adjust to widely varying colors of illumination in order to approximately preserve the appearance of object colors. It is the largely independent sensitivity regulation of the mechanisms of color vision. (1) An example of this is viewing an object with a tungsten light source and also viewing it in daylight. Humans would not see much change in the color with these different illuminations. If a photograph were made of the object in these two conditions, they would end up looking different. The picture taken with the tungsten light source would look yellowish, instead of the bluish tint in daylight. This is due to the fact that film does not have the ability to adjust to the different conditions like humans do.

The data used when studying chromatic adaptation is obtained from corresponding-colors data. Corresponding colors are two stimuli, when viewed under different conditions, appear to be the same color. An example of this is the tristimulus values of one object, XYZ_1 , viewed in one set of conditions, might seem to be approximately the same as a second set of tristimulus values, XYZ_2 , under another, different set of viewing conditions. These two sets of tristimulus values are referred to as corresponding colors. Information about viewing conditions of each must also be included with each respective set of tristimulus values. Although the two might appear to be the same, they usually do not have the same numerical values. (1)

The transformation from XYZ_1 to XYZ_2 is done using a chromatic adaptation model or chromatic adaptation transform. These models do not include information about lightness, chroma, or hue. The chromatic adaptation model can now be used with corresponding-colors data. Instead of visually recording the data under a second set of viewing conditions, input the values for the first viewing condition into the model, and depending on how good the model is, the output should be an accurate prediction of the second set of tristimulus values.

A general form of a model can be described using the following equations:

$$L_a = f(L, \dots) \quad (1)$$

$$M_a = f(M, \dots) \quad (2)$$

$$S_a = f(S, \dots) \quad (3)$$

This model will just predict the three cone signals L_a , M_a , and S_a (for long, medium, and short) after the effects of adaptation have acted upon the initial L , M , and S and well as various other factors. A chromatic-adaptation model can be converted to a chromatic-adaptation transform by using the forward model for one set of viewing conditions and the inverse of the second set of viewing conditions. This is usually done in terms of CIE (International Commission on Illumination) tristimulus values:

$$XYZ_2 = f(XYZ_1, \dots) \quad (4)$$

To be more accurate, the CIE XYZ values must be expressed in terms of cone signals, LMS (or RGB for red,

green, and blue). This can be done by a linear transformation (3 x 3 matrix). This is used in chromatic-adaptation and color appearance models that use CIE colorimetry.

Using these pieces, a generic chromatic-adaptation transform can be made. Starting with CIE tristimulus values for the initial viewing condition, transform these values to cone excitations. Taking into account the various effects of the viewing conditions, use the chromatic-adaptation model to predict the adapted cone signals. Now invert the process by taking the second set of viewing conditions to determine the corresponding colors in terms of cone signals. Finally convert these signals to CIE tristimulus values. This is shown in the following figure:

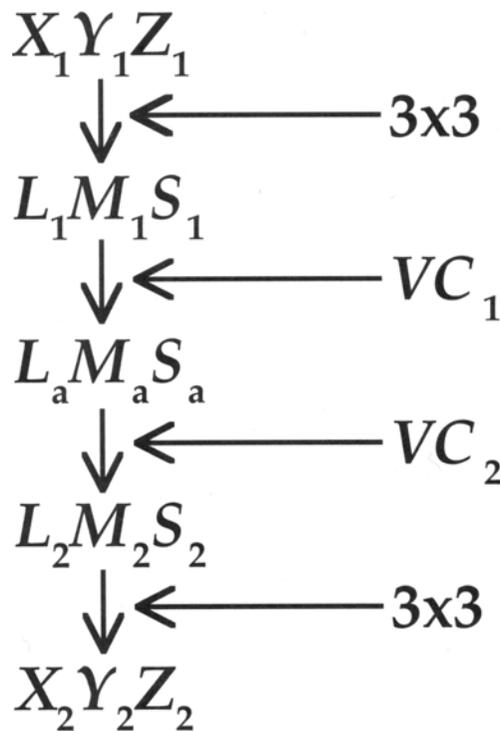


Figure 1:

A flow chart of the application of a chromatic-adaptation model to the calculation of corresponding colors. (1)

In CIECAM97s (CIE Color Appearance Model, 1997), a Bradford chromatic adaptation model was used with a few modifications. The key parts of the model are that it has a nonlinearity (exponent) on the blue, or short, response and uses a unique matrix transformation to go from *XYZ* to *RGB* (or *LMS*). There is also a D factor that was set to one. The classic model of chromatic adaptation is called a von Kries model. This just transforms *XYZ* values to *RGB*

and then normalizes the result by a white stimulus. This is done by a linear calculation and works well. The changes in the Bradford model seem to improve on this though. (2)

Theory

CIEL*a*b*

Since the color temperature of daylight changes constantly, a mean daylight has been standardized at 6500K. This is what D₆₅ refers to; a standard illuminant at 6500K. (3) CIELAB was created in 1976 in an attempt to promote uniformity in calculating color differences. To calculate CIELAB coordinates, start with the two sets of CIE XYZ tristimulus values provided. One of these is for a stimulus and the other is for a reference, X_n, Y_n, Z_n . Normalize these to those of the white by dividing the stimulus values by the reference values. These adapted signals are then subjected to a compressive nonlinearity represented by a cube root in the CIE equations. These signals are then combined into three response dimensions of the opponent-colors theory of color vision. Finally, proper constants are used in the equations that will provide the required perceptual spacing and proper relationship between the three dimensions. This entire process is shown in the following equations:

$$L^* = f(Y/Y_n) - 16 \quad (5)$$

$$a^* = 500[f(X/X_n) - f(Y/Y_n)] \quad (6)$$

$$b^* = 200[f(Y/Y_n) - f(Z/Z_n)] \quad (7)$$

$$f(\omega) = (\omega)^{1/3} \quad \omega > 0.008856 \quad (8)$$

$$f(\omega) = 7.787(\omega) + 16/116 \quad \omega \leq 0.008856 \quad (9)$$

L^* represents lightness, a^* approximates redness-greenness, and b^* approximates yellowness-blueness. This will represent the data in Cartesian coordinates to form a three dimensional space. This can be also represented in terms of cylindrical coordinates that will predict chroma, C^*_{ab} , and hue, h_{ab} .

$$C^*_{ab} = \sqrt{a^{*2} + b^{*2}} \quad (10)$$

$$h_{ab} = \tan^{-1}(b^*/a^*) \quad (11)$$

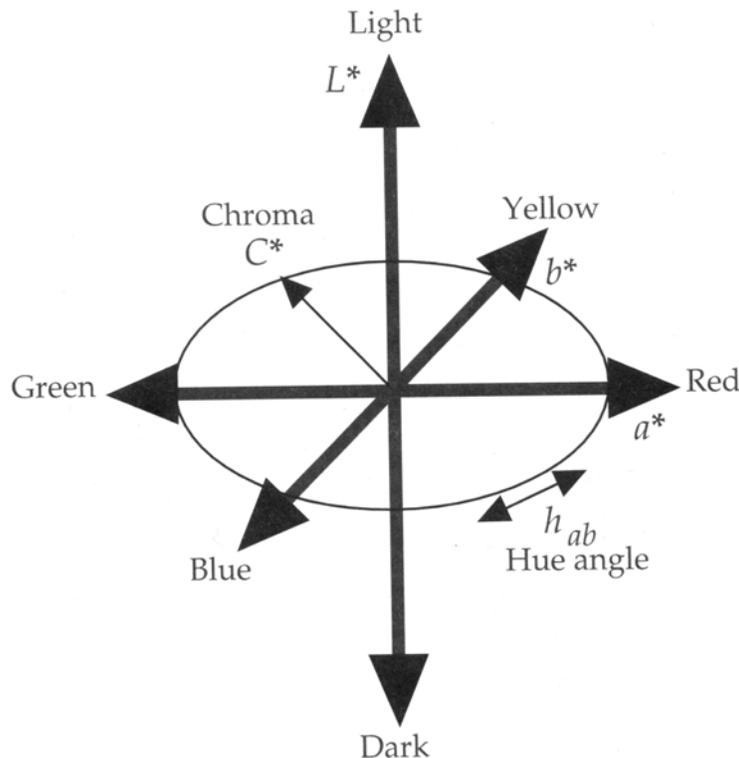


Figure 2: Cylindrical CIELAB color space (1)

ΔE^*_{94}

ΔE^*_{94} is a color-difference calculation based upon the Euclidean distance between the color of a sample under test and reference sources. The ΔE^*_{94} is a simplified version of an earlier ΔE formula. The equations used to calculate this are:

$$\Delta E^*_{94} = [(\Delta L^*/k_L S_L)^2 + (\Delta C^*_{ab}/k_C S_C)^2 + (\Delta H^*_{ab}/k_H S_H)^2]^{1/2} \quad (12)$$

$$S_L = 1 \quad (13)$$

$$S_C = 1 + 0.045 C^*_{ab} \quad (14)$$

$$S_H = 1 + 0.015 C^*_{ab} \quad (15)$$

C^*_{ab} is referring to the CIELAB chroma of the color difference pair. The k_L , k_C , and k_H are used to offset any experimental variables and may be set to 1 under defined reference conditions. [\(1\)](#)

Methods

Generation of Test Data Set

The first step in the procedure of this project was to obtain a data set to test the models with. This was obtained from the Munsell Book of Color samples from Dave Wyble's work. [\(4\)](#) Three separate data sets were tested. The first was the colors that physically appeared in the 1929 Munsell Book of Color. The second being real colors only, "real" being those lying inside the Macadam limits. The third data set used all the Munsell data, including extrapolated colors. Note that extrapolated colors are in some cases unreal. That is, some lie outside the Macadam limits. [\(5\)](#) This gave data for the x and y chromaticity values as well as the Y tristimulus value. To find the X and Z tristimulus values, the following equations were used:

$$X = \frac{xY}{y} \quad (16)$$

$$Z = \frac{(1.0 - x - y)Y}{y} \quad (17)$$

Now a data set of XYZ values are known which were used as input into the CIECAM97s and linear models. These were read into an IDL program that was written to perform the following calculations.

Implementation of Bradford Model

The CIECAM97s model uses a specific chromatic-adaptation transform to go from source conditions to reference viewing conditions. The test data set was normalized and transformed to cone responses by:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} := Mb \cdot \begin{bmatrix} X \\ \overline{Y} \\ Y \\ \overline{Y} \\ Z \\ \overline{Y} \end{bmatrix} \quad (18)$$

$$Mb := \begin{bmatrix} 0.8951 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & -0.0685 & 1.0296 \end{bmatrix} \quad (19)$$

The difference between the von Kries and the CIECAM97s transform that follows is an exponential nonlinearity on the B , or S signal. This exponential is what this project was trying to eliminate. The D , which describes the degree of adaptation, in the following transformation was always set to 1 for all work in this project.

$$R_c = [D(1.0/R_w) + 1 - D]R \quad (20)$$

$$G_c = [D(1.0/G_w) + 1 - D]G \quad (21)$$

$$B_c = [D(1.0/B_w^p) + 1 - D]|B|^p \quad (22)$$

$$p = (B_w/1.0)^{0.0834} \quad (23)$$

These new RGB values were then transformed back to a set of XYZ values that are the output of the Bradford model.

$$\begin{bmatrix} X_{brad} \\ Y_{brad} \\ Z_{brad} \end{bmatrix} := Mb^{-1} \cdot \begin{bmatrix} R_c \cdot Y \\ G_c \cdot Y \\ B_c \cdot Y \end{bmatrix} \quad (24)$$

Development and Implementation of Optimization Technique for Linear Model

Now that data from the Bradford model was known, a new linear model was created to give similar results. The general for this is:

$$\begin{bmatrix} X \\ Y \\ X \end{bmatrix}_A = M^{-1} \cdot (A_A)^{-1} \cdot A_{D65} \cdot M \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{D65} \quad (25)$$

The A matrices are linear and diagonal. Each one can be represented as:

$$A_A := \begin{bmatrix} \frac{1}{L_A} & 0 & 0 \\ 0 & \frac{1}{M_A} & 0 \\ 0 & 0 & \frac{1}{S_A} \end{bmatrix} \quad (26)$$

$$A_{D65} := \begin{bmatrix} \frac{1}{L_{D65}} & 0 & 0 \\ 0 & \frac{1}{M_{D65}} & 0 \\ 0 & 0 & \frac{1}{S_{D65}} \end{bmatrix} \quad (27)$$

Since the nonlinearity of the Bradford model is no longer present, the M chromatic adaptation transform matrix needed to be changed in order to get XYZ

values that were similar to those found previously. This M matrix was found using the AMOEBA function in IDL. The AMOEBA function performs multidimensional minimization of a function using the downhill simplex method. This function altered the values of the Bradford M matrix for a number of iterations and found a new M matrix that when utilized in the linear model, would give data similar to the output XYZ values from the Bradford model. This routine is written into the IDL language. Once this routine returned the values for the new matrix, the new values were implemented into the linear model. A new set of XYZ from the linear model was then calculated. Now that there is a set of XYZ values from both the CIECAM97s model and the linear model, the accuracy of the model was evaluated. To do this, the XYZ values were converted to CIE L*a*b* values for both models, and the ΔE_{94} was then calculated to compare the two.

For comparison, three matrices were tested along with the new matrix found using the AMOEBA function. The first two come from personal communications with my advisor. The third is just the average of these two. These resulted from research whose goal was similar to this project. The three matrices are:

$$\begin{bmatrix} 0.9881 & -0.0770 & -0.1328 \\ 0.4212 & -0.9068 & -0.0180 \\ 0.0296 & -0.0314 & 0.9991 \end{bmatrix}$$

$$\begin{bmatrix} 0.7892 & 0.3389 & -0.1371 \\ -0.5918 & 1.5512 & 0.0406 \\ 0.0008 & -0.0239 & 0.9753 \end{bmatrix}$$

$$\begin{bmatrix} 0.88865 & 0.1310 & -0.13495 \\ -0.0853 & 0.3222 & 0.0113 \\ 0.0152 & -0.02765 & 0.9872 \end{bmatrix}$$

Results

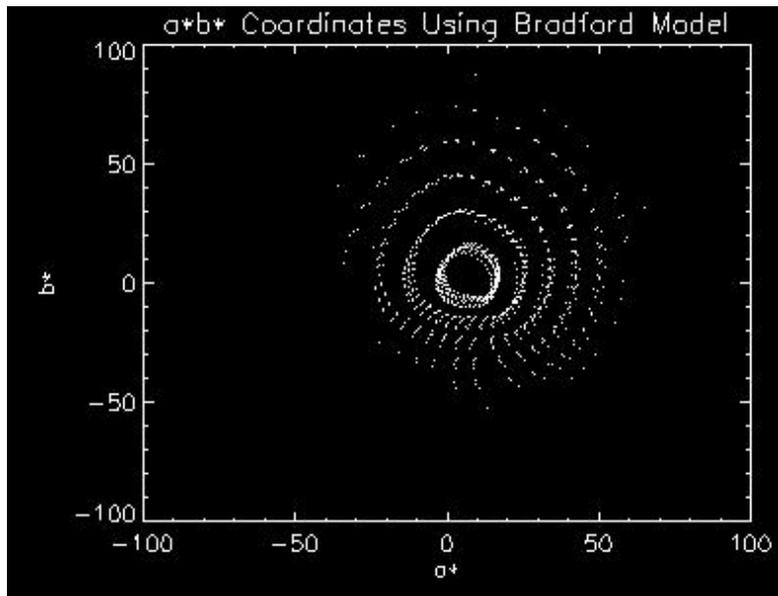


Figure 3: Output data from Bradford model using 1929 Munsell data

This is the new M matrix that was found using the AMOEBA function in IDL and the 1929 Munsell data.

$$\begin{bmatrix} 2.53642 & 0.693174 & -0.192602 \\ -0.722866 & 1.45464 & -0.415604 \\ -0.219843 & -0.353057 & 0.766218 \end{bmatrix}$$

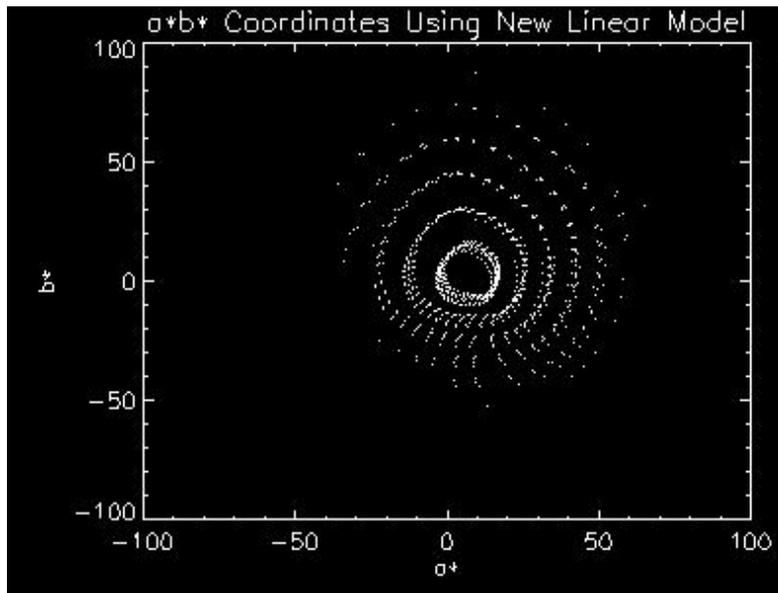


Figure 4: Output data from linear model and 1929 Munsell data

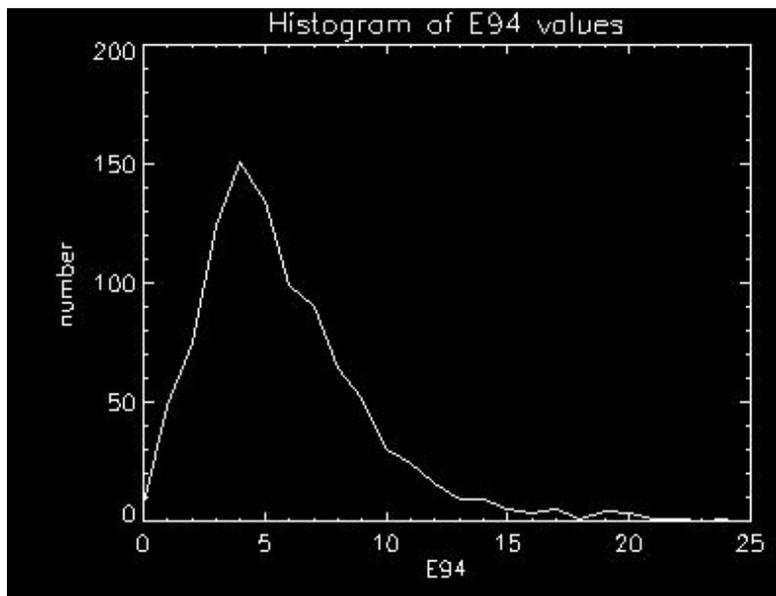


Figure 5: Histogram of ΔE^*_{94} values using 1929 Munsell data

ΔE^*_{94} data from 1929 Munsell data.

$$\Delta E^*_{94} \text{ min} = 0.670628$$

$$\Delta E^*_{94} \text{ mean} = 6.90528$$

$$\Delta E^*_{94} \text{ max} = 25.1795$$

$$\Delta E^*_{94} \text{ median} = 6.18096$$

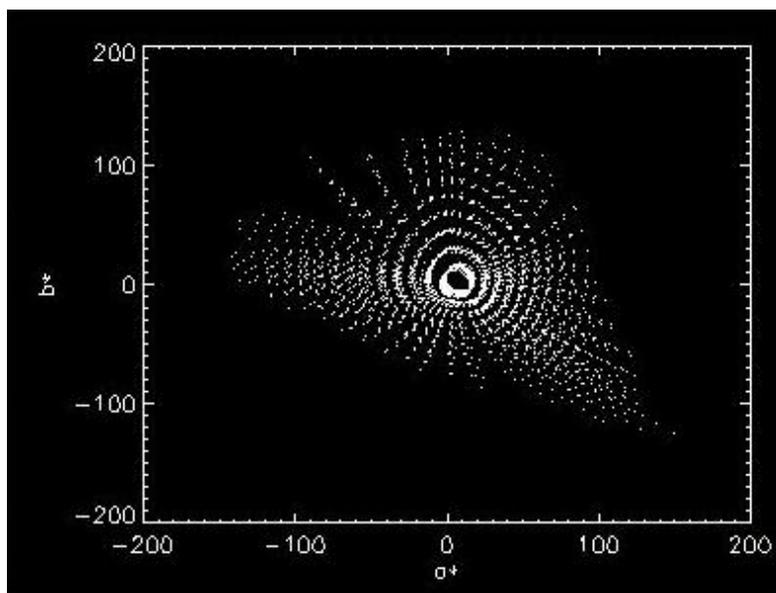


Figure 6: Output data from Bradford Model using real Munsell data

This is the new M matrix that was found using the AMOEBA function in IDL and the real Munsell data.

$$\begin{bmatrix} 3.08106 & -1.42243 & -0.775664 \\ -0.145055 & 3.35200 & 2.37083 \\ 0.156840 & 0.0565373 & 3.36035 \end{bmatrix}$$

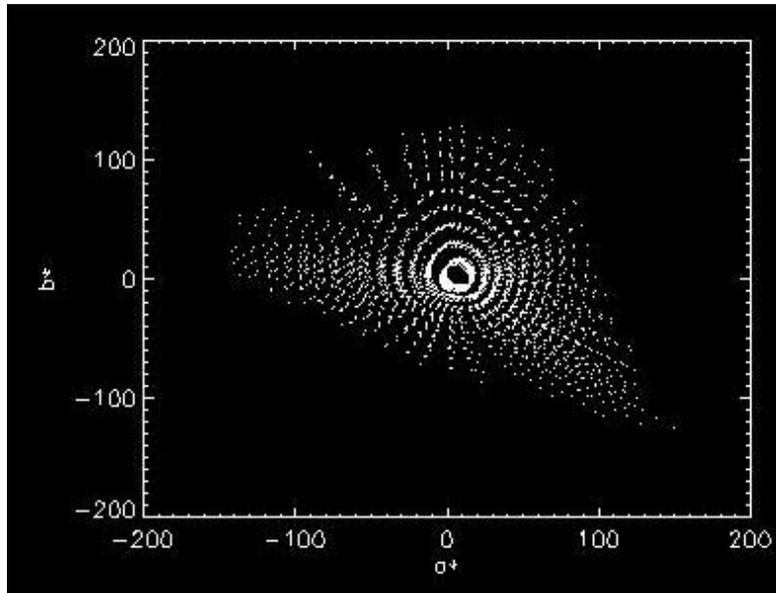


Figure 7: Output data from linear model using real Munsell data

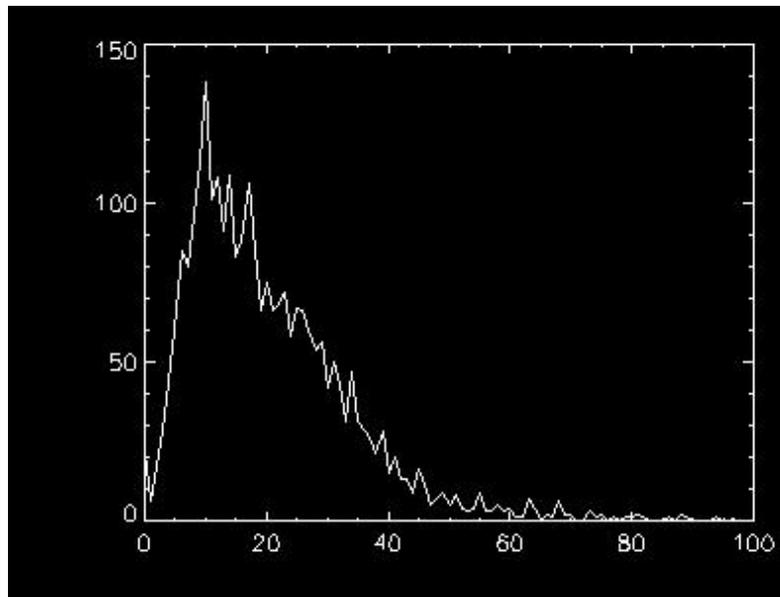


Figure 8: Histogram of ΔE^*_{94} values using real Munsell data

$$\Delta E^*_{94} \text{ min} = 0.391057$$

$$\Delta E^*_{94} \text{ mean} = 21.2884$$

$$\Delta E^*_{94} \text{ max} = 98.0225$$

$$\Delta E^*_{94} \text{ median} = 18.3195$$

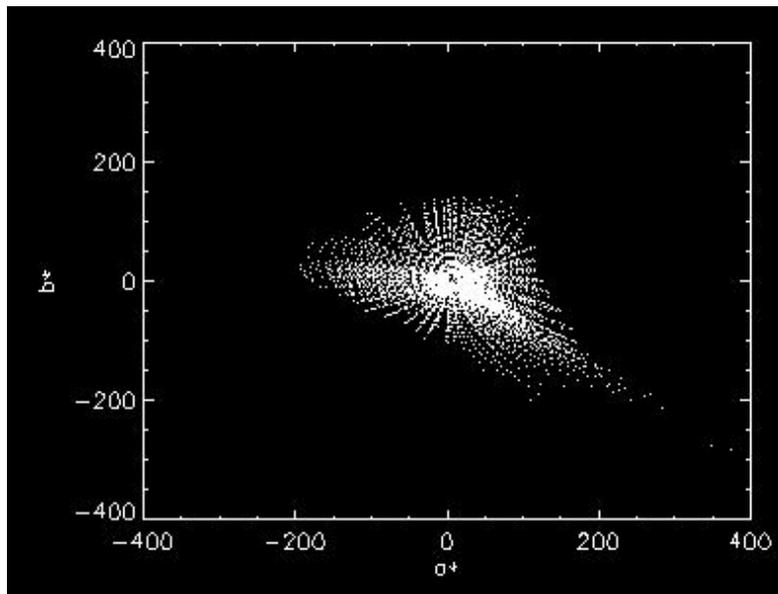


Figure 9: Output data from Bradford model using all Munsell data

The following ΔE^*_{94} data is for the "mystery" matrix, the "derby" matrix, and the average of these two, respectively.

$$\Delta E^*_{94} \text{ min} = 0.603249$$

$$\Delta E^*_{94} \text{ mean} = 11.4141$$

$$\Delta E^*_{94} \text{ max} = 47.3711$$

$$\Delta E^*_{94} \text{ median} = 9.86326$$

$$\Delta E^*_{94} \text{ min} = 0.542887$$

$$\Delta E^*_{94} \text{ mean} = 12.0115$$

$$\Delta E^*_{94} \text{ max} = 49.7402$$

$$\Delta E^*_{94} \text{ median} = 10.3158$$

$$\Delta E^*_{94} \text{ min} = 0.486392$$

$$\Delta E^*_{94} \text{ mean} = 11.9741$$

$$\Delta E^*_{94} \text{ max} = 48.2328$$

$$\Delta E^*_{94} \text{ median} = 10.3222$$

Discussion

The graphs that resulted from the Bradford model and the linear model give a visual comparison of the two models. There are obvious similarities between the two, but the accuracy of the two can be examined further. At best, the new transform that was found using the 1929 Munsell data had a mean of 6.90528 which is on the border of acceptability. The visual uncertainty for such determinations is about 4 units. Thus, the disagreement between the models is significant. However, it might be biased by some very large errors for colors that have never really been studied experimentally. This would explain the maximum of 25.1795 as well as the presence of other high values in the histogram. This may also be pulling the mean to such a high value. It is good to note that most of the ΔE^*_{94} occur at lower values, but still not in the range that was expected.

When using the real Munsell values, the presence of more extreme colors created less accurate data. When all of the Munsell data was used, a new optimized transform could not even be found due to the extremity of the colors. It may be useful to try other data sets as input or to try to eliminate some of the colors that have not been studied previously. This may result in a better transform, but as the data set is truncated, it may be less reliable over a larger gamut of colors. The optimized transform found using the 1929 data resulted in a better fit than when using the two matrices provided by Fairchild and averaged matrix. This is better for these particular data, but that's to be expected since it was fit to the 1929 data, and the data set for the others was different. It works better for what has been tested so far, but further independent tests would be required to make a robust conclusion..

Conclusions

The hypothesis for this research project was that a new transform from *XYZ* to *RGB* coordinates should be obtained that will allow a chromatic adaptation model to perform as well as the Bradford model in CIECAM97s, but while using the linear von Kries rules. Although a new linear transform was found, it did not perform as accurately as the Bradford model.

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