Analysis and Correction of the Joensuu Munsell Glossy Spectral Database

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Abstract

The spectral reflectances for the Munsell glossy data found in the Joensuu spectral database were analyzed and differences with the Munsell Renotation data were visualized showing discrepancies. Two methods of correcting these differences were explored. The first method attempted to correct for differences in specular exclusion of the measurement devices. The second method of correcting the spectral reflectances resulted in correctly matching the colorimetry defined by the Munsell renotation data set. Additionally, color inconstancy index results were visualized depicting possible aspects of chromatic adaptation as well as the areas where spectral reflectances might be found that better maintain relationships with neighboring colors under different lighting conditions.

Introduction

The Munsell color system was developed (starting in 1905) by A. H. Munsell to define color perceptions using the terms Hue, Value, and Chroma. In 1915, the system was first produced as the *Atlas of the Munsell Color System*. Experiments performed during the 1920's both improved the Atlas' visual uniformity and expanded its color gamut resulting in the 1929 *Munsell Book of Color* (MBC). The MBC was defined by its physical samples and as such, was equivalent to a spectrally-based color order system.[1] With usage, the 1929 MBC was found to still lack visual uniformity and further visual experiments were performed during the late 1930's and early 1940's. This resulted in the Munsell re-notations.[2] Of particular importance was that the system changed from a spectral system to a colorimetric system. Chromaticities and luminance factor for CIE illuminant C and the 1931 standard observer defined the Munsell system. Since the colorimetry was published in the Journal of the Optical Society of America, the Munsell system became public domain. Producing a collection of samples, such as the MBC, is within the commercial world, and the spectral data are not made available.

The Color Research Laboratory at the University of Eastern Finland (formerly Joensuu University) has measured matte finish and glossy finish MBCs manufactured in 1976. The spectrophotometer was a Perkin-Elmer Lambda 18 with an integrating sphere attachment. Specular excluded mode was used, matching the MBC's reference geometry. They have made these data available online[3] and have been used extensively in color and imaging research. However, the Lambda 18 is not identical to a GE Recording spectrophotometer (initially used for quality control when manufacturing the MBC),[4] and it is unlikely that any specific book would have identical colorimetry to the Munsell re-notation data because of manufacturing variability. Therefore, the published spectral reflectance data in the Joensuu data sets may not match the Munsell system.

The purpose of this research was to compare how well the spectral reflectances of the Joensuu Munsell glossy spectral data set corresponded to the colorimetry defined by the Munsell re-notation data set, implement a simple method of correcting for any differences found, and analyze color appearance aspects of the corrected spectral reflectances.

Methodology

The Joensuu spectral reflectance measurements (JSRM) of the 1600 glossy Munsell color chips were transformed to colorimetry for the 1931 two degree standard observer under Illuminant C. Both the JSRM and the Munsell re-notation data (MRD) were converted to CIELAB and compared using the CIEDE2000 formula with overall results shown in Table 1, and a histogram of the color differences plotted in Figure 1.

Table 1 – ΔE_{00} Color difference statistics between JSRM and MRD

Minimum ΔE_{00}	Mean ΔE_{00}	Maximum ΔE_{00}	Standard Deviation
0.12	3.45	23.68	2.95

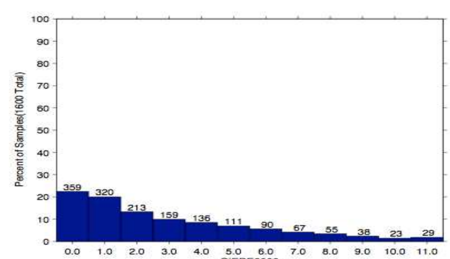

Figure 1 – Histogram of CIEDE2000 color differences between JMSR and MRD

As can be seen from both Table 1 and Figure 1, there are significant colorimetric differences between the JMSR and MRDs. A mean color difference of 3.45 indicates that the differences on the average will be noticeable with an extremely noticeable maximum difference. Only 43% of the color chips have a ΔE_{00} of 2.0 or less.

To analyze how these differences affect the visual spacing, a visualization technique was developed to convert the colorimetry and color difference information into an understandable form. The colorimetric data were first chromatically adapted to D50 using CIECAT02 and then rendered as a CIELAB tiff image ordered by both Munsell Value and Hue, shown in Figure 2. For the Value slices, each gray background had the equivalent Value. Because our visual system has greater contrast sensitivity to luminance, we can see that certain regions have systematic differences in Value, e.g., the GY and Y region at Value 4 and 3.

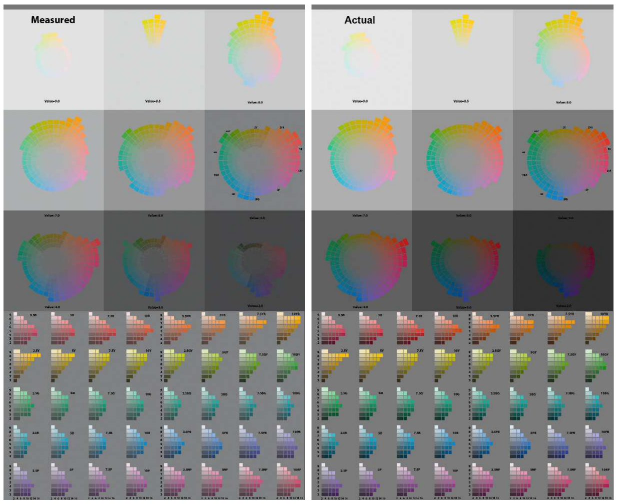

Figure 2 – Image renderings using the Joensuu Spectral database (left) and Munsell re-notation data (right)

False-color visualizations, ranging between 0 and 14+ in 1Δ unit-differences, were also made for ΔE_{00}, ΔL^*, ΔC^*_{ab}, and ΔH^*_{ab}, shown in Figures 3 and 4.

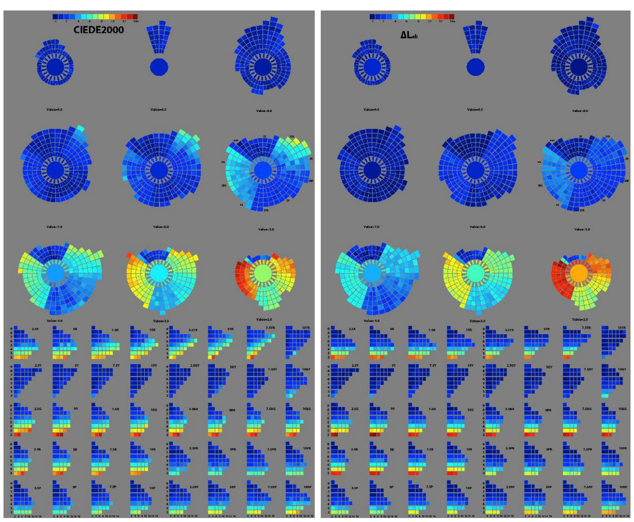

Figure 3 – Color difference maps between JMSR and MRD with ΔE_{00} (left), ΔL^*_{ab} (right)

Most of the large color differences occurred for darker colors or more chromatic colors with small differences occurring as a result of hue shifts. Having large errors in lightness and chroma for dark colors is indicative of a difference in the specular port employed by the devices used to measure the colors and can be corrected by adding a small constant to the spectral reflectance.[5]

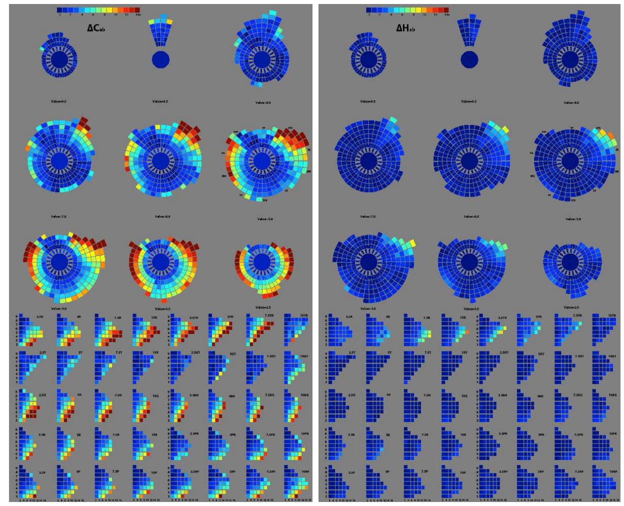

Figure 4 – Color difference maps between JMSR and MRD with ΔC^*_{ab} (left), and ΔH^*_{ab} (right)

To test this, an optimization to find the best value for k in Equation 1 was performed (minimizing the average CIEDE2000 between adjusted JMSR and MRD).

$$\mathbf{r}_{adjusted,\lambda} = \mathbf{r}_{measured,\lambda} + k \quad (1)$$

The optimization resulted in a k value of -0.0254, and the min, mean, max, and standard deviation of adjusted color differences to the MRD data are shown in Table 2, and corresponding false-color visualization of the adjustments are shown in Figure 5.

Table 2 – Color difference statistics between adjusted JSRM and MRD colorimetry

Minimum ΔE_{00}	Mean ΔE_{00}	Maximum ΔE_{00}	STD
0.18	2.18	22.42	1.68

As can be seen from Table 2 and Figure 5, there is an appreciable improvement in the average color difference and standard deviation confirming that differences in sphere geometry was a large contributor. However, the maximum errors are still very large which is likely due to errors in manufacturing rather than other differences in spectrophotometers such as wavelength scale or bandwidth.[5]

To completely correct for the differences, a strategy was used that is similar to batch correction, commonly used in colorant formulation.[6] The method involved deriving a pseudo-inverse-based matrix that estimates spectral reflectance from colorimetry:

$$\mathbf{E} = \mathbf{R}\mathbf{C}^{-1} \quad (2)$$

where $\mathbf{C}^{-1}$ represents the pseudo-inverse of a (3x1600) matrix of tristimulus values, **R** is a (401x1600) matrix of spectral reflectance, and **E** is the (401x3) estimated transformation matrix.

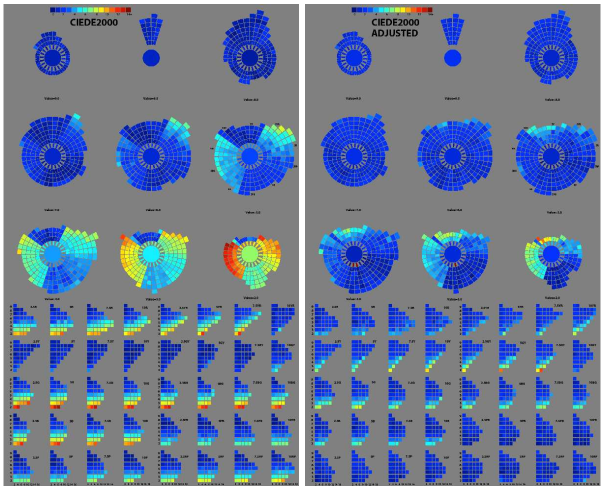

Figure 5 – JMRD color difference (left), Adjusted JMRD color difference (right)

A plot of the **E** matrix is shown in Figure 6. The spectra are quite smooth, particularly at long wavelengths, and represent "pseudo-colorants".

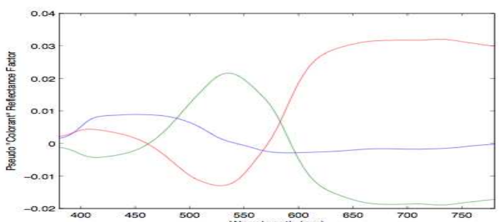

Figure 6 – Pseudo "Colorants" associated with estimation matrix **E** *from Equation 2*

The pseudo-colorants were used to batch correct the measured spectral data for each Munsell chip:

$$\mathbf{r}_{corrected} = \mathbf{r}_{actual} + \mathbf{E}\left(\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{renotation} - \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{actual}\right) \quad (3)$$

where $\mathbf{r}_{corrected}$ is a 401 element column vector representing the corrected spectral reflectance of the Munsell chip, $\mathbf{r}_{actual}$ is a 401 element column vector representing the actual JMSR of the Munsell chip, **E** is the (401x3) matrix derived using Equation 2, $[XYZ]_{renotation}$ is the MRD tristimulus values for the Munsell chip, and $[XYZ]_{actual}$ is the tristimulus values corresponding to $\mathbf{r}_{actual}$.

As can be seen from Equation 3, $\mathbf{r}_{corrected}$ will differ from the $\mathbf{r}_{actual}$ only by the amount that the renotation colorimetry differs from the actual colorimetry. Additionally, since **E** is derived directly from the JMSR data set it is believed that the characteristics of the estimated corrected reflectances will correspond to realistic spectral reflectances. This method is similar to parameric corrections used for determining indices of metamerism.[7]

This is exemplified in Figure 8 with JMSR and corrected spectral reflectance curves for a series of chips with a large variation in JMSR vs MRD colorimetric differences. In this plot curves corresponding to Munsell hue of 5G, chroma of 6 and varying value are depicted. (Note: These colors were picked because they exhibit the largest color differences in Figure 4). Although a single correction factor is not implied by the corrections in Figure 7, the bulk of the corrections have a magnitude of less that 0.05, and the general trends of the spectral reflectances are maintained.

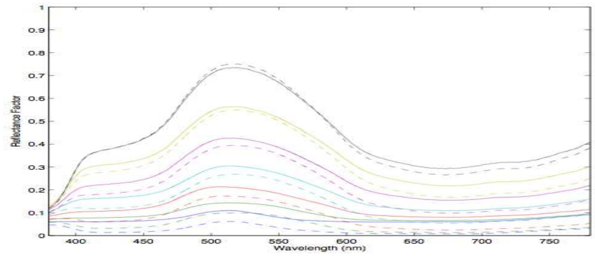

Figure 7 – Spectral reflectance differences between JMSR data (solid) and corrected (dashed) for patches with Munsell hue of 5G and chroma of 6

With corrections to the JMSR data in place we now have spectral reflectances that match the MRD, however the next question one might ask is, "How well do these reflectances maintain the visual spacing of the MBC for sources other than illuminant C?" To answer this question, potential issues of color inconstancy for the corrected JMSR spectral reflectances were analyzed. Figure 8 contains a representation of the Munsell colors under 21 different illuminants (listed in Table 3) chromatically adapted to D50 using CIECAT02.

Each row represents chromatically adapted renderings of the Munsell colors with the same Munsell value for different illuminants. The illuminants used for rendering each column going horizontally from left to right across Figure 8 are given in Table 3.

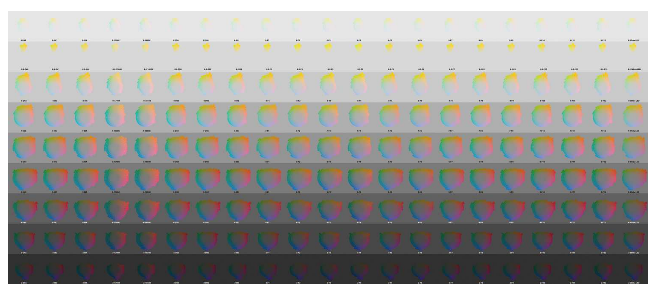

Figure 8 – Adapted Representation of corrected JMSR data under 21 different illuminants

Table 3 – Illuminants used to assess color inconstancy

1. D65	8. Illuminant E	15. F7
2. Illuminant C	9. F1	16. F8
3. Illuminant A	10. F2	17. F9
4. 1700K black body radiator	11. F3	18. F10
5. 1850K black body radiator	12. F4	19. F11
6. D50	13. F5	20. F12
7. D95	14. F6	21. Generic white LED

The normalized spectral power distributions for the illuminants used to render Figure 8 are shown in Figure 9:

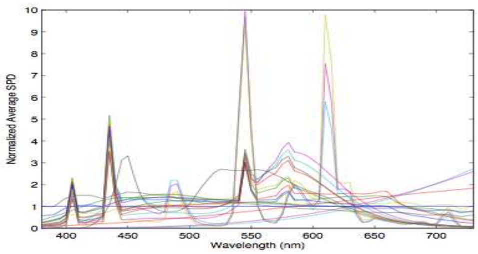

Figure 9 – Normalized spectral power distributions used for calculating CII results

In Figure 10 an index of color inconstancy based on the corrected JSRM (using a CAT02 transform and ΔE_{ab} to calculate the CII) for each color depicted in Figure 8 was calculated (relative to D65) and rendered as a false-color map (with the same false color metric for steps as in Figure 5).

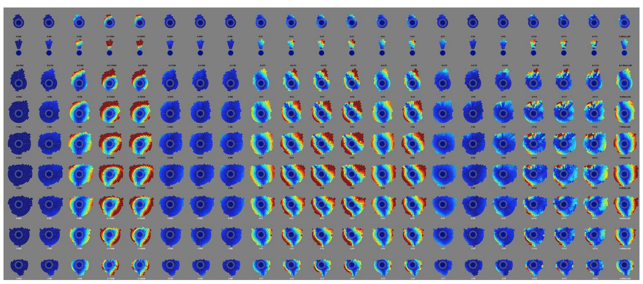

Figure 10 – Color Inconstancy Index calculations for each color in Figure 8

As can be seen from Figure 10 the illuminants that have a lower CCT have the greatest CII factors for high chroma. There is some question as to whether this is an actual aspect of the color inconstancy or a limitation of the CAT used to accurately predict the corresponding color under the illuminant used to calculate color inconstancy.

One area of concern from viewing Figures 8 and 10 is the color inconstancy of the yellow and yellow-green regions. For some light sources (most noticeably F10 through F12) the color inconstancy doesn't have consistent transitions going from chip to chip. An example of this is depicted in Figure 11.

As can be seen in this figure there is significant variability in the apparent hue for the spectral reflectances of the Munsell 7.5 hue page under illuminant F11. Hue variability appears to be associated with variations in the general shape of the spectral reflectance curves. These relative shifts in hue are a result of changes in formulation of the 7.5Y page from this particular edition of the Glossy MBC. This is seen for 7.5Y 8.5/12 where its spectrum is very different from surrounding samples, resulting in an appreciable green caste compared with the other samples.

It is important to note that color constancy is generally not achievable for the MBC under all light sources using real colorants,[8] but if possible, it is desirable to have the relative relationships between the colors remain consistent with one another as their colors shift due to color inconstancy. Since this did not occur, further research is required to see if better reflectances can be found that maintain more consistent relationships between Munsell colors for various changes in illuminant. This is a topic of research currently being investigated.

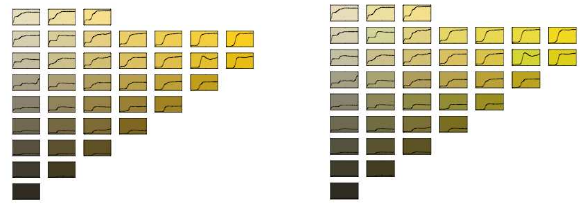

Figure 11 – Appearance comparison of corrected JSRM curves for Munsell 7.5Y hue plane under Illuminant C (left), and F11 (right). Both were chromatically adapted to D65, with curves depicted for each Munsell chip ranging from 380nm to 780nm

Conclusions

The spectral reflectances for the Munsell glossy data found in the Joensuu spectral database were analyzed and compared to the Munsell Renotation data, and discrepancies revealed. Two methods of correcting these differences were implemented: one that compensated for sphere geometry and the second that corrected the spectra using principles of batch correction. The latter method was most successful and from these corrected spectra, analyses performed to evaluate the color inconstancy of the Glossy MBC when viewed under real illuminants quite dissimilar from illuminant C. These analyses revealed that significant improvements are possible in developing a physically-based MBC with improved color inconstancy.

Note

The depicted figures as well as the corrected Munsell glossy spectral reflectances can be found at the following web location: http://www.cis.rit.edu/mcsl/research/CorrectedMunsellData.

References

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