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Individual Differences in Color Matching and Adaptation: Theory and Practice

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Abstract

Individual differences in color matching functions are well known and have recently been well modeled and quantified. The phenomenon even carries a unique name, observer metamerism. However, to date, no research has explored the effects of observer metamerism (or other individual differences in physiological mechanisms) on chromatic adaptation and color appearance. This paper presents a computational study of the effects of observer metamerism on predicted corresponding colors, the result of chromatic adaptation. The ranges of predicted corresponding colors are computed, analyzed and explored. The differences in predicted chromatic adaptation (using a von Kries model) are very significant and could have practical importance. Additionally, a computation of the required precision in psychophysical experiments on chromatic adaptation indicates that the precision required to adequately model individual differences (well less than one CIELAB unit) is an order of magnitude better than that of previously published research on which models such as CIECAM02 are built.

Introduction

Colorimetry is built upon two sets of average color matching functions known as the CIE Standard Colorimetric Observers.[1] The 1931 observer was created using a two-degree visual field and the 1964 observer was created using a ten-degree visual field (excluding the central two-degree area that includes the macular pigment). These two mean functions capture one of the largest physiological variations between observers and field of view, the presence or absence of the yellow macular pigment. These two colorimetric observers have served industry well for many decades and will continue to do so as parts of many important color standards. More recently, the CIE has recognized the need for a more physiologically-based and flexible set of color matching functions and published the CIE 2006 model that allows computation of color matching functions for a continuous range of field sizes from one-degree to ten-degrees and mean observer ages from 20 to 80 years.[2] A selection of eight of these CIE 2006 observers is used in this research. While allowing further useful exploration of observer metamerism with very accurate color matching functions, the CIE 2006 model is limited in that it only predicts mean color matching functions for a given age and field size. It does not allow direct computation or modeling of individual color matching functions.

The desire to measure and model individual color matching functions and their statistical distributions has led to two recent physiologically-based models of color matching that take into account individual variation in more components such as cone pigment optical density and peak absorption wavelength and density of several components of ocular media in addition to age and field size.[3,4] This work shows great promise in allowing individual observers to have customized colorimetry tailored to their own color matching functions and in allowing the prediction of the spread of observer matches for metameric stimuli. However, the availability of individual color matching functions leads one to pose the next-level question: should chromatic adaptation transforms (CATs) also be tailored to individuals? Such tailoring would include optimizing the adaptation transform matrix to perform von Kries scaling on the individual's cone fundamentals as a minimum. At the more extreme end one might consider the need for individual chromatic adaptation transforms that are more complicated than von Kries scaling, or even that differ across individuals. The computational exercise described in this paper begins to explore these issues.

Theory of the Appearance Problem

The theory of the observer metamerism and individual CATs problem is illustrated conceptually in Fig. 1. Each of the panels of Fig. 1 illustrate a set of colors under one illumination (say Ill. A represented by the yellow background) with the theoretically appearance-matched corresponding colors under a second illumination (say Ill. D65 represented by the blue background. The four panels represent four possible scenarios for colorimetry and physiology.

Figure 1(a) shows typical colorimetric practice in which the six physically-identical colors seen by six observers (the six color disks) are seen as identical under the first illuminant because a single set of mean color matching functions. Additionally the corresponding colors for the six disks are also identical because the identical tristimulus values from the first viewing condition (Ill. A) are all transformed to the second viewing condition using the identical CAT (say a simple von Kries transform on average cone fundamentals).

Figure 1(b) illustrates the traditional observer metamerism case. In this situation, each of the six observers sees a slightly different color in the first viewing condition because they have different color matching functions. However the corresponding colors continue to share a similar relationship in the second viewing condition because they are all computed using exactly the same CAT regardless of the individual (represented by one arrow from A to D65.

Figure 1(c) represents the very unlikely scenario where individuals share a single set of color matching functions (or a mean set is used) but have significantly differing CATs. The group of matching color disks under the first illumination are transformed by the various CATs into a disparate set of corresponding colors, one for each observer. It is far more physiologically plausible that the color matching functions differ but the CATs are similar (panel b).

Lastly, Fig. 1(d) illustrates the physiologically most likely (although practically never yet implemented) situation in which each of the six observers have individual color matching functions

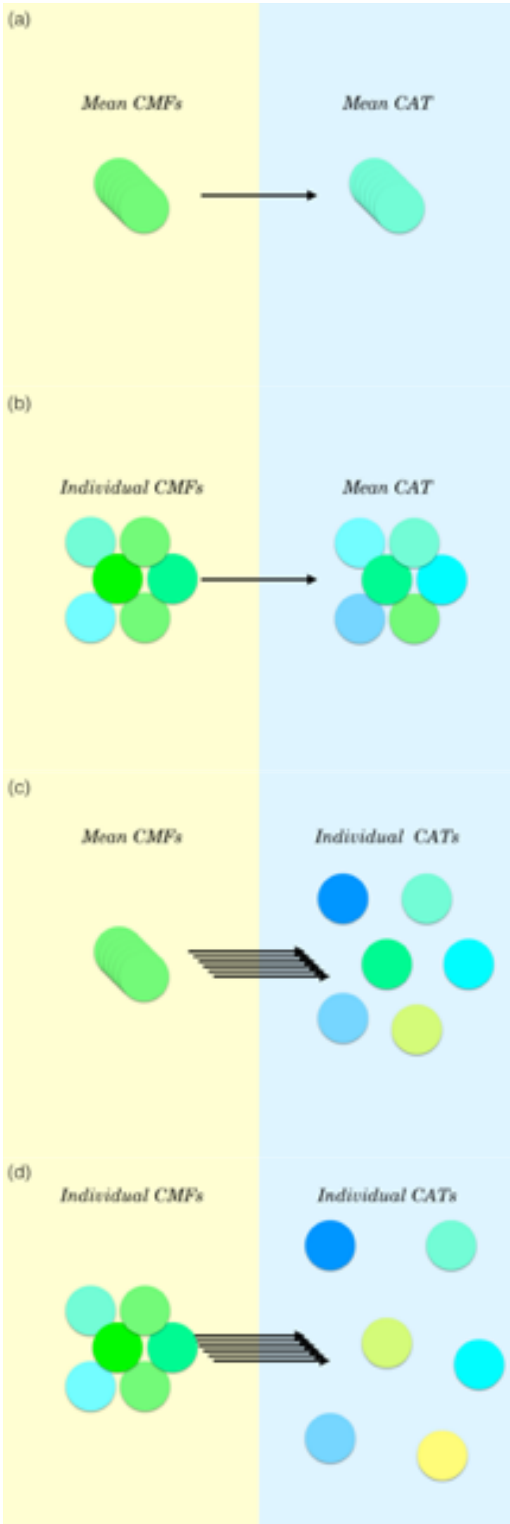

Figure 1. Theoretical representation of individual differences in color matching (CMFs) and chromatic adaptation (CATs). (a) Current prototypical use of mean CMFs and a single average CAT. Predictions do not depend on observer. (b) Colorimetric representation of individual CMFs, but a single average CAT. The observer metamerism prediction. (c) Use of a mean CMF with individualized CATs. Variation introduced by the CATs alone. (d) Likely reality in which there are both individual CMFs and individual CATs further increasing individual variability in color appearance.

(spread under the first viewing condition, Ill. A) and also have individually-disparate CATs resulting in an even wider dispersion of color appearance for the six corresponding colors under the second illumination (D65). Measuring and modeling the existence and magnitude of this likely physiology is the objective that this paper just begins to explore. The ultimate goal is to move colorimetry from the practice represented by Fig. 1(a) to the likely reality represented by the theory of Fig. 1(d).

On the Paucity of Data and Precision

The practice of colorimetry and color appearance modeling has survived intact for nearly a century based on the fact that most of the available psychophysical data on color matching, corresponding colors, and color appearance are extremely noisy and have been collected in a very small number of research efforts utilizing an extremely small number of observers.[5] Color matching functions typically have inter- and intra-observer variability on the order of two percent of their maximum values, corresponding colors data sets have inter-observer variability on the order of 4-6 CIELAB units (and often have no estimate of intra-observer variability doe to single trials per observer),[6] and color appearance scales have uncertainties ranging from seven percent of scale values for hue, to about 10-15 percent for lightness, to over 20 percent for chroma (even larger uncertainties are obtained in brightness, colorfulness, and saturation scaling). Such large uncertainties in the visual data lull users into believing that a small number of mean color matching functions and a simple chromatic adaptation transform (such as CAT02 within CIECAM02) are predicting accurate results when, in reality, the standard of success has only been to make predictions within the spread of the population of observers, not to accurately predict the mean, or individual, results.[5]

Recent work [2-4] that has provided improved and individual color matching functions has clearly shown that gains can be made by using either refined mean color matching functions or individual color matching functions. They have also showed that mathematical modeling approaches together with smaller volumes of high-precision data (small numbers of accurate and precise color matches) can actually produce better results than larger spans of data with poorer precision. Regardless, the signs are available that more precise color matching data, and more of it, are required to fundamentally improve the system. Given that insight, the next question is to examine chromatic adaptation transforms and corresponding colors data. The computational experiment described below attempts to begin to elucidate this question by examining how much changes in individual color matching functions impact predictions of corresponding color with a simple von Kries model in order to determine how precise future experiments will have to be in order to develop an individualized colorimetry and color appearance system.

Simple Computational Experiment

A computational experiment was performed to examine the potential effect of individual color matching functions on the prediction of corresponding colors for a simple change in chromatic adaptation. This section outlines the details of the experiment.

Eight sets of color matching functions were explored. These were all derived using the CIE 2006 model.[2] Observers were created with each possible combination of one- and ten-degree fields of view and ages of 20, 40, 60, and 80 years. While these are mean color matching functions for these ages and field sizes, previous work [3] has illustrated that they roughly span the range of color matching results for a reasonable human population. Figure 2 shows two of the sets of color matching functions at the extremes of this population. The first is an 80 year old observer with a one-degree field of view. This observer includes both an average macular pigment and a high-density lens pushing the functions toward longer wavelengths. The second is a 20 year old observer with a ten-degree field. This observer has no macular pigment and a low density lens and thus the functions are pushed to shorter wavelengths.

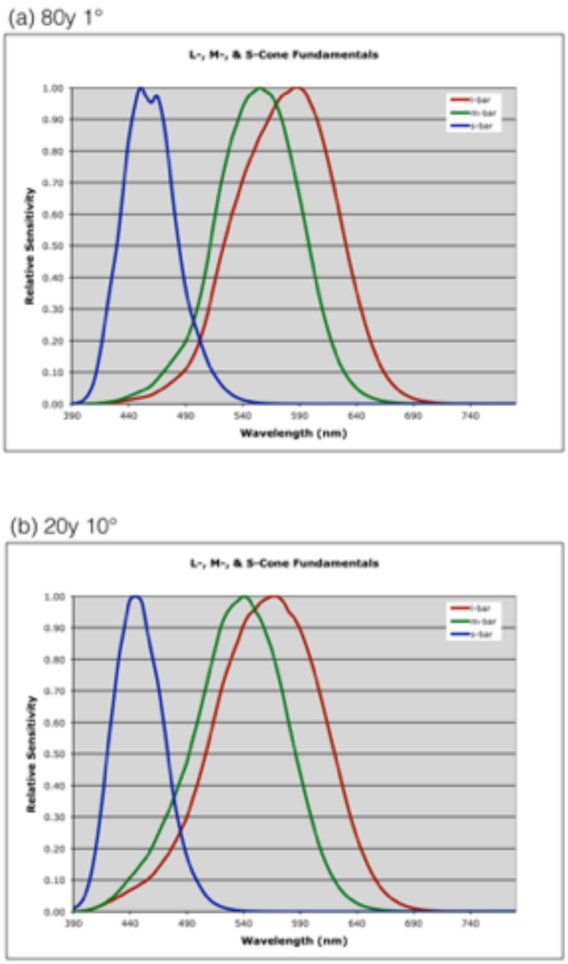

Figure 2. Extreme examples of the CIE 2006 CMFs used in the computational experiment to illustrate the range of differences. Observers were used for 1° and 10° fields of view and ages of 20, 40, 60, and 80 years.

Three reflectance functions of real color samples were used in the computation. These were a muddle gray, an orange, and a purple (flower) samples from the Munsell Color Checker Chart (actual measurements used). Their spectral reflectance factors are illustrated in Fig. 3. The LMS (cone fundamental) tristimulus values were computed for each color sample and each set of color matching functions under CIE Illuminant D65. The LMS tristimulus values for illuminant D65 and illuminant A were also computed assuming the reflectance of a perfect reflecting diffuser.

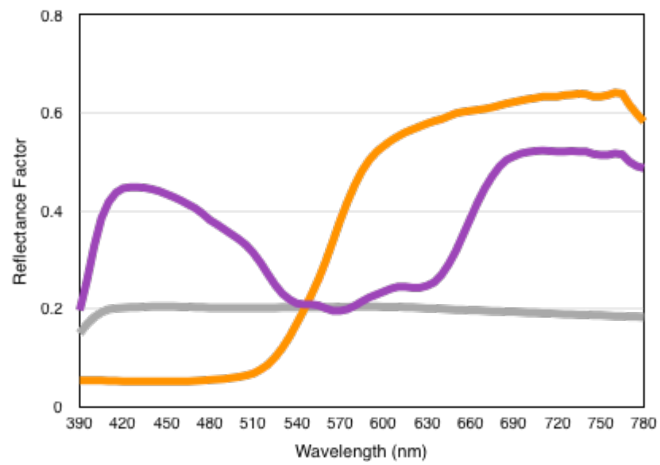

Figure 3. Spectral reflectance factors of the three samples (gray, purple, and orange) used in the computational experiment. Reflectances derived from Munsell Color Checker Chart samples (purple is the “flower” sample).

The chromatic adaptation model examined was a simple von Kries coefficient scaling on the LMS tristimulus values for each observer with complete adaptation to the illuminant.[5] The sample LMS values under D65 were divided by the illuminant values for D65 and then multiplied by the illuminant values for A in order to compute the predicted corresponding colors for illuminant A. Equation 1 illustrates this computation. It does differ, probably in no significant way, from the CAT02 computation. Unfortunately the CAT02 computation is only defined for a single colorimetric observer and could not be used.

$$L_{corresponding} = \frac{L}{L_{D65}} L_A$$
$$M_{corresponding} = \frac{M}{M_{D65}} M_A$$
$$S_{corresponding} = \frac{S}{S_{D65}} S_A \quad (1)$$

The corresponding colors results, in terms of LMS under illuminant A, are plotted in Fig. 4 (M vs. L, S vs. M, and S vs. L). Three general clusters of results can be seen in each plot with two sub-clusters that represent field size). The clusters are most difficult to distinguish on the M vs. L plot. Cursory analysis of the plots shows that the ranges of the corresponding colors data are large enough to almost make orange, purple, and gray samples overlap. Clearly there are significant differences in chromatic adaptation predictions caused by color matching functions alone.

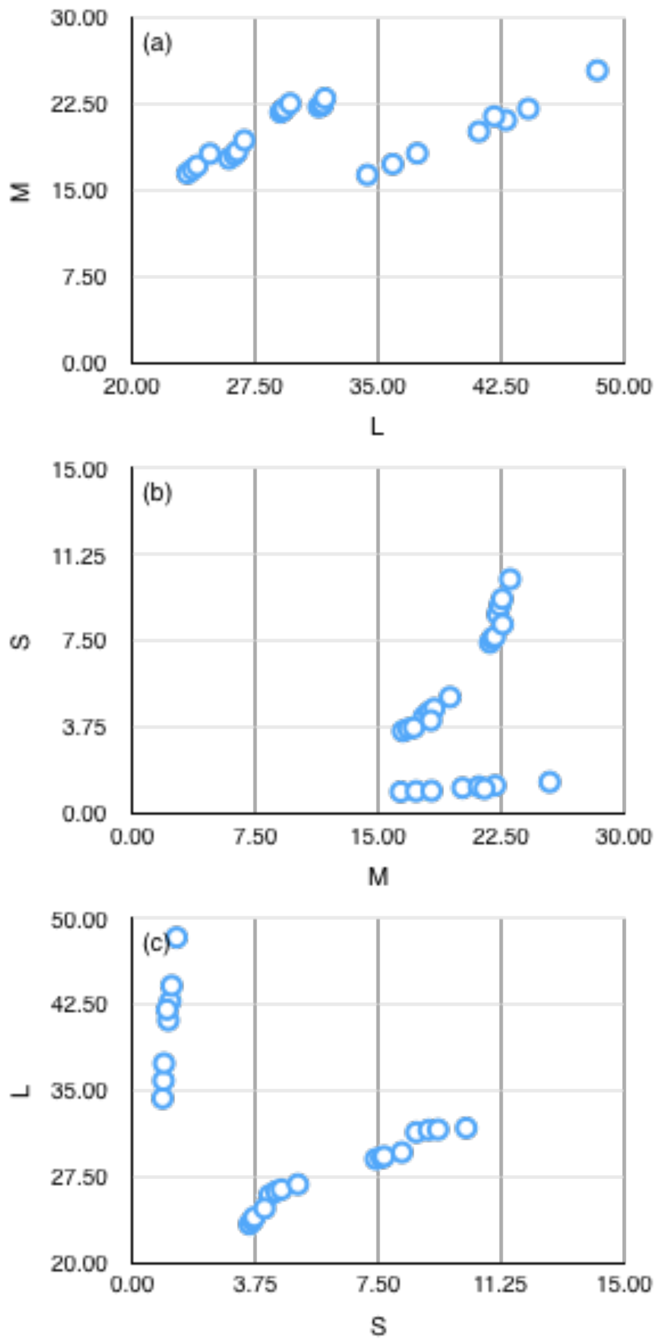

Figure 4. Scatter plots of predicted corresponding colors for the eight observer and three colors in terms of cone fundamental tristimulus values.

Table 1. Statistics for computed Ill. A corresponding colors across the eight computational observers for the gray color. Goal SEM indicates the desired standard error for psychophysical experiments aimed at distinguished between observers. Overall average Goal SEM is 0.88 percent of the tristimulus value.

GRAY	L	M	S
Mean	25.15	17.81	4.15
Std. Dev.	1.37	0.93	0.51
Min.	23.38	16.51	3.58
Max.	26.85	19.38	5.05
25th Percentile	23.90	17.10	3.71
75th Percentile	26.28	18.27	4.44
Percent Std. Dev.	5.43	5.24	12.19
Percent Deviation Min.	7.04	7.28	13.85
Precent Deviation Max.	6.74	8.83	21.72
Goal SEM	0.54	0.52	1.22

Table 2. Statistics for computed Ill. A corresponding colors across the eight computational observers for the purple color. Goal SEM indicates the desired standard error for psychophysical experiments aimed at distinguished between observers. Overall average Goal SEM is 0.88 percent of the tristimulus value.

PURPLE	L	M	S
Mean	30.44	22.35	8.52
Std. Dev.	1.24	0.39	0.97
Min.	29.05	21.82	7.43
Max.	31.76	23.04	10.19
25th Percentile	29.25	22.07	7.66
75th Percentile	31.59	22.57	9.11
Percent Std. Dev.	4.09	1.76	11.34
Percent Deviation Min.	4.55	2.37	12.79
Precent Deviation Max.	4.34	3.11	19.55
Goal SEM	0.41	0.18	1.13

Table 3. Statistics for computed Ill. A corresponding colors across the eight computational observers for the orange color. Goal SEM indicates the desired standard error for psychophysical experiments aimed at distinguished between observers. Overall average Goal SEM is 0.88 percent of the tristimulus value.

ORANGE	L	M	S
Mean	40.77	20.29	1.10
Std. Dev.	4.65	2.94	0.14
Min.	34.34	16.38	0.93
Max.	48.36	25.46	1.36
25th Percentile	37.01	18.02	0.97
75th Percentile	43.13	21.64	1.17
Percent Std. Dev.	11.41	14.50	13.20
Percent Deviation Min.	15.75	19.27	14.87
Precent Deviation Max.	18.62	25.48	23.96
Goal SEM	1.14	1.45	1.32

Tables 1-3, gray, purple, and orange respectively, provides some summary statistics of these results. They begin with the mean and standard deviation of the corresponding colors predictions across the eight observers. Next are the minimum, maximum, 25th, and 75th percentiles of these data. The standard deviations are converted to percent standard deviations (similar to uncertainties in color matching functions) for each of the cone types and then reported along with the minima and maxima of percent deviation for any given observer. Finally, a goal for the standard error of the mean is computed as ten percent of the percent standard deviation. This Goal SEM can be used to guide a desired precision for psychophysical experiments in order to reliably discriminate chromatic adaptation adaptation results across a population of observers. When the goal SEM is averaged across all three colors and cone fundamentals a value of 0.88 percent is obtained. This suggests that corresponding colors experiments should aim to have an uncertainty in the mean values better than one percent of the values themselves. This is far better than typical corresponding colors experiments (but can be obtained) and even better than most color matching experiments.

Finally, table 4 includes an analysis of the above results in terms of CIELAB units. This is a difficult representation to complete since there is no one defined transformation from individual cone fundamentals to XYZ tristimulus values and then to CIELAB. An approximation was accomplished by taking the percentage magnitude of one standard deviation (on average) in LMS cone fundamentals and applying that to the XYZ tristimulus values (which are on the same scale and should have similar percent standard deviations) for each color. A CIELAB color difference was then computed between the mean corresponding color (Ill. A) and a color one standard deviation away in each tristimulus value. These color differences are reported in the first row of table 4. The second row contains aim color differences for experimental precision (essentially goal standard errors of the mean expressed in color difference terms) for each of the colors. These range from 0.29 for gray (typically an accurate/precise corresponding color) to just over 0.5 for both orange and purple. Averaging the three values provides an overall goal for uncertainty in individual corresponding colors measurements of about 0.4 CIELAB units. This is about an order of magnitude better than experiments reported to date and necessary to significantly improve chromatic adaptation and color appearance models.

Table 4. Computed CIELAB color differences between mean corresponding color for all observers and a plus-one-standard-deviation color. Ten percent of that difference is taken to be the goal for standard error o the mean in psychophysical experiments aimed at measuring individual differences in chromatic adaptation. The overall mean goal of 0.4 CIELAB units is approximately an order of magnitude greater precision than published corresponding colors experiments to date.

	Gray	Purple	Orange
ΔE*	2.87	5.36	5.08
0.1 ΔE*	0.29	0.54	0.51
Overal Goal	0.4		

Conclusions

With the establishment of the high precision needed to evaluate individual chromatic adaptation transforms together with individual color matching functions, it is reasonable to ask if the design of experiments with such performance is feasible. Future work will be aiming to do just that, but preliminary results (submitted for publication) indicate that an uncertainty on the order of 0.5 CIELAB units can be obtained for carefully designed experiments with large numbers of replications. There is reason to hope this can be achieved.

The big need, as it has always been, is for more experimental data on both metameric color matching and corresponding colors (and then ultimately color appearance scales). Such data need to include more colors, more viewing conditions, more observers, and more replications. Given that this paucity of data has been a long standing problem in the field of color science, one can speculate on whether the desire, or need, for more accurate colorimetric models exists. Time will tell.

Lastly, remains a need for detailed theory of color matching functions, chromatic adaptation transforms, and color appearance scales that can keep pace with improved data should it become available. This part can be tackled by the students of color science (of all ages and station) whether or not data become available. However, data will make it better.

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