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The threshold of color inconstancy

Che Shen, Mark D. Fairchild; Rochester Institute of technology; Rochester, New York

Abstract

Color inconstancy refers to significant changes in the perceived color of an object across two or more different lighting conditions, such as daylight and incandescent light. This research focusses on defining the threshold of color inconstancy between generated D65 and A illumination through a psychophysical experiment. Although modern color appearance models provide equations to calculate the degree of adaptation, a neutral grey match experiment was completed to produce a more accurate D values for the experimental viewing conditions. Like setting an instrumental color tolerance experiment, a second, sorting, experiment was used to define the threshold of color inconstancy. This threshold is the color shift, expressed in color difference terms, required for observers to notice a color change across changes in illumination. In addition, the tolerance ellipsoid for each Munsell principal hue group was also established.

Introduction

Color inconstancy, a widespread effect, is a feature of the human visual system that the perceived color of object normally changes somewhat different under varying illumination conditions. As early as the 19th century, Claude Monet, a pioneer of French Impressionist painting, had noticed that the objects show different colors under changing weather. His works, Stacks of Wheat, showed this color inconstancy phenomenon very well. In the jewelry industry, gemstones with color inconsistency effect (also known as alexandrite effect) are very precious. A famous kind of gemstone with color inconstancy effect is named alexandrite. This color inconstancy effect in gemstones was discovered in Cr-bearing chrysoberyl from the Ural Mountains in the 19th century. This unique gemstone is green under daylight while exhibiting a reddish color under incandescent light (White 1967; Gübelin and Schmetzer 1982). Therefore, the alexandrite effect is used to describe this tremendous color inconstancy or color change phenomenon.

As a matter of fact, except for nonselective reflectance grey materials under conditions of complete chromatic adaptation, most materials show color inconstancy because the lighting condition has changed (Wright 1981). Fairchild (2013) also explained that literal color constancy doesn't exist in humans as was understood at least as far back as Helmholtz. However, people sometimes don't perceive color inconstancy in real viewing conditions. This is because that the human visual system has the ability to adjust to the varying illumination in order to approximately preserve the appearance of object colors (chromatic adaptation and discounting the illuminant). Brady et al. (2013) also suggested that due to our poor color memory, we may not recognize the color change at some point. Hence, the threshold of color inconstancy is important to be able to define whether the perceived color is changed or not.

In order to obtain meaningful tristimulus values under specific lighting condition, a chromatic adaptation transformation should be used. The chromatic adaptation transform (CAT), one of the most important parts of color appearance models, is the function that helps to predict the color appearance under different lighting conditions. Now, the most widely used CAT models are CAT02, which is embedded in CIECAM02 (Fairchild 2013) and CAT16, which embedded in CAM16 (Li et al. 2017). Chromatic adaptation is not always complete. It will be less complete as the saturation of adapting stimulus increases and more complete as the luminance of the adapting stimulus increases (Fairchild 1991). In CAT02 and CAT16, the degree of adaption (D) is the factor to represent how complete the adaptation is. When the D value equals 1, it indicates that the chromatic adaptation is complete and when D the value equals 0, it means no adaptation. There is a specific equation in CAT02 and CAT 16 to calculate D values. However, this equation only depends on the luminance of adapting field and surround induction factor. Some important factors are not taken into consideration like chromaticity of illuminants (Zhai and Luo, 2018). Hence, the accurate D value for a specific lighting condition is significantly important in this study.

Besides the D value in CAT models, the color inconstancy index is also crucial in this research. The color inconstancy index is the metric that defines the degree of the color inconstancy. Normally, the higher the color inconstancy index value, the more prominent the color inconstancy effect can be perceived. Berns and Billmeyer (1983) proposed a color inconstancy index by using a more accurate CAT to transform the tristimulus values from any illuminant to D65 along with CIELAB color differences. Luo et al. (2003) suggested using CMCCON02 as the index of color inconsistency. Berns (2019) also recommended to use ΔH_{00} or ΔH_{ucd} as a color inconstancy index because a total color difference, like CIEDE2000, is a measure of magnitude but not direction. Consequently, in this research, we selected two color inconstancy indexes (CIEDE2000 and ΔH_{ucd}) to define the threshold of color inconstancy, both with an optimized CAT.

In this study, we designed two experiments. The one was the neutral grey match experiment under two illuminants (D65 and A). The aim of the first experiment was to obtain the accurate D values. The other experiment was the color inconstancy tolerance experiment. In the second experiment, observers were required to sort many samples under specific lighting condition (either D65 or A) into two piles (acceptable matches and not acceptable). This experiment was designed for calculating the threshold of color inconstancy.

Experiment 1

275 Near-grey patches with 11 lightness values (L^* = 25-75 at 5 unit intervals, which helps to cover the most of lightness levels) were selected for the neutral grey match experiment. These near-grey patches were custom printed on Miller's professional imaging deep matte paper by a professional photographic service (Mpix). For each printed page, 25 different near-grey patches with same lightness value were randomly distributed. The GretagMacbeth Coloreye 7000a spectrophotometer with de:8° measurement method was used for reflectance measurement of these patches (see figure 1). These colors were calculated based on D65 lighting condition and plotted in u'v' uniform-chromaticity scale diagram (see figure 2). Two lighting conditions, approximations of CIE Illuminants D65 and A, were generated by ETC lighting system (see lighting condition section for detail explanation) and three luminance levels (100,200 and 350cd/m2) were used for the visual match experiment.

There are four participants who completed this experiment. One observer (observer 1) participated in the experiment under three luminance levels and the other three observers took part in this experiment under only one luminance level (200cd/m2).

Firstly, the observers adapted the D65 for 2min for steady-state adaptation (Fairchild 1995). After 2min adaptation, the observers needed to select the one perfect neutral grey patch from each page of 25 samples. Next, the observer re-adapted for illuminant A for 2min and then selected the neutral grey sample again.

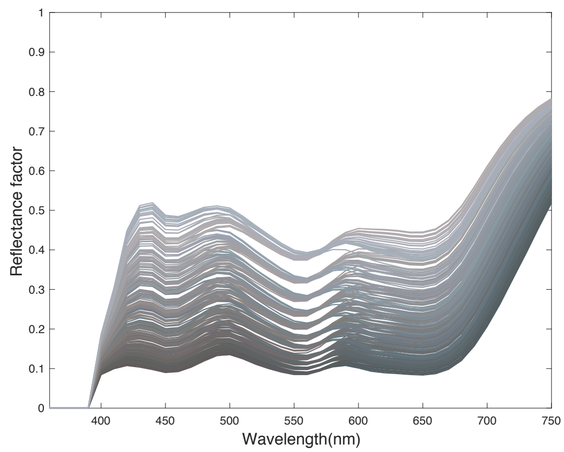

Figure 1. Spectral reflectance factor of 275 near grey patches.

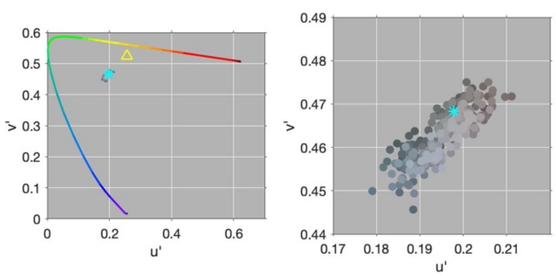

Figure 2. 275 near grey colors are plotted in u'v' uniform-chromaticity scale diagram. The cyan star in the figure represents the chromaticity value of the D65 while the yellow triangle represents the chromaticity value of illuminant A.

Lighting condition

Seven channel ETC LED lighting systems were used to generate two lighting condition in order to simulate the D65 and illuminant A respectively (Yuan et al. 2021). However, it is impossible to generate exactly the same spectral power distributions (SPD) as D65 and A based on this lighting system. Therefore, by using the MATLAB fmincon optimization function, two SPDs were created with correlated color temperature (CCT) the same as D65 and A respectively. We also minimized the error function (RMS spectral error) between generated SPDs and aimed SPDs (D65 and illuminant A) at the same time. Figure 3 and 4 show the SPDs of two generated light sources. The color vector graphics were from TM-30 standard calculator. The higher Rf and Rg values indicate that the two generated light conditions are both appropriate for this experiment.

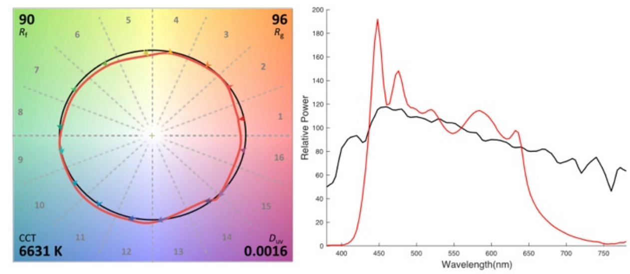

Figure 3. Left: The color vector graphic of generated SPD (near 6500K). Right:The SPD of generated light source (red line) and D65 (black line).

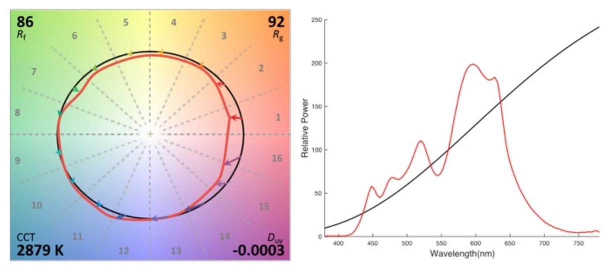

Figure 4. Left: The color vector graphic of generated SPD (near 2856K). Right:The SPD of generated light source (red line) and illuminant A (black line).

Neutral grey patch experiment

The neutral grey is important color for color science research and applications. A typical example is the gray card, which is used for correcting white balance in photography. In this experiment, the selected neutral grey colors were designed for calculating the D value. The D value could be simply calculated between the distance from chromatic value of selected neural grey to reference point (D1) and chromatic value of adapting stimulus of light source to reference point (D2) on the u'v' chromaticity diagram. In CIECAM02 and CAM16, equal-energy (EE) illuminant is selected for reference point. However, recent experiment results from Fairchild (2020) suggested that sky blue at 15000K is more physiologically plausible than commonly used EE or D65. Our experiment results also exhibited the line segment connecting the adapting stimulus to the neutral grey project toward sky blue 15000K, rather than D65 or EE (see figure 5). Therefore, in this research, the chromatic value at 15000K was chosen as the reference point.

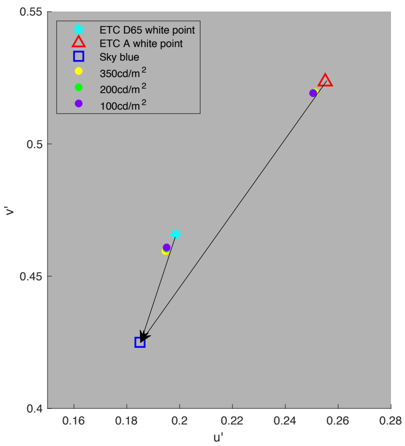

Figure 5. Results of neutral grey appearance (average value) under 300cd/m2 (yellow dot), 200cd/m2 (green dot) and 100cd/m2 (purple dot) from observer 1. The cyan star represented the adapting stimulus of ETC_D65, the red triangle represented the adapting stimulus of ETC_A and the blue square represented the sky blue (15000K). Black lines represent projections to reference point from each adapting chromaticity.

D value calculation

As discussed in the Neutral grey patch experiment section, the D value could be simply calculated based on distance. Therefore, observer 1's data were used to calculate the D value under different luminance levels (see table 1). Moreover, we also would like to know if there is any relationship between the D value and the object's lightness. The D values of two lighting condition with different lightness are shown on figures 6 and 7. Error bars in figures 6 and 7 represent the 95% confidence interval of the visual data. From the figure 6 and 7, no obvious relationship of D value with lightness value was found. Hence, we suggested to use the average D value to represent the degree of adaptation for specifical luminance level.

What is surprising is that the D value of D65 lighting condition under three luminance level doesn't follow the rules from widely used color appearance models (CAM02 or CAM16). It can be seen from the results of D65 light that when the adapting luminance increased, the D value decreased. In addition, the D value from illuminant A is all the same under three adapting luminance level. However, In CAM02 or CAM16, when the adapting luminance increased, the D value should also increase. There might be two possible reasons to explain that difference. One reason is that our results were only based on one observer and the other reason is that the reference point in CAM02 or CAM16 was equal-energy illuminant but not sky blue. In this research, the goal was not to find the relationship between D factor and adapting luminance level. Instead, the aim is to get this accurate D value for use in experiment 2. Table 2 showed the D value under 200 cd/m^2 from other three observers.

Table 1. Average D value of the two lighting conditions under three different luminance levels

	D65	A
350cd/m2	0.84	0.95
200cd/m2	0.86	0.95
100cd/m2	0.87	0.95

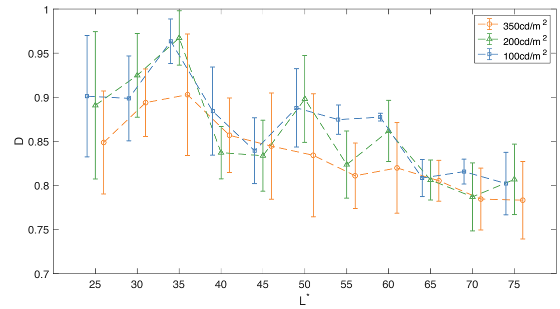

Figure 6. The D value of generated D65 lighting condition under three different luminance level (orange line:350cd/m^2, green line: 200 cd/m^2 and blue line:100cd/m^2).

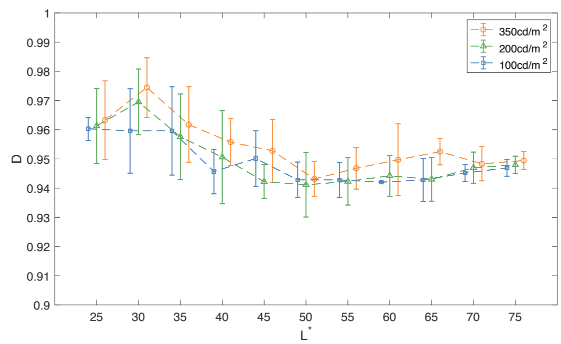

Figure 7. The D value of generated Illuminant A under three different luminance level (orange line:350cd/m2, green line: 200 cd/m2 and blue line:100cd/m2).

Table 2. Average D value of two lighting condition under 200 cd/m^2.

	D65	A
observer 2	0.80	0.98
observer 3	0.65	0.92
observer 4	0.76	0.96

Experiment 2

In experiment 2, we selected five Munsell principal hues (5P 5/6, 5R 5/6, 5Y 5/6,5G 5/6, 5B 5/6) as reference colors. For each reference color, we also created 200 color patches as test color. The color difference values (CIEDE2000) between reference color and 200 color patches are randomly distributed between 2-20. These colors (both reference and test) were created digitally and printed photographically (also from Mpix by using Ultra-thick matte paper). The X-rite Model SP62V spectrophotometer with de:8° measurement method was used for reflectance measurement of all printed color patches (see figure 8). The CIELAB values of these color patches are plotted in figure 9.

Firstly, the observers adapted to the generated D65 light for 2min and remembered the color appearance of reference color. Next, the observers adapted to generated incandescent light for 2min. After fully adapting to incandescent light, the observers were required to sort the test samples into two piles. One pile is acceptable matches (apparent color constancy) to what they saw under D65 light and the other pile is not acceptable matches (apparent color inconstancy). One thing should be mentioned is that two observers (observer 1 and 3) participated this experiment under 200cd/m2. Therefore, based on the results from table 1 and table 2, the D value of D65 is 0.86 for observer 1 and 0.65 for observer 3 while the D value of illuminant A is 0.95 for observer 1 and 0.92 for observer 3.

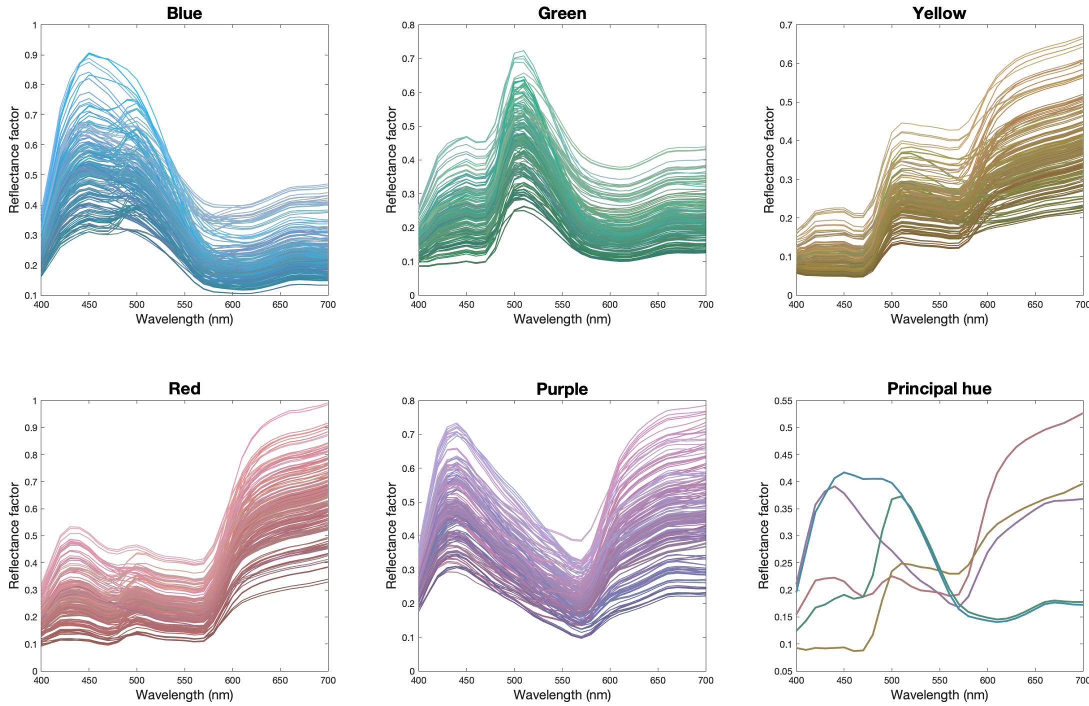

Figure 8. Reflectance spectra of 1000 test colors (Blue, Green, Yellow, Red and Purple) and 5 reference colors (Principal hue).

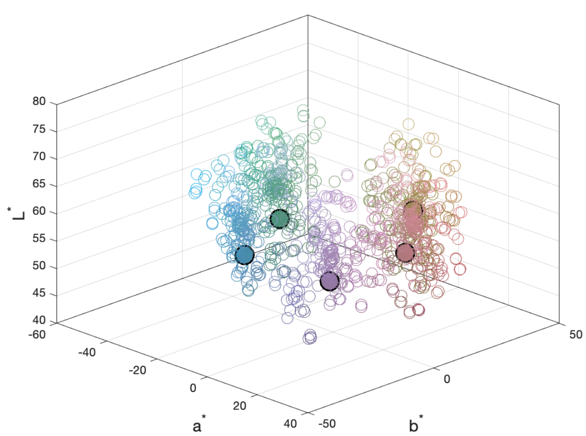

Figure 9. CIELAB data of the reference colors (filled color circle with black edge) and test colors (hollow circle).

Sorting experiment

Basically, the sorting experiment is similar to an experiment for setting an instrumental color tolerance experiment except with a change of illumination in between. The method of setting an instrumental color tolerance from instrumental and visual historical data was explained in detail by Berns (2019).

In our sorting experiment, firstly, the chromatic adaptation transformation was used to get more accurate colorimetric data. The procedures are as follow:

Calculate tristimulus value for the adapting white using Eq. (1). Where T represents the color matching function and S represents the spectral power distribution of light source

$$\begin{pmatrix} X_w \\ Y_w \\ Z_w \end{pmatrix} = TS \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} \quad (1)$$

Transform the tristimulus values from step 1 as well as tristimulus values of all color patches (both test and reference colors) to pseudo-cone fundamentals using Eq. (2).

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = M_{CAT16} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad (2)$$

Calculate the adapted tristimulus response by using the von Kries transformation with accurate D value from our first experiment.

$$R_c = \left[\left(100 \frac{D}{R_w} \right) + (1 - D) \right] R \quad (3)$$

$$G_c = \left[\left(100 \frac{D}{G_w} \right) + (1 - D) \right] G \quad (4)$$

$$B_c = \left[\left(100\frac{D}{B_w}\right) + (1-D)\right]B \quad (5)$$

Calculate corresponding tristimulus values by using Eq. (6).

$$\begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} = M_{CAT16}^{-1}\begin{pmatrix} R_c \\ G_c \\ B_c \end{pmatrix} \quad (6)$$

Next, it is important for us to choose a metric to exhibit color inconstancy effect. Technically, the higher the metric value, the more prominent the color inconstancy perceived. In this sorting experiment, two different metrics, CIEDE2000 (Luo et al ,2000) and ΔHucd (Berns, 2019) were examined as color inconstancy indices.

Finally, the samples were sorted in pass and fail based on the psychophysical experiment. Cumulative percentages were calculated for each group of reference color (see figure 10). Simply, the threshold of color inconstancy can be defined as the intersection of two lines (pass line and fail line in figure 10). For these data, the intersection value could minimize the number of wrong decisions. These threshold values with two different color inconstancy indexes are shown on table3.

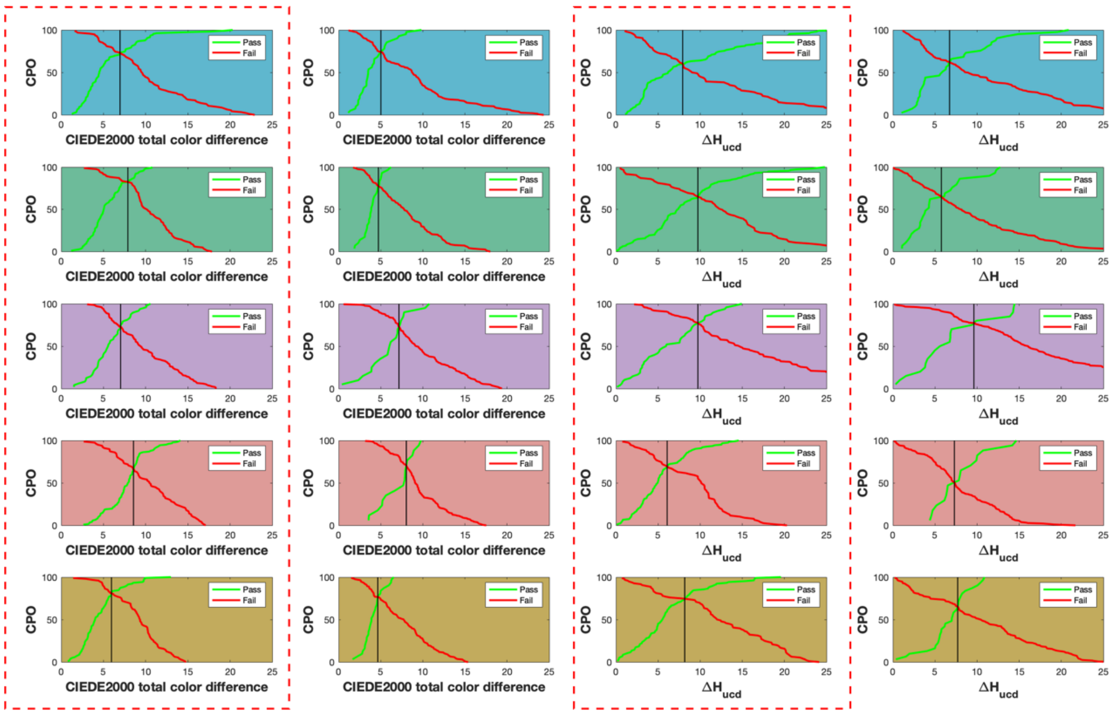

Figure 10. Cumulative percentage of pass and fail samples along with each principal hue group's color inconstancy index (CIEDE2000 and ΔHucd) without adaptation. The background color of each subplot represents different hue group (blue, green, purple, red and yellow). The CPO on y-label means cumulative percentage of observations. The intersection of the two lines defines the threshold of color inconstancy that minimizes wrong decisions. The results of observer 1 are shown on column 1 and 3 (red dotted box) while the other two columns represent the data from observer 3.

Table 3. The threshold of color inconstancy for five principal hues

	Blue	Green	Purple	Red	Yellow
CIEDE2000 (observer1)	6.96	7.89	7.03	8.56	5.94
CIEDE2000 (observer3)	5.02	4.73	7.17	8.04	4.65
ΔH_{ucd} (observer1)	7.92	9.73	9.73	6.08	8.16
ΔH_{ucd} (observer3)	6.73	5.76	9.62	7.30	7.70

Tolerance ellipsoids

Tzeng and Berns (2005) suggested that the coefficients of the variance-covariance matrix are recommended to build an ellipsoid about the mean data. In this section, CIEDE2000 as well as ΔHucd color constancy tolerance ellipsoids were built (with 99% confidence interval) from selected passing CIELAB values and plotted in Figure 11. The tolerance values were based on the threshold of color inconstancy values shown in table 3. Overall, these ellipsoids perform well because most of passed samples were within the tolerance ellipsoid while most of failed samples were outside the tolerance ellipsoid.

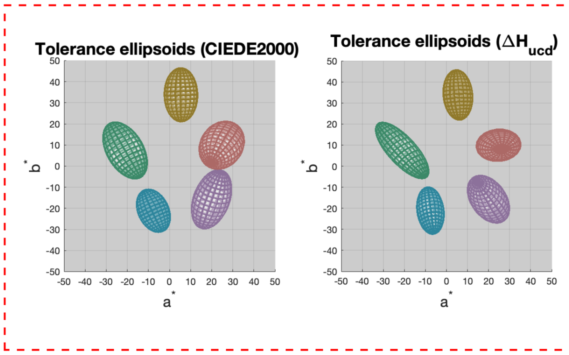

Figure11. The color constancy tolerance ellipsoids generated from CIEDE2000 and ΔHucd. The results of observer 1 are shown on column 1 and 2 (red dotted box) while the other columns represent the data from observer 3.

Without adaptation

Now, let's take a step back and rethink the definition of color inconstancy again. Color constancy can be considered the general tendency of the color of an object to remain approximately constant when the level of the illumination is changed (ASTM 2013). Therefore, when the light condition changes, the color of the object doesn't remain constant. Normally, if viewing a color inconstant object, the observer will perceive the color change once the illumination is changed. There is no time for observer to adapt to the light source. In the above experiments, observers were required to make a choice after fully adapting to the light source. However, in real viewing condition, people often make decision by flipping the lights back and forth. Based on the characteristic of judging color inconstancy phenomenon, another set of experiments (both selecting neutral grey and sorting experiment) was completed without adaptation.

The average D values of two illumination without adaptation (200cd/m2) are listed in table 4. Again, the observer 1&3 were selected to do the sorting experiment without adaptation. As mentioned above, the threshold values are derived from the intersection of two lines. These threshold values are shown on table5.

Color constancy tolerance ellipsoids (figure 12) were also built based on the threshold values from table 5. Based on the results, however, there is no significant difference between adaptation and no adaptation. More observers' data should be collected in the future work.

Table 4. Average D value of the two illuminations without adaptation (200 cd/m^2).

	D65	A
observer 1	0.89	0.93
observer 2	0.83	0.96
observer 3	0.68	0.93
observer 4	0.84	0.94

Table 5. The threshold of color inconstancy for five principal hues (without adaptation)

	Blue	Green	Purple	Red	Yellow
CIEDE2000 (observer1)	4.55	5.17	7.65	8.32	4.60
CIEDE2000 (observer3)	5.31	4.80	7.71	8.18	5.54
ΔH_{ucd} (observer1)	4.43	7.78	9.73	5.59	5.70
ΔH_{ucd} (observer3)	7.58	6.33	10.01	6.67	4.88

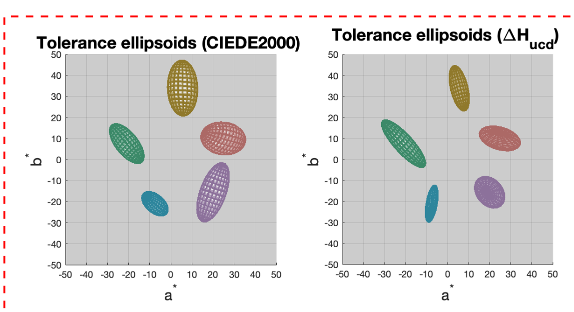

Figure12. The color constancy tolerance ellipsoids (without adaptation) generated from CIEDE2000 and ΔHucd. The results of observer 1 are shown on column 1 and 2 (red dotted box) while the other columns represent the data from observer 3.

Conclusions

By using a neutral grey matching experiment, this study identified the accurate D values for the experimental viewing conditions. In summary, Table 3 and 5 provided the threshold of color inconstancy for each principal hue. Moreover, the color constancy tolerance ellipsoids based on two different color inconstancy indexes (CIEDE2000 and ΔHucd) were also established. The results of these ellipsoids indicate that the color, compared to reference color, can be perceived as constant when perceived CIELAB value is within the ellipsoid. In addition, this research is also consistent with the results from Fairchild (1990)'s previous work that color inconstancy happens when changing illumination causes an object to shift from one color category to another. In other words, the threshold for color inconstancy is large and color memory is often poor.

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Author Biographies

Che Shen received his BS in Gem and Material Engineering from Hebei GEO University (2016) and his MS in Gemology from China University of Geosciences (2019). He is currently a Ph.D. student in the Munsell Color Science Laboratory at Rochester Institute of Technology majoring in Color Science.

Mark D. Fairchild is a Professor at Rochester Institute of Technology and Director of the Program of Color Science and Munsell Color Science Laboratory. He received his B.S./M.S. degrees in Imaging Science from Rochester Institute of Technology and his M.A./Ph.D. degrees in Vision Science from the University of Rochester. He is a Fellow of IS&T and OSA.