D-CIELAB: A Color Metric For Dichromatic Observers

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Abstract
A color metric for dichromatic subjects is proposed and evaluated empirically. The color metric extends the widely used CIELAB color difference metric, an international standard for trichromatic observers. The dichromatic extension (D-CIELAB) is implemented by specifying a linear transformation that maps the two types of cone absorptions in dichromats to the three types of cone absorptions in trichromats and then applies the standard CIELAB color metric to these values. The linear mapping is derived from between-eye color-matches of observers who are dichromatic in one eye and trichromatic in the other eye. We evaluate the accuracy of the D-CIELAB metric by predicting and measuring color discrimination thresholds for two dichromatic observers.

Keywords
Dichromatic Color Metric; CIELab; ΔEab; Psychophysics

1. Introduction
The CIELAB color difference metric is an international standard for a trichromatic observer that is based on the Euclidean distance between two colors in CIELAB space. The metric is often used in industry contracts to specify the minimum visible difference (expressed in units of ΔE_{ab}) that is acceptable for color reproductions. In this paper, we describe how to extend the CIELAB color difference metric to dichromatic observers (D-CIELAB). The extension is based on a linear transformation that maps the two types of cone absorptions in dichromats into the three types of cone absorptions in trichromats. Following this mapping we apply the standard CIELAB color difference metric to quantify the visible difference between colors for dichromatic observers.

We consider a variety of 2D to 3D mappings. Brettell et al [1] introduced a piecewise linear mapping that is derived from between-eye color-matches of observers who are dichromatic in one eye and trichromatic in the other eye [2-4]. In a separate paper [5] we provide a theoretical explanation for the color matches made by these unilateral dichromatic observers and derive a single linear transform for the dichromatic to trichromatic representation. We show that the transform is similar to the empirical mapping described by Brettell et al [1]. In this paper, we use the dichromatic color transform to map the two types of cone absorptions in dichromats into the three types of cone absorptions in trichromats. We then use the standard CIELAB color difference metric to predict the visibility of color differences for dichromatic observers. Finally, we test the accuracy of these predictions using psychophysical measurements on dichromatic and trichromatic subjects.

2. The D-CIELAB Color Transform
Dichromats possess two of the three different types of cones. For each type of dichromat, we derived a theoretical transformation that interpolates a value for the missing cone type from by a linear combination of the values of the existing cones. The motivation for this transformation is provided in [5]. For protanopes, the missing values for L cones can be estimated as $L= 1.3855M - 0.285S$. Similarly, missing M (deuteranopes) and S (tritanopes) cone values can be estimated as $M=0.6949L + 0.2614S$ and $S=-0.9623L + 1.7595M$ respectively.

Based on these equations, when a dichromat is shown a stimulus with cone absorptions (C1, C2), we can predict the equivalent cone absorptions in a trichromat (C1, C2, C3), where C3 = L(C1,C2). We tested the accuracy of the dichromatic linear transform by analyzing whether color discrimination thresholds for dichromats shown stimuli (C1, C2) and (C1', C2') matched the color discrimination thresholds of trichromats for the transformed stimuli (C1, C2, C3) and (C1', C2', C3').

3. Experimental Methods

3.1. Participants
Two male dichromats (one protanope, one deuteranope) and two trichromats (one male and one female) took part in the experiments. The color vision deficit in each dichromat was confirmed by genetic diagnostic tests performed by Maureen Neitz [6].

3.2. Apparatus
The experimental stimuli were controlled using the Psychtoolbox extensions [7-9] and color depth was boosted to 14 bits by the Cambridge Bits++ Stimulus Processor. A calibrated NEC CRT display was used to present the stimuli.

3.3. Experiment Tasks
Color discrimination thresholds were obtained using a two-alternative spatial forced-choice (2AFC) method (Figure 1a). A fixation point was always visible in the middle of the screen, which comprised a constant achromatic background (56 cd/m2). The test was briefly presented (500 ms) either 1-degree above or below the fixation point. After each stimulus presentation, the subject indicated if the color stimulus occurred above or below the fixation point.

The color test stimuli were square patches that subtended a visual angle of 3 degrees. To remove visible edges and reduce the effects of chromatic aberration, the patches were convolved using a Gaussian window. We provided auditory feedback to indicate whether their response was correct or incorrect.

The color test stimuli sampled 12 different directions in LMS (cone) color space. The directions swept out the relevant directions for the deuteranope (Figure 1b) or protanope (Figure 1c). Discrimination thresholds for each color direction were obtained using a staircase procedure that kept performance near 80% correct.

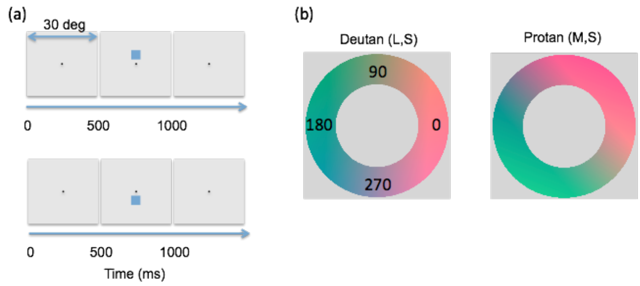

Figure 1. (a) The two alternative spatial forced-choice detection task. The 3-degree test stimulus was presented on a 56 cd/m2 achromatic background with a small fixation dot. The test was presented for 500 milliseconds, and its center was 2.5 degree above or below the fixation. (b) The color appearance and angular directions of the test stimuli in cone space are shown. The range of color stimuli for the dichromatic subjects swept out all directions in their cone space: (L, S) for the deuteranope and (M, S) for the protanope.

For each color direction, the appropriate color transform was applied to the stimuli and 2AFC discrimination measurements were carried out with two trichromatic observers. The 12 directions evaluated for protanopes were in the MS plane, since these subjects are blind to changes in the L plane. Similarly, the 12 were in the LS plane (M=0) for deuteranopes and in the ML plane (S=0) for tritanopes. Of course, the 12 transformed color directions for trichromats reside within a plane in the 3D LMS space.

If the D-CIELAB prediction is correct, the discrimination probabilities of the dichromat and trichromat should be the same on the corresponding stimuli. Therefore, to assess the quality of the D-CIELAB metric we compared the discrimination performance of the dichromats to the discrimination performance of the trichromats on these stimuli.

4. Results

Figure 2 plots discrimination probability as a function of the ΔE_{ab} color difference. These values are computed in the usual way for the trichromats and computed using D-CIELAB for the dichromats. The data for the deuteranope is shown in green and the data for the two trichromatic observers is shown in gray. The circle radii are proportional to the number of trials (stimuli with fewer than 3 trials are not shown). The solid line corresponds to the best-fitting Weibull psychometric curve. The performance of the deuteranopic observer is similar to the trichromatic observers as predicted by D-CIELAB.

Results for the protanopic observer are shown in Figure 3. In this case there are deviations between the protanope and one of the trichromats.

The scatter plots in Figure 4ab compare the ΔE_{ab} values of the stimuli that are correctly detected 80% of the time for the dichromats and the trichromats. Each point compares the ΔE_{ab} value for one color direction. Were the D-CIELAB predictions perfect, the points would fall on the dotted identity line. For the deuteranope the points fall close to this line. For the protanope the points fall near the identity line when compared with one of the trichromats but not the other. Note that the two trichromats differ from one another by about 0.5 to 1 ΔE_{ab} unit.

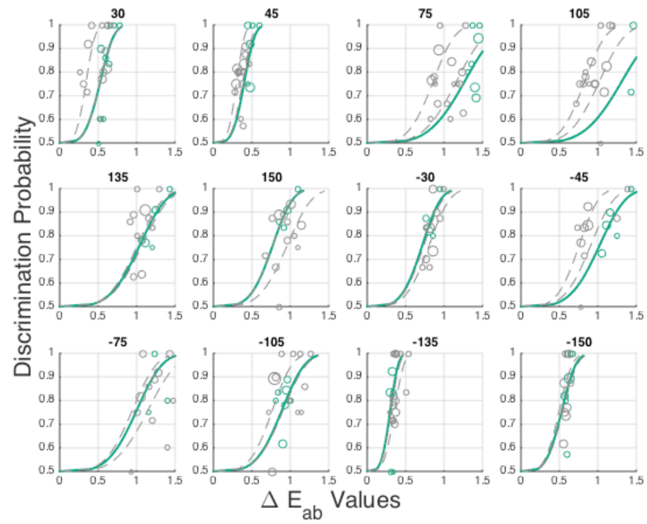

Figure 2. Discrimination probabilities (y-axis) plotted as a function of D-CIELab ΔE_{ab} value for a deuteranopic observer (denoted in green) and two trichromatic observers (denoted in gray). Each panel shows discrimination in a different color direction. Best-fitting Weibull functions are shown in solid lines and the size of the circle is proportional to the number of data points. The dichromatic color transform is accurate when the curve for the deuteranope is close to the curves for the two trichromats. The largest deviation is in the panel at the upper right.

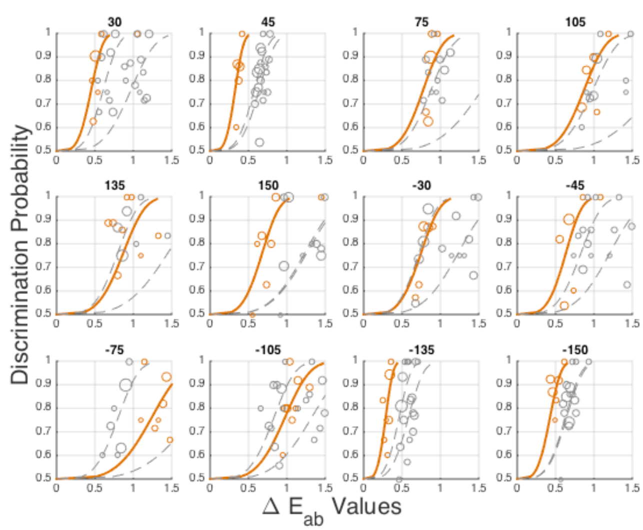

Figure 3. Discrimination probabilities (y-axis) plotted as a function of D-CIELab ΔE_{ab} value for a protanopic observer (denoted in red) and two trichromatic observers (denoted in gray). The curves are best fitting Weibull functions and the size of the circle is proportional to the number of data points. Again, the dichromatic color transform is accurate when the curve for the deuteranope is close to the curves for the two trichromats. The largest deviation is shown in row three, column three.

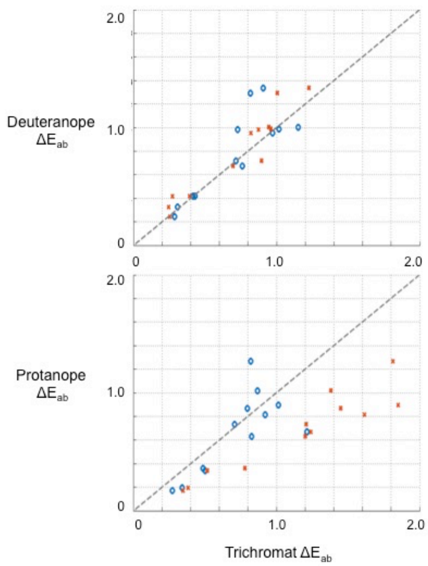

Figure 4. Comparisons of ΔE_{ab} at 80% correction detection for the controls and dichromats. (a) The scatter plot shows the ΔE_{ab} values for the deuteranope on the horizontal axis and the trichromatic controls on the vertical axis. For a perfect CIELAB ΔE_{ab} model all the thresholds would be the same. In a perfect D-CIELAB model the data points would fall on the identity line. (b) The same as (a) but for the protanopic subject.

5. Discussion

The CIELAB color difference metric is widely used to predict the ability of trichromatic observers to detect small color-differences. In this paper, we propose and test an extension (D-CIELAB) that predicts the ability of dichromatic observers to detect small color differences. The D-CIELAB calculation linearly computes the missing cone absorption rate from the two absorption values present in a dichromat [5]. The three cone absorption values are converted to XYZ coordinates and the standard CIELAB calculation is applied.

The experiments show that the performance of the dichromatic observers (Figures 2 and 3) is within the range of the trichromatic observers. The ΔE_{ab} values for just noticeable color difference can vary in a range from 0.2 to 1.5, depending on the color direction. There is a systematic departure for one of the trichromatic observers (Figure 4b). Variance between trichromatic observers has been well documented [10] and attributed to variation in X-linked L/M genes [11]. We should expect, therefore, to see variance across dichromatic observers as well.

These preliminary results explain the principles of a dichromatic color metric as well as an approach for testing the metric. Additional data are needed to characterize the variability across both trichromatic and dichromatic observers.

To support future research and applications for D-CIELAB, we provide the psychophysical experimental code, data and analyses in a GitHub repository [12]. We also provide a webpage [13] that allows users to compute the D-CIELAB ΔE_{ab} values and visualize transformed images.

6. References

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[12] https://github.com/hjiang36/colorVisionExperiment

[13] http://hjiang36.github.io/D-CIELAB/dCIELAB.html