Interactive Color Correction of Display by Dichromatic User

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Abstract. Applications supporting dichromats based on confusion loci are proposed. We propose an interactive method to correct display color by measuring confusion color pairs for using such an application. The method measures 11 confusion color pairs on a display that shows an unknown color gamut. It estimates the most similar pattern from the confusion loci database, which is composed of scaling up/down one of R, G and B. It corrects display color to the sRGB gamut. We showed a tendency of confusion loci pattern for scale change and measured results for a dichromat. It improved the color difference in six of eight color settings.

Keywords: dichromatism, confusion loci, color correction, color gamut.

1 Introduction

Recently, lots of applications to assist dichromats have been released. Some are intended for dichromats to use by themselves. They use a color appearance model for dichromats [1] to present the regions that are confusion colors in a captured image or a web page. Then, it converts them to easily discriminative colors (e.g. [2]). The confusion colors of the model are aligned on the line in the chromaticity diagram of color space called confusion lines or loci. The algorithms based on the confusion lines may not always work well for devices in different settings, e.g. a tablet outdoors, a laptop PC for presentation in a dim room, a desktop monitor in an office. The color characteristics or settings for devices or illuminants are quite different. Brightness and chromaticity do not correspond on each device, although the application outputs the same RGB signals. Therefore, it is necessary to calibrate the color of a device display whenever a dichromat utilizes such an application. Interactive correction of color profile has been proposed (e.g. [3]), but it was not designed for this use.

Here, we focused on the strength of the R, G, B light sources of the device.

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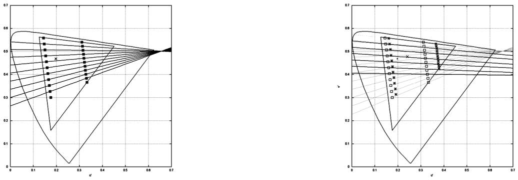


(a) sRGB (b) R × 1.4

Fig. 1. Shift of chromaticity and confusion loci. (□ : sRGB, ∗ : scaled state).

2 Proposed Method

2.1 Confusion Loci

Each confusion locus represents the position of confusion colors for dichromats in the chromaticity diagram of some color space. In the $u'v'$ chromatic diagram, a locus does not distribute on a curve, but does on a line. If some confusion color pairs are given, the lines are almost converged at one point. The convergence points are different according to the type of dichromatism. If the display is set in sRGB correctly, the locus pattern is obtained as in Fig. 1(a). This figure shows the pattern of protan type, and coordinates of its conversion point are $(u', v') = (0.656, 0.502)$.

We propose an interactive method of color calibration of the display based on measurements of confusion color pairs by a dichromatic user. We utilize the change of the geometrical pattern of the confusion loci according to the strengths of R, G, B signals.

We model the status of the display, which is not set to sRGB, as the state is scaling up/down with one of three signals for the standard color. For example, R×1.4 means that the R signal is 1.4 times sRGB, and G and B are raw values. Supposing we use such a display, R signal is high-intensity scaling of 1.4, and we measure the confusion loci for the same R, G, B signals of sRGB settings; then we obtain the locus pattern as in Fig. 1 (b).

2.2 Database of Confusion Loci Pattern Changing Scaling of One Primal Color

As the confusion color pairs, we selected the colors on two parallel lines to the line that passes through the coordinates of green and blue primary colors. They correspond to the left vertex and bottom vertex of a triangle in Fig. 1(a). The positions of selected colors are shown by square marks in Fig. 1(a). The center of the triangle corresponds to the white point. We defined the position of the left line as the ratio 3:7 of the edge connected between green and blue to the white point. Also, we defined the right line at the position of three times its distance from the white point. Eleven color pairs are selected on the right line by equal spaces. Thus, we defined 11 confusion color pairs, and we set the brightness to $Y = 20.0$. The selected confusion color pairs are shown in Table 1.

We constructed the database of loci patterns as follows. First, the scaling coefficient is defined. We set the scaling (w) from 0.5 to 2.0 every 0.1 in sRGB signals.

Table 1. Confusion color pairs

u'	v'	R	G	B	u'	v'	R	G	B
0.176	0.301	86	110	246	0.333	0.366	226	0	188
0.173	0.327	83	115	226	0.331	0.384	221	40	175
0.170	0.352	80	120	207	0.328	0.401	216	54	163
0.166	0.378	78	124	189	0.326	0.418	212	64	150
0.163	0.404	75	127	171	0.324	0.436	208	71	137
0.160	0.430	73	129	153	0.322	0.453	205	78	124
0.157	0.455	71	132	135	0.320	0.470	201	83	110
0.153	0.481	70	134	116	0.318	0.488	198	88	95
0.150	0.507	68	136	94	0.315	0.505	195	92	78
0.147	0.533	66	137	68	0.313	0.523	192	95	56
0.144	0.558	65	139	19	0.311	0.540	189	99	0

(Y=20.0)

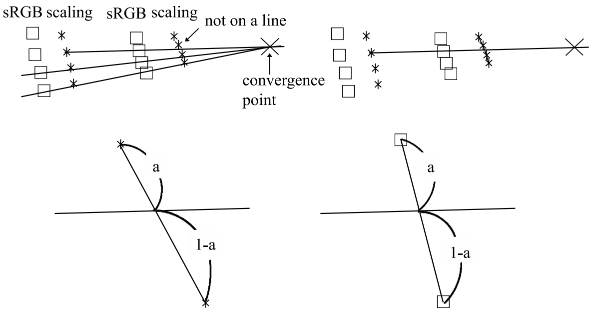
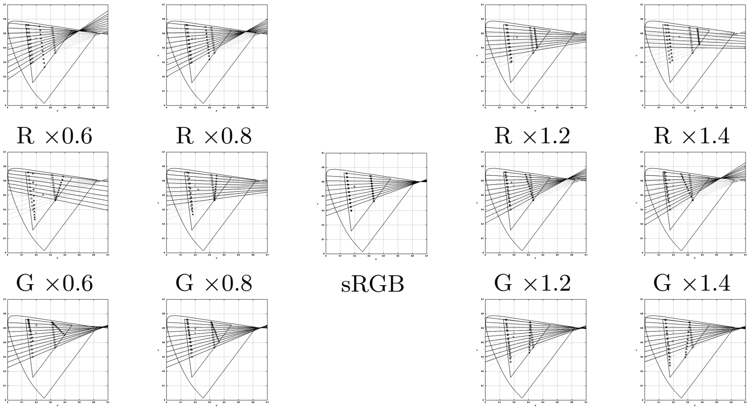


Fig. 2. Calculation of the shift of a confusion locus

It can transform the scaling for the linear RGB signals with the calculation of $w^{2.2}$. Here, we supposed the gamma of the display is set to 2.2. Then, the RGB signal is presented by the form of (w_rR, w_gG, w_bB). One of three coefficients is scaling up/down. The others are set to 1.0.

If we displayed one pair of confusion colors on the display setting at sRGB correctly, the positions of original colors in the $u'v'$ chromaticity diagram are located on the line as in the top left figure in Fig. 2. Under the condition of scaling up/down of one of R, G, B, the colors that are located at asterisk marks are displayed; then they and the convergence point are not aligned on a line. The point of the right asterisk mark is not on a line.

Here, we consider that the color of the left side asterisk is fixed. Also, we'll find the confusion color pair on the interpolate line of the right side groups of colors with asterisk marks in the top right figure. It is found in the line that passes through the left side asterisk and convergence point. Next, we calculate the interpolate point between the positions of asterisk colors as in the bottom left figures. This applies the transformation of the original color, which is shown by the right side square with the interpolate ratio. Thus, we calculate the line (a confusion locus) that passes through the position of the left square mark and the interpolated point for right side squares at the bottom right figure. We stored the slope of the line as locus patterns in the database. For 11 confusion



R ×0.6 R ×0.8 R ×1.2 R ×1.4

G ×0.6 G ×0.8 sRGB G ×1.2 G ×1.4

B ×0.6 B ×0.8 B ×1.2 B ×1.4

Fig. 3. Confusion loci of protanopia for one among R, G, B was scaled up/down

Fig. 4. Illustration of visual stimuli

color pairs, we tried to calculate the slope and, if an interpolation of right side asterisks could not be found, the color confusion pairs were excluded. A part of the database is shown in Fig. 3.

2.3 Color Matching by Dichromatic User

A dichromatic user performs a color-matching task with a display that has to be calibrated for color property.

The visual stimuli on the display are shown in Fig. 4. Three squares are presented. The center one is painted a reference color that corresponds to the left side confusion color. Its color is greenish or bluish. Then, it does not change until completion of a trial. Both end squares are painted the test color to match. Their colors are assigned in the neighborhoods of its confusion color pair. Their colors are reddish. A dichromatic user judges which of the test patterns is more similar to the reference color in the center square. After judgment, the non-selected test pattern is changed to a color that is the averaged color of the test patterns. The sides of the test patterns are changed randomly, and presented again; the user again judges the colors of the test patterns. The bisection method was adopted. When the user judges that the colors of test patterns are not discriminative, the trial is completed. If both initial test patterns are not perceived as similar to the reference color, its trial is skipped and recorded as such. Eleven confusion color pairs are measured. We calculate the slope of a line that passes through the reference color and confusion color, from which are obtained the color matching.

2.4 Evaluating Similarity between Measured Confusion Loci Patterns and Ones in Database

To estimate the color status of the display, we evaluate the similarity between the measured confusion loci patterns and confusion loci patterns in the database, which are composed by 11 slopes of lines of confusion color pairs.

The line of confusion colors is described as follows. To measure confusion lines, it holds that

$$A_i u' + B_i v' + C_i = 0. \tag{1}$$

The index of i represents the i_{th} confusion color pair. Similarly, for the database,

$$D_{s,i} u' + E_{s,i} v' + F_{s,i} = 0. \tag{2}$$

The index of s represents the status of the display. That is, the status of scaling up/down for one of three signals (R, G, B) (e.g. R ×1.4).

Here, we consider the perpendicular vectors for each of the lines, $\mathbf{x}_i = (B_i, -A_i)^T$, $\mathbf{y}_{s,i} = (E_{s,i}, -D_{s,i})^T$. With these, we calculate the following evaluation function.

$$e_s = \alpha_s \sum_i \left(1 - \frac{|\mathbf{x}_i \cdot \mathbf{y}_{s,i}|}{\|\mathbf{x}_i\| \|\mathbf{y}_{s,i}\|} \right) \tag{3}$$

We estimate the settings s that minimized e_s as the color status of the display. Here, α_s is calculated by the ratio of 11 to the number of complete measured trials. If no trials are completed for some setting, then it is excluded from the estimation candidates.

2.5 Color Correction for Display

We constructed the database changing the scaling up/down for one of three primary color signals in the sRGB setting. The scaling factor is transformed to the scaling factor under the linear RGB space by $(w^{2.2})$ with γ-value. We supposed the relation of RGB and CIE XYZ as follows.

$$\mathbf{A} \begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \tag{4}$$

For the given scale and RGB signals, CIE XYZ is calculated by the following equation.

$$\mathbf{P}\mathbf{A}^T = \mathbf{Q}, \tag{5}$$

where $\mathbf{P} = \begin{pmatrix} R_1 \; G_1 \; B_1 \\ R_2 \; G_2 \; B_2 \\ \vdots \\ R_n \; G_n \; B_n \end{pmatrix}$, $\mathbf{Q} = \begin{pmatrix} X_1 \; Y_1 \; Z_1 \\ X_2 \; Y_2 \; Z_2 \\ \vdots \\ X_n \; Y_n \; Z_n \end{pmatrix}$. We estimated the matrix of $\mathbf{A}^T$ by the least square method. Then, we obtained equations $\mathbf{A}^T = \left(\mathbf{P}^T\mathbf{P}\right)^{-1} \mathbf{P}^T\mathbf{Q}$, $\hat{\mathbf{A}} = \mathbf{Q}^T\mathbf{P}\left(\mathbf{P}^T\mathbf{P}\right)^{-1}$. Thus, the following equation is derived.

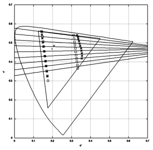


Fig. 5. Confusion loci under the raw color status of the monitor

$$\hat{\mathbf{A}}^{-1}\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} R \\ G \\ B \end{pmatrix}. \tag{6}$$

We define $\hat{\mathbf{A}}^{-1}$ for each status of scaling. We can estimate the color $(X, Y, Z)^T$ should be displayed with $\hat{\mathbf{A}}^{-1}$ and $(\hat{R}, \hat{G}, \hat{B})^T$. With this transformation, we can calibrate the color status of the display.

3 Experiment

3.1 Experimental Setup

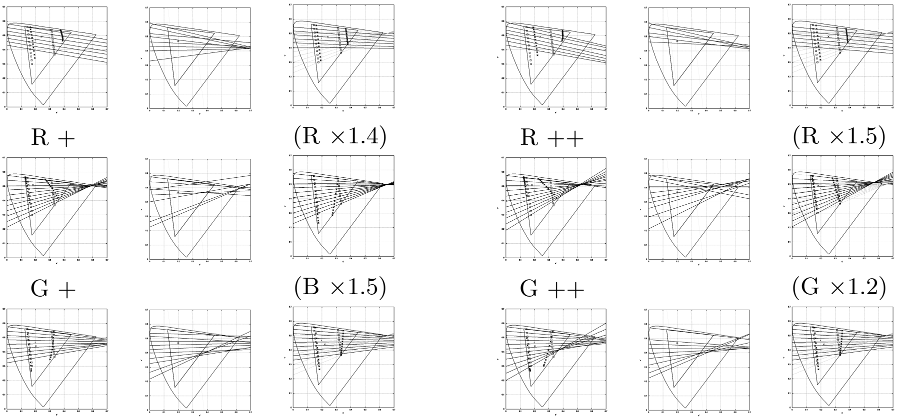
The proposed method is implemented as the program components with C++ (VisualStudio) and G++ (Cygwin) on a personal computer (OS: Windows 7). We used an LCD Monitor (Sharp LL-T2015H) with the following specifications: Screen size, 408[mm] × 306[mm]; Resolution, 1,600[pixels] × 1,200[pixels]; Color Scale, 256[steps] for each color. We measured the chromaticity for raw primary color (R, G, B) signals by luminance color meter (Konica Minolta, CS-200). We calculated the confusion loci from the raw color status (standard) of this monitor. It is shown in Fig. 5. There are shifts from the loci pattern of sRGB (Fig. 1(a)).

The measurement was performed in a darkroom. We set the monitor at a distance of 0.45[m] from the user. Visual angle of a square's side is 11 [arc deg].

We set the six kinds of contrast of the monitor's settings. We denote them as R+, R++, G+, G++, B+, B++. Even if we index R, G or B, it does not mean the color shift caused by only one signal. Because shifts from sRGB have already occurred, the multi colors affect them. We also measured for the two preset settings as 'cool color' and 'warm color'.

3.2 Result

A dichromat user who had consented to participate in a psychological experiment served as the subject. The confusion loci measured by luminance color meter (left), user's response (center) and the estimated pattern from the database (right) for each setting are shown in Fig. 6. The results for the preset color setting are shown in Fig. 7. To show quantitative estimation, we calculate the color difference in the $u'v'$ chromaticity diagram for the test colors. Test colors and color differences in test colors are shown in Tables 2 and 3.


R + (R ×1.4) R ++ (R ×1.5)

G + (B ×1.5) G ++ (G ×1.2)

B + (G ×0.8) B ++ (G ×0.8)

Fig. 6. Loci patterns of displayed(left), user's response(center), estimated(right)


cool color (G ×0.8) warm color (R ×1.4)

Fig. 7. Loci patterns of user's response(left) and estimated(right)

First, we will discuss Fig. 6 and Table 3. If we obtain the locus patterns for the left and right columns, figures are quite similar for each setting, the estimation is correct, and the color differences are reduced from the state before correction.

For the results of changing R, we can see that the convergence point is located outside of the figure. As we see in Fig. 3, for a larger scale factor of R, or smaller one of G, the convergence point is located more at the right side because the u' axis shows reddish and greenish components, which are in a complementary color relationship to each other. Therefore, we can conjecture that it is reasonable that the shift of the convergence point along the axis was observed. It holds that this is similar to the converse shift (left side) for a small factor of R or a large one of G. The user's loci disperse little, and estimated patterns are similar to the figures of the displayed patterns. Certainly, color differences are reduced, and the strength of scale is reflected. The scale of R++ is larger than that of R+.

For the results of changing G, we can see the large fluctuation of the user's response confusion pairs in the figure of G+. The estimated loci pattern is B ×1.5. It is not a good estimation. The color difference was expanded as in Table 3. Although the fluctuation also can be in G++, we can reduce the color difference in the estimated pattern G ×1.2.

For the results of changing B, we can see the abrupt changes of slope of lower confusion loci. It is caused by the saturation by reaching the maximum output of the light source B. Therefore, it is a larger factor, i.e. B++ has more effect. If we exclude the user's loci that correspond to saturation, the arrangement of the remaining loci is similar in both cases. Both settings estimate the scale of G ×0.8. This monitor color is biased to reddish, as in Fig. 5. As the relationship

Table 2. Test colors

u'	v'	R	G	B	u'	v'	R	G	B
0.15	0.50	66	135	101	0.18	0.53	106	130	67
0.17	0.32	76	115	232	0.23	0.33	158	89	221
0.34	0.45	214	68	125	0.33	0.51	201	88	70

(Y=20.0)

Table 3. Estimation for each setting and color difference of before/after correction

setting	estimation	before	after	success	setting	estimation	before	after	success
R+	R ×1.4	0.059	0.034	Yes	R++	R ×1.5	0.086	0.045	Yes
G+	B ×1.5	0.053	0.088	No	G++	G ×1.2	0.083	0.041	Yes
B+	G ×0.8	0.025	0.024	Yes	B++	G ×0.8	0.051	0.029	Yes
cool	G ×0.8	0.012	0.032	No	warm	R ×1.4	0.050	0.029	Yes

between G and R is complementary, G ×0.8 means the monitor color shifts to reddish. On the other hand, as in Fig. 3, changing of factor B does not affect the shift of the convergence point. Finally, it is reasonable that the scale of G ×0.8 is estimated. Color differences are reduced for both cases, certainly.

For preset settings, the scale of G ×0.8 is estimated in cool color, and color difference reduction was not obtained. We think the blue component is more or less strong in the 'cool color' setting. The saturation in the user's loci graph is observed. Together with B+, B++ and this result, we think parameters in equation (3) do not work well for such a factor (i.e. saturation). Therefore, we think it is of value to consider parameters in future work. For a warm color setting, we obtained good results such that the scale of R ×1.4 is reddish and color difference was reduced.

4 Conclusions

We proposed an interactive method to correct display color by a dichromatic user measuring confusion color pairs. The method measures 11 confusion color pairs on a display that has an unknown color gamut. The system outputs the most similar pattern from the confusion loci database, which is composed of scaling up/down one of the primary color signals (R, G, B). We showed a tendency of confusion loci pattern for scale change and measured results for a dichromatic user. We found that the color differences in six of eight color settings were reduced.

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