Color reproduction from desktop display to projector based on visual matching

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We present a novel method of color reproduction from desktop displays to projectors via visual assessment. The model is based on visual matching nine color patches between a display and a projector. The effects of the method to improve color reproduction are tested for 30 samples by visual and color difference evaluations. The expeirmental results of visual evaluation show that the color reproduction is improved by 87.5%. The maximum, minimum, and average color differences between the displayed colors and the projected ones before and after correction are 28.94, 4.35, 16.78, 16.51, 0.64, and 3.51 ΔE^*_{ab} units respectively, which are consistent with the results of visual evaluation.

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It has become popular that color images and graphs are displayed on computer screens, and furthermore projected on the large white screen or wall by projectors. Color reproduction from displays to projectors is important in some cases. However, it often happens that the projected colors by a projector look different from the ones on a display screen. Generally, color management system (CMS) for achieving cross-media reproduction needs color measurement instruments for device characterizations[1,2], color appearance models, and gamut mapping[3,4]. However, this is for professionals (such as graphic arts industry) and color critical users (such as medical imaging), and the color measurement instruments are expensive and also not convenient for general users.

With the publication of the color appearance model CIECAM02 in 2004 by the International Commission on Illumination (CIE)[4], the model for cross-media color reproduction is becoming more and more accurate and complex. A great deal of researches on cross-media color reproduction have been concentrated on the case between computer displays and printers. There are much less researches on color reproduction between displays and projector. The studies on the projected color of projectors were focused on color characterization, display characteristic, optimization of tiled display color uniformity, and color gamut[5−10].

In this letter, we present a sample method to match several dispalyed and projected color patches by human vision without using any color measurement instrument. The transformation between two devices in color space is then attained by implementing simple mathematical optimization based on matching color appearance in the CIELAB color space. The method is tested by visual and color difference evaluations.

One color with *RGB* (red, green, and blue) values in the computer video memory is displayed on a display screen and simultaneously projected on the large white screen/wall by a projector with the same *RGB* values. In general cases, there is the difference in color appearance between displayed color and projected one, as shown in Fig. 1, which is the case of no matching color appearance in the CIELAB color space.

To achieve color matching between projected and displayed one, the *RGB* values of the color on the display screen should be corrected or converted to $R'G'B'$ values projected by the projector, as shown in Fig. 2.

The principle and method to attain $R'G'B'$ from *RGB* are described as follows.

A simple model of display characterization is shown as[1,2]

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} (R/255)^{\gamma_{\rm dis}} \\ (G/255)^{\gamma_{\rm dis}} \\ (B/255)^{\gamma_{\rm dis}} \end{bmatrix} = A \times \begin{bmatrix} (R/255)^{\gamma_{\rm dis}} \\ (G/255)^{\gamma_{\rm dis}} \\ (B/255)^{\gamma_{\rm dis}} \end{bmatrix}, \quad (1)$$

where $\gamma_{\rm dis}$ is the display gamma, and A is the linear matrix of colorimetric characterization for the display. At the same time, according to the principle of additive color for a projector, a simple model of projector characteriza-

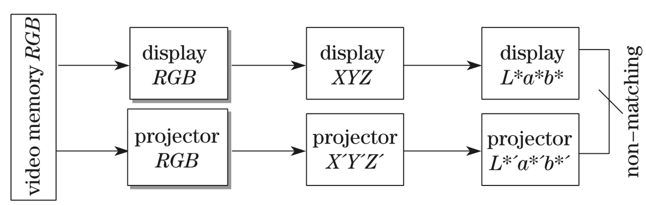

Fig. 1. The case of no matching between projected color and displayed color.

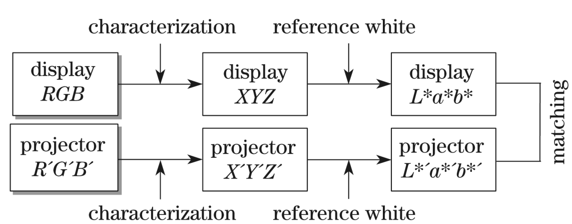

Fig. 2. The case of matching between projected color and displayed color.

tion is shown as[11−13]

$$\begin{bmatrix} X' \\ Y' \\ Z' \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} (R'/255)^{\gamma_{\rm pro}} \\ (G'/255)^{\gamma_{\rm pro}} \\ (B'/255)^{\gamma_{\rm pro}} \end{bmatrix} = B \times \begin{bmatrix} (R'/255)^{\gamma_{\rm pro}} \\ (G'/255)^{\gamma_{\rm pro}} \\ (B'/255)^{\gamma_{\rm pro}} \end{bmatrix}, \qquad (2)$$

where $\gamma_{\rm pro}$ is the projector gamma, and B is the linear matrix of colorimetric characterization for the projector.

According to Fig. 2, to attain $R'G'B'$ values from RGB values for color matching in the CIELAB color apperance between displayed and projected colors, two gammas, two linear matrices, and two white points must be known. Based on the facts that two gammas and two white points can be set, and the linear matrix A of a display adopts approximately standard data for phase alternative line (PAL) or the National Television System Committee (NTSC) system, the key is to attain the linear matrix B. For example, if two white points are the same and the linear matrix A is given, the transform matrix C form RGB to $R'G'B'$ is attained as

$$\begin{bmatrix} (R'/255)^{\gamma_{\rm pro}} \\ (G'/255)^{\gamma_{\rm pro}} \\ (B'/255)^{\gamma_{\rm pro}} \end{bmatrix} = C \times \begin{bmatrix} (R/255)^{\gamma_{\rm dis}} \\ (G/255)^{\gamma_{\rm dis}} \\ (B/255)^{\gamma_{\rm dis}} \end{bmatrix}, \qquad (3)$$

where $C = B^{-1}A$.

In this letter, the method to attain the matrix C is presented, which is to match by human vision at least three color patches displayed on the display screen and projected on the large white screen/wall by the projector. Considering the practicality and accuracy of the method, the color patches used in the matching should meet the following requirements. The number of color patches is more than three, but as few as possible; the color patches should include single-channel ones for ease to match by human vision; the color patches should include several gray ones that contain the interaction between color channels; in view of the different gamuts of two output devices, the color patches with the bigger or smaller RGB values should not be chosen, in order to avoid the mismatching due to the limited gamut of two devices[14].

The devices and experiment processes are as follows[15]. The display is a 21-inch Sony-G520 cathode ray tube (CRT) display. Set the display at professional mode, frequency 85 Hz, spatial resolution 1024×768, luminance 50, contrast ratio 100, white point D65, $\gamma = 2.0$. The projector is a Sony VPL-CX5 liquid orystal display (LCD) projector. Set the projector at luminance 85, contrast ratio 77, $\gamma = 2.0$. Light source of the projector is metal halide lamp, and normal color temperature is 6500 K. The images were projected on a general white wall, which was 2.0 m from the projector lens. Matching and test experiemts were carried out in a dark room. Binocular successive matching (BSM)[16] was adopted for color matching of visual psychophysics. Four subjects with normal color vision engaged in the experiment of visual matching and visual evaluation.

The experiments were divided into two processes. One is to attain the matrices C and B by matching several color patches and implementing simple mathematical optimization; the other is to test the method by visual and color difference evaluations.

Table 1. Matching Values between the Display RGB and the Projector $R'G'B'$

No.	Display			Projector		
	R	G	B	R'	G'	B'
1	120	120	120	89	116	94
2	150	150	150	117	140	120
3	195	195	195	161	179	164
4	140	220	0	0	200	0
5	115	170	0	0	150	0
6	160	0	0	151	13	0
7	200	0	0	193	17	0
8	0	0	160	0	0	146
9	0	0	200	0	0	176

Nine color patches were chosen in color matching experiment by human vision for attaining the transform matrix C and the matrix B of the projector. Only one of the four subjects joined in this experiment. In the experiment, one color with certain RGB value was displayed on the display screen, and at the same time, another color with the same RGB value was projected on the white wall, and the subject adjusted projected color RGB to $R'G'B'$ that matched the displayed color on screen. The matching values between RGB and $R'G'B'$ are listed in Table 1.

Based on the same chromaticity values of white points, the same gamma, and the characterization matrix A for a PAL display given by

$$A = \begin{bmatrix} 43.01 & 34.25 & 17.82 \\ 22.20 & 70.73 & 7.17 \\ 2.04 & 13.01 & 93.95 \end{bmatrix}, \qquad (4)$$

and the matching values between RGB and $R'G'B'$ listed in Table 1, the matrix C is calculated according to the minimum linear fit using Eq. (3), and meanwhile B is calculated. The transformation matrix C and the normalization matrix B are shown as

$$C = \begin{bmatrix} 0.9523 & -0.3627 & 0.0401 \\ 0.0142 & 0.8166 & 0.0088 \\ -0.0214 & -0.0126 & 0.7666 \end{bmatrix}, \qquad (5)$$

$$B = \begin{bmatrix} 35.68 & 49.45 & 16.13 \\ 17.57 & 76.91 & 5.52 \\ 3.64 & 15.77 & 97.35 \end{bmatrix}. \qquad (6)$$

The performance of the correction method was evaluated by visual and color difference evaluations for 30 samples including 3 gray and 27 colored samples that produce the form combination of the three values 70, 130, and 200 for R, G, B channels, respectively. The corrected $R'G'B'$ values for the samples were calculated through Eq. (5).

Four subjects numbered $1^{\#} - 4^{\#}$ joined in the visual evaluation. The evaluation environment was the same to that in the above matching experiment, including the dark room, the size of samples, and the method of visual psychophysics. One sample with certain RGB values was displayed on the display screen, and at the same time, the sample with the same RGB values and its corrected version with $R'G'B'$ were projected on the wall. The subjects were required to compare displayed color with two projected colors, i.e., uncorrected and corrected colors, and answer improvement levels. The levels were divided into four grades A, B, C, and D representing great improvement, improvement, non-improvement, and becoming bad, respectively.

Average levels for each sapmple, which are attained from taking out the best and worst levels from evaluation results of four subjects, are listed in Table 2. The average results show that 87.5% of the color reproduction has been improved. At the same time, visual evaluations were made on four International Organization for Standardization (ISO) images: Party, Picnic, Portrait, and Fruit, and also on the image including 24 patches of Gretag Macbeth Color Checker. The improvement effect of color reproduction was obvious.

The performance of the correction method was evaluated by calculating the color differences between the displayed colors and projected ones before and after for 30 samples. The method for calculating CIELAB color difference is shown in Fig. 3.

In this process, the chromaticity values of white points of the display and projector and the characterization matrix A of the display were measured with X-Rite Eye-One colorimeter, and used in calculating color difference. The maximum luminance and white point of the display were 97.70 cd/m^2, $X_{\max} = 94.811$, $Y_{\max} = 100$, and $Z_{\max} = 107.304$ (color temperature 6480 K). The characterization matrix A of the display is shown as

Table 2. Test Samples and Results of Visual Evaluation

Sample							Results of Evaluation				
No.	R	G	B	R'	G'	B'	1#	2#	3#	4#	Average
1	70	70	70	55	65	57	B	B	B	B	B
2	70	70	130	47	60	102	A	A	B	B	A/B
3	70	70	200	29	51	152	B	B	D	B	B
4	70	130	70	0	122	65	B	B	A	B	B
5	70	130	130	1	119	107	B	B	B	A	B
6	70	200	70	0	188	76	B	B	C	B	B
7	70	200	130	1	187	116	B	B	B	B	B
8	70	200	200	0	183	161	B	D	B	B	B
9	70	130	200	0	115	154	B	B	B	B	B
10	130	70	70	127	68	62	C	C	C	C	**C**
11	130	70	130	124	64	102	A	B	B	B	B
12	130	70	200	120	56	153	B	B	B	B	B
13	130	130	70	106	123	68	B	B	B	B	B
14	130	130	130	101	122	107	B	B	A	A	A/B
15	130	130	200	94	118	156	B	B	C	B	B
16	130	200	70	33	189	79	A	B	A	B	A/B
17	130	200	200	0	185	162	B	B	B	B	B
18	130	200	130	16	188	114	B	B	B	B	B
19	200	70	70	205	74	66	B	C	D	B	**B/C**
20	200	70	130	202	70	107	B	B	A	A	A/B
21	200	70	200	200	65	157	B	B	A	B	B
22	200	130	70	190	127	73	C	C	C	C	**C**
23	200	130	130	188	125	110	A	B	B	A	A/B
24	200	130	200	185	120	160	A	B	B	B	B
25	200	200	70	163	192	84	B	B	A	B	B
26	200	200	130	160	190	118	B	B	B	B	B
27	200	200	200	157	186	164	B	B	C	B	B
28	155	155	155	121	145	129	A	B	B	B	B
29	120	120	120	94	112	98	A	B	B	B	B
30	85	85	85	66	79	70	B	B	B	A	B
A: Great Improvement (%)							23.3	3.3	20.0	16.7	**15.8**
B: Improvement (%)							70.0	83.3	56.7	76.7	**71.7**
C: Non-Improvement (%)							6.7	10.0	16.7	6.7	**10.0**
D: Becoming Bad (%)							0.0	3.3	6.7	0.0	**2.5**

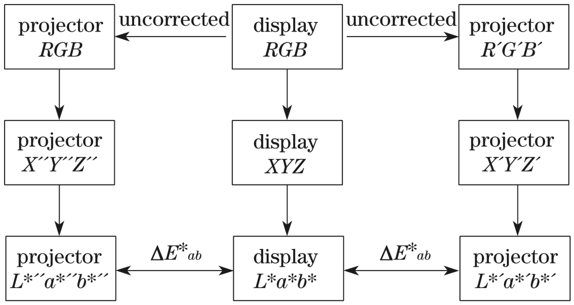

Fig. 3. Flow chart of calculating color differences.

$$A_{\mathrm{Measure}} = \begin{bmatrix} 43.53 & 30.19 & 19.56 \\ 23.86 & 65.88 & 9.57 \\ 2.67 & 12.18 & 89.90 \end{bmatrix}. \qquad (7)$$

The chromaticity values of the white points of the projector were measured for different measurement distances from the colorimeter to the projected screen. The results are listed in Table 3. It can be seen that the tristimulus values of white point, X_n, Y_n, Z_n (n indicates the white point), are different for different distances, but after normalizing Y_n to 100, there are the same tristimulus values approximately. The average values were used as data of the white points for calculating color difference.

Similar to measuring the white points of the projector, the data for projector characterization matrix B were measured through measuring the maximal tristimulus values of each color channel. The normalization matrix B is shown as

$$B_{\mathrm{Measure}} = \begin{bmatrix} 20.47 & 47.39 & 14.17 \\ 10.97 & 82.53 & 6.50 \\ 1.58 & 4.44 & 76.01 \end{bmatrix}. \qquad (8)$$

The color differences between the displayed colors and projected ones before and after correction for 30 samples are listed in Table 4. Compared with the color differences between the uncorrected projected colors and the displayed ones, the color differences between the corrected projected colors and the displayed ones are smaller for all samples, and the maximum, minimum, and average color differences change from 28.94, 4.35, 16.78 ΔE^*_{ab} to 16.51, 0.64, 3.51 ΔE^*_{ab} units, respectively.

The results of color difference with those of visual evaluation are found to be consistent. For example, the results of visual evaluation are non-improvement for samples No. 10, 19, and 22 (marked with bold in Tables 2 and 4), which is consistent with the small change in color difference before and after correction.

In conclusion, in order to achieve the color reproduction from a computer display to a desktop projector, based on the color appearance matching in CIELAB space, the characterization matrix of a projector has been obtained by matching nine color patches between the display and the projector. The subjective evaluation by human vision on 30 samples shows that the corrected colors get great improvement compared with the uncorrected ones, and is consistent with the objective evaluation by calculating the color differences between the screen colors and projected ones before and after correction.

Although the presented method has a significant improvement on color reproduction from a display to a projector, color reproduction can be further improved according to the following aspects. Firstly, the color appearance model CIECAM02 should be used instead of CIELAB for predicting changes in color appearance across disparate viewing conditions, because displays and projectors are two different media of self-emission and reflection. Secondly, color gamut mapping should be considered, because the two devices have different color gamuts. In this study, 24 patches of Gretag Macbeth Color Checker were also used as an evaluation sample,

Table 3. Values of the White Points for the Projector at Different Measurement Distances

Distance (m)	X_n	Y_n	Z_n	Normalizing Y_n to 100			Average		
1.5	78.54	94.38	77.77	83.22	100	82.40			
2.0	77.73	92.62	75.07	83.92	100	81.05	83.82	100	81.58
2.5	72.51	86.00	69.92	84.31	100	81.30			

Table 4. Samples and Color Differences between the Displayed and Projected Colors Before and After Correction

No.	1	2	3	4	5	6	7	8	9	**10**
Uncorrected	10.16	16.37	19.54	14.49	19.73	25.71	23.69	28.94	25.03	7.84
Corrected	1.80	3.07	1.74	3.99	5.74	16.44	16.51	15.37	5.02	2.79
No.	11	12	13	14	15	16	17	18	**19**	20
Uncorrected	15.18	18.95	8.06	14.55	21.35	21.65	24.09	17.72	7.20	16.50
Corrected	1.03	0.94	2.92	1.36	0.64	2.35	1.16	1.28	1.24	1.77
No.	21	**22**	23	24	25	26	27	28	29	30
Uncorrected	20.65	4.35	11.66	19.40	19.38	11.06	18.95	16.19	13.87	11.33
Corrected	1.29	2.10	1.02	1.83	2.33	1.72	1.88	2.45	1.39	2.09
Uncorrected	Maximum Color Difference **28.94**				Minimum		**4.35**	Average		**16.78**
Corrected	Maximum Color Difference **16.51**				Minimum		**0.64**	Average		**3.51**

and corrected $R'G'B'$ for nine color patches were bigger than 255, i.e., out of the projector gamut. Lastly, in this study, only one subject joined in the color matching experiment, and the aim is for simplicity and convenience in practical applications. The increase of number of subjects in the color matching process will improve the accuracy of the matrix B or C. In our experiments, it can be found that there are some divergences by four subjects in the visual evaluation on samples such as No. 3, 8, and 19.

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