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Methods to improve colour mismatch between displays

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Abstract

With the rapid development of display technology, the colour mismatch of the colours having same tristimulus values between devices is an urgent problem to be solved. This is related to the well-known problem of observer metamerism, caused by the spectral power distribution (SPD) of primaries and the difference between individual observers' and the standard CIE colour matching functions. An experiment was carried out for 20 observers to perform colour matching of colour stimuli with a field-of-view of 4° between 5 displays, including two LCD and two OLED, against a reference LCD display. The results were used to derive a matrix-based colour correction method. The method was derived from colorimetric visually matched colorimetric data. Furthermore, different colour matching functions were evaluated to predict the degree of observer metamerism. The results showed that the correction method gave satisfactory results. Finally, it was found that the use of 2006 2° colour matching function outperformed 1931 2° CMFs with a large margin, most marked between an OLED and an LCD display.

Introduction

The cornerstone of the colorimetry is the colour matching function (CMF), which defines the average human perception to match stimuli across the visible spectrum. CIE standardized two sets of standard colorimetric observers, CIE 1931 and 1964 standard colorimetric observers, or 2° and 10° observers [1,2]. The data were published in CIE 15:2018 [3]. When performs colour matching, two stimuli match perfectly for one observer, but may be a mismatch for the other observers. This phenomenon is called the Observer Metamerism [4]. The observer metamerism is caused by the different visual response of individual observers, and different spectral functions of the two stimuli. In 2006, CIE [5] also published a 2° CMF based on individual optical densities of macular pigment, visual pigment, and lens density. The procedure can be applied to compute CMF by considering varying viewing fields from 2° to 10° at different ages.

The problem encountered by the display industry is the mismatch [6-9] between a pair of stimuli on different displays having same XYZ values. The phenomenon can be explained by math expression in equations (1) and (2).

$$\begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} = CMF1 * \begin{bmatrix} S_{R1} \\ S_{G1} \\ S_{B1} \end{bmatrix} * \begin{bmatrix} R_1 \\ G_1 \\ B_1 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = CMF2 * \begin{bmatrix} S_{R2} \\ S_{G2} \\ S_{B2} \end{bmatrix} * \begin{bmatrix} R_2 \\ G_2 \\ B_2 \end{bmatrix} \quad (2)$$

where $[X_1\ Y_1\ Z_1]$ and $[X_2\ Y_2\ Z_2]$ express the tristimulus values of colours on two displays; CMF1 and CMF2 are the CMFs of two observers; $[S_{R1}\ S_{G1}\ S_{B1}]$ and $[S_{R2}\ S_{G2}\ S_{B2}]$ are the SPDs of the RGB primaries of two displays; $[R\ G\ B]$ are the signal for RGB channels.

For observer metamerism, XYZ values in equations (1) and (2) are equal, meaning a colour match under one condition, but a mismatch under the other conditions. Hence, the industrial problem of mismatch between display colours having same XYZ values is affected by both CMFs and the SPD of display's primary colours [7-10], which can be resolved by chosen suitable CMF and display primaries.

Wei *et. al* [11] recently investigated the observer metamerism. Fifty observers performed colour matching task of six colour stimuli with a field-of-view about 5° between four test displays (i.e., one LCD and three OLED) against a reference OLED display. It was found the CIE 1931 2° CMFs cannot accurately characterize the colour matches between the LCD and OLED displays, while little differences, in terms of colour mismatch and observer metamerism, were found between the same type of displays. The CIE 2006 2° CMFs were found to have better performance than the CIE 1931 2°, 1964 10°, and 2006 10° CMFs.

This paper was aimed to verify Wei *et al.*'s results and to derive a colour correction (CC) model to reduce the observer metamerism.

Experimental

Displays

In total five displays were used in the present study, including 3 LCD and 2 OLED displays, for which an LCD display was used as reference in this study. Table 1 summarises their colorimetric information. All of them were first characterized using the GOG (gain-offset-gamma) model [13]. Two OLED displays were later characterized using the 9x9x9 Look-Up-Table method [14], for which GOG model did not perform well.

Table 1. The u', v', CCT of white point, and the peak luminance for different displays

Displays	u'	v'	L(cd/m^2)	CCT(K)
Ref(LCD)	0.1954	0.4650	528	6880
A (LCD)	0.2060	0.4709	194	5850
B(OLED)	0.1964	0.4671	519	6673
C (LCD)	0.1850	0.4543	465	8616
D (OLED)	0.1955	0.4618	409	7099

Table 2 gives their performance of characeterisation model in CIEDE2000 (ΔE_{00}) and $\Delta u'v'$ colour differences in predicting the 24 colours on the XRite ColorChecker chart (MCCC). Table 2 results indicate a reasonable accuracy of the characterization models for all displays. Note that the models were not used to obtain the data, because visual results were measured directly, not via models' prediction. Figure 1 shows the colour gamuts of the displays studied. All gamuts are larger than that of sRGB, and the reference LCD display is the largest gamut, even bigger than DCI-P3.

Table 2. The characterization models and its accuracy for different displays

Displays	Characterization Model	Accuracy (ΔE00)	Accuracy (Δu'v')
Ref (LCD)	GOG	0.3	0.0004
A(LCD)	GOG	0.38	0.0008
B (OLED)	LUT	0.69	0.0049
C(LCD)	GOG	1.08	0.0075
D (OLED)	LUT	2.00	0.0166

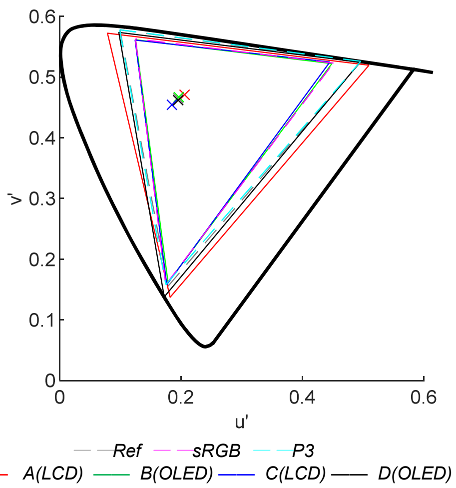

Figure 1. *Colour gamut and the white points (cross symbols) of the five displays under CIE 1931 2° CMFs, together with the sRGB and DCI-P3 colour gamuts.*

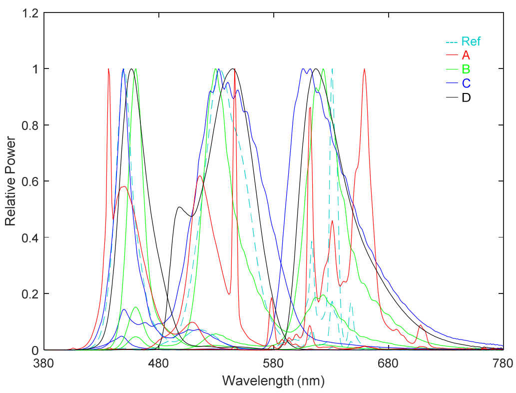

Figure 2. *Nomalised SPDs of the primaries of the five displays studied.*

Observers and procedure

The colour matching experiment was carried out in a dark environment with 20 observers (8 males, 12 females), with an average age of 25 and a standard deviation of 2.25. Figure 3 shows the experimental situation. The filed size of each colour patch was 4° against a black background, which was a black paper. The two patches had a 10 cm apart. Each had a visual subtense of 4º field of view. Observers were asked to first adapt in the dark environment for 2 minutes before the experiment. They were then to perform matching task for 14 and 4 stimuli in the two parts of experiment, respectively (see later). Each observer adjusted colour via arrow keys on the keyboard using two CIELAB attributes, a* and b*. Each observer's results in terms of RGB were recorded. These were reproduced on screen and measured by a Konica-Minolta CS2000 tele-spectroradiometer in terms of their SPD.

The observer metamerism was quantified by CIEDE2000 formula [16] between the SPDs of reference and matched stimuli with white point set at *[94.81 100.00 107.32]*. Same method was used to calculate colour difference in the unit of $\Delta u'v'$.

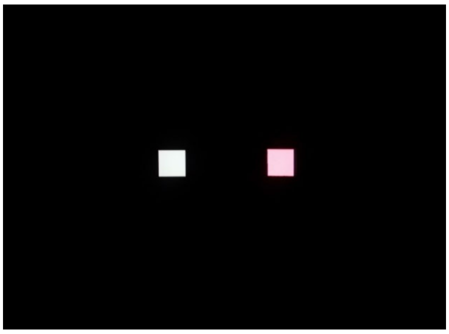

Figure 3. *The environment of colour matching experiment, including the reference colour (right) and test colour (left) to be adjusted.*

The experimental stimuli used in Parts 1 and 2 are different. Part 1 used the 12 colours on the MCCC as shown in Figure 4 (left). Part 2 includes 4 colours as shown in Figure 4 (right). The first experiment was performed colour matches between the reference and only Display A. The results were also used to investigate the number of minimum colours required to develop the colour correction (CC) model. Firstly, 14 test colours were chosen from an MCCC, 12 of them were chromatic colours and additional 2 were achromatic colours. The results showed that only four stimuli, red, yellow, blue together with the grey are sufficient to develop a model to give similar degree of accuracy as that using 14 colours. So, for tasks on the other 3 displays, only four test colours were chosen to match.

Figure 4. *14 test colours for Display A from X-rite ColorChecker chart (left); and 4 test colours for Displays B, C, and D (right)*

The XYZ values of colours on the MCCC were measured by a Konica-Minolta CM-700d spectrophotometer. Their corresponding RGB values for each display were calculated through the GOG model, Finally, these RGB values were shown on the display to be matched. And the colours were shown on two displays standing side-by-side as Figure 3 shown.

Data Analysis

As mentioned before, the colour difference between observers matched and the reference colours was used to quantify observer metamerism. By using different CMFs when transfer SPDs to XYZ values, XYZ values of matching results and reference colours under a CMF were recorded, as shown in equations (3) and (4). Finally, the ΔE_{00} and $\Delta u'v'$ were reported to represent degree of observer metamerism as shown in Figure 4. The former was calculated by setting the XYZ values of the reference white as *[94.81 100.00 107.32]*. The results had good agreement as $\Delta u'v'$ ranged from 0.0074 to 0.0109.

$$\begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} = CMF * P1 \quad (3)$$

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = CMF * P2 \quad (4)$$

where P1, P2 refer to SPDs of reference and observers' matched colours, respectively. A CC model as given in equation (5) was developed by simply applying a 3x3 correction matrix between the reference and matched colours between the reference and each of the 4 testing displays, for which, the 1964 10° CMF was used. The calculation from SPDs to XYZ values were calculated using equations (3) and (4) for the reference and test displays, respectively.

$$\begin{bmatrix} X'_2 \\ Y'_2 \\ Z'_2 \end{bmatrix} = \begin{bmatrix} C_1 & C_2 & C_3 \\ C_4 & C_5 & C_6 \\ C_7 & C_8 & C_9 \end{bmatrix} \begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} \quad (5)$$

where the 9 matrix coefficients form the CC model were used to correct from $[X_2\ Y_2\ Z_2]$ to $[X_2'\ Y_2'\ Z_2']$ The coefficients were optimized via the xx optimizer in MATLAB program to minimize ΔE_{00} calculated between the $[X_2'\ Y_2'\ Z_2']$ and target $[X_1\ Y_1\ Z_1]$. The results from the CC model are also given in Figure 5. Note that one 3x3 matrix, or a cc model, was optimized for all the colours between the reference and a particular display.

In the experimental design, it was divided into 2 parts. Part 1 experiment was conducted using 14 MCCC colours between Display X (an LCD) and the reference display, and Part 2 experiment using 4 test MCCC colours.

Results

As reported by Wei *et. al*, different CMFs could have a big impact on observer metamerism. This was also investigated here by calculating the transformed XYZ using 5 different CMFs, i.e., 1931 2° CMF, 1964 10° CMF, 2006 2° CMF, 2006 10°, 2006 4° CMF.

The SPD data of observer's and reference colours were transformed to XYZ values using equations (3) and (4). Figures 5 summarises the results for each display in terms of ΔE_{00}, respectively, together with the inter-observer variation.

The Mean of Colour Differences from the Mean (MCDM) was used to represent the disagreement between observers' matching results. The column named 'model' shows the model' performance (equation (5))., the column named 'Inter' represents inter-observer variation in ΔE_{00} unit. The mean MCDM values for A, B, C, D displays was 2.71, 2.52, 2.31, 2.79, respectively. These correspond to $\Delta u'v'$ of 0.0082, 0.0065, 0.0048, 0.0053 respectively, while Wei *et. al*'s results were between 0.0027 and 0.0122 and the average of 0.0059. This indicates good agreement between two studies.

Figure 5 results showed that the mean observer metamerism values for 1931 2° CMF, 1964 10° CMF, 2006 2° CMF, 2006 10°, 2006 4° CMF are 4.93, 3.94, 3.83, 4.04, 3.54, respectively. This indicates that to quantify observer metamerism using 1931 2° CMF would always produce unsatisfactory results, large errors, while very similar results are found between other three CMFs, although 2006 2° CMF's result is little better and 2006 10° CMF's result is a little worse. Figure 8 gives the same plot using $\Delta u'v'$ colour difference unit. It can also be seen that the CC model worked well which can improve the matching greatly.

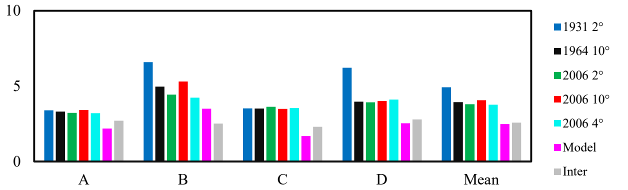

Figure 5. *The observer metamerism calculated by different CMFs (ΔE_{00}) and CC model together with the inter-observer variation.*

Figures. 6a-d show the 95% confidence tolerance ellipses in u'v' space for 4 displays against the reference display. These were fitted based on the results from 20 observers. Ellipses were plotted for each centre based on the calculation of XYZ values using different CMFs, including those typically used (1964 10°, 1931 2°, 2006 10°, 2006 2°) and 2006 4° CMFs corresponding to the present observer's field of view, and CC method, respectively.

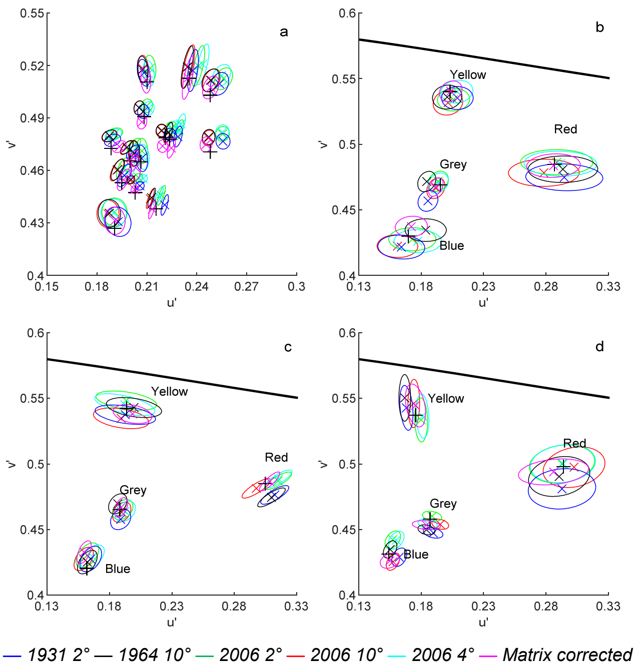

Figure 6. *Chromaticities, together with the 95% confidence tolerance ellipses for Displays A, B, C and D respectively. Each centre includes 6 ellipses calculated using 1964 10°, 1931 2°, 2006 10°, 2006 2°, 2006 4° CMFs and corrected method. The colour centre for each CMF was drawn as coloured crosses and a plus for the reference colour. (To make the figure clearer, the size of all ellipses in Fig 5.a has been reduced to 0.5 times; in other figures, the size of ellipses keeps it as it is.)*

It can be seen that the model predicted ellipse is always the most accurate (close to the target). The red ellipse (CIE 2° observer) was most deviate from the centre. Figure 7 plots only the colour centres of CMFs and model predicted for display B, C, and D, to increase legibility. As mentioned before, the first experiment was done between the reference and Display A, 14 test colours were used in experiment, and only 4 test colours were chosen for other four displays. Figure 7 shows the colour centres ellipses in u'v' space for B, C, D displays against the reference display.

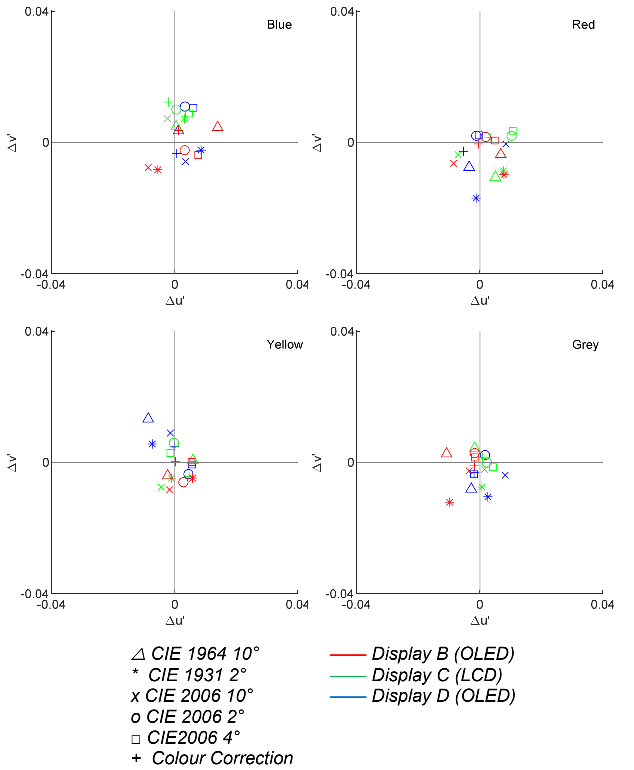

Figure 7. *The centre of 95% confidence error ellipses, of the 4 colours matched by the 20 observers on B, C, D displays in Δu' Δv' space. (Note: the text shown on the figures represent the colour being matched; the (0, 0) point is the reference colour when other symbols of different colour were the centre of ellipses)*

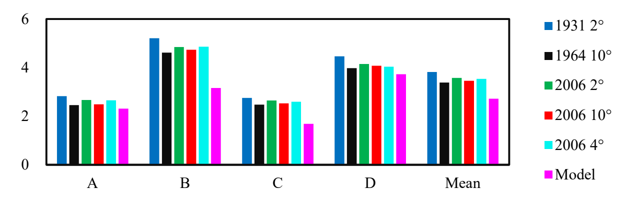

Figure 8. *The area of ellipses (*10^-4) of observers' matching results on u*v* plane.*

Figures 8 and 9 show results plotted in bar chart for easily to compare the ellipse size and distance between the ellipse centre and target.

The results in Figure 8 also indicates that using different CMFs made little difference to the areas of the ellipse (observer consistency), together with the CC matrix reduces the inter-observer variation of observers' data. When considering colour shift between the centre of ellipses and reference colours, 2006 2° gave the smallest mean distance, while the results from 1931 2° CMF performed the worst. However, the CC model results always performed best, i.e. having the smallest distance between the ellipse centre and target than that calculated by CMFs.

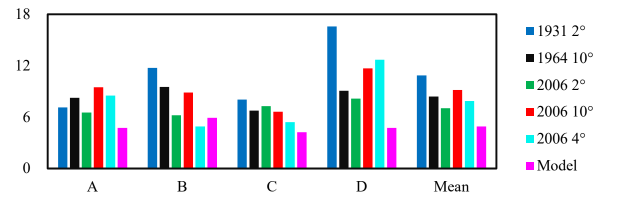

Figure 9. *The distance between the centre of ellipses of observers' matching results and reference colours on the u'v' plane (*10^-3).*

From Figure 9, it can be seen the CC model's predictions were always more accurate than those calculated using different CMFs. Comparing the size of ellipses from CMFs, the 1931 2° CMF always gave the largest size, i.e., indicating the least consistent between observers.

Figure 9 showed two clear trends. Firstly, the least deviations came from the CC model prediction (see green bars) for the 2 LCD displays. Secondly, the blue bars are always giving the least deviation for the two OLED displays, even better than the CC model's prediction (see violet bars). The results confirmed those found by Wei *et al.* [11] and Hu [10], again, that 1931 2° CMF performed the worst.

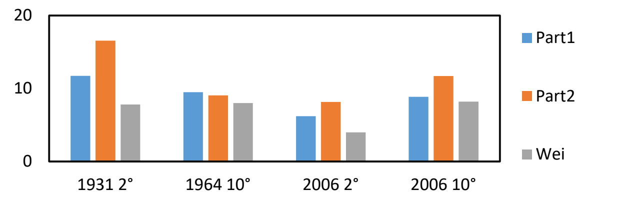

Figure 10. *The comparison between this paper's and Wei's result when the two displays are one LCD type and one OLED type. (Distance between the centre of ellipses of observers' matching results and reference colours on the u'v' plane (*10^-3).)*

Figure 10 shows the comparison of result between this paper and the investigation of Wei *et. al*. There were three sets of experiment to compare between an LCD and an OLED display. Part 1 and Part 2 results came from the present study together with the results from Wei *et. al.* Although the displays used in the experiments were different, the trend was clear, i.e. the 2006 2° CMF always gave the best performance.

Conclusion

This paper examines the problem of colour mismatch, between displays, for which these colours having the same CIE tristimulus colours. This is known as observer metamerism. The extent of this is caused by the spectra of the display primaries and observer's CMF.

The results showed that the chosen of CMF do have a great impact on the observer metamerism between the two devices. It seems that the use of 2006 2° CMFs can reduce the observer metamerism and the 1931 2° CMF would always produce large observer metamerism. This is most obvious to occur between two different types of displays, i.e., an OLED and an LCD. The finding agrees well to that found by Wei *et al.* This implies that it is about time to consider to take the former CMF to be applied in digital imaging applications.

A CC model was developed to overcome the mismatch problem between a pair of displays. The model derived from the visual matching results can be effectively reduced the value of the observer metamerism.

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