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A new independent dataset to verify the performance of colour appearance models for predicting simultaneous contrast effect

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Abstract

A web-based experiment was conducted worldwide including eight universities from four countries. An independent and comprehensive dataset considering three colour attributes (lightness, chroma and hue) and cross-term effects was accumulated for verifying the prediction performance of colour appearance models on simultaneous colour contrast effect using categorical judgement method. The small observer variation indicates that the web-based method is robust for this experiment while offering convenience and large scale. CC_Z model derived from the authors and CC_W model proposed by Wu and Wardman using Hunt94 model's colour contrast adaptation functions were tested. The results show although the latter gave a good performance on lightness contrast, the predictions on hue, chroma and cross-terms were unsatisfactory. The CC_Z model performed well on all of the types of contrast effects, especially the lightness and chroma contrast. Although the result was slightly scattered for the hue contrast, it still gave a good consistency.

Introduction

Colour appearance models can predict various visual phenomena under different viewing conditions [1]. The CIE recommended CIECAM97s in 1997, and it was modified to CIECAM02 which has been a widely-used colour appearance model for scientific research and industrial application [2]. But there are some mathematic problems in CIECAM02, a new CIE technical committee JTC10 was formed to recommend the CAM16 to replace CIECAM02 [3].

CIECAM02 can predict many colour appearance phenomena. However, the model cannot predict the simultaneous contrast effect, for which the appearance of a colour is affected by the surrounding colour. The appearance of the colour considered moves toward the opposite colour of the surrounding colours, that is the colour shifts arising from simultaneous contrast follow the opponent colour theory [4]. The phenomenon is illustrated by Albers' pattern in Figure 1, the tristimulus values of the crosses ('X') in each diagram are the same. The Albers' pattern in the shape of the double-crosses was used in the present experiment [5].

One of the main reasons for the poor predictions provided by existing colour contrast models is a lack of visual datasets. Up to now, the most widely-used dataset to develop and test colour appearance model is the LUTCHI dataset. But the prediction for the simultaneous contrast effect was not included [6]. To solve the problem, Luo *et al.* and Wu and Wardman established their own datasets using different experimental conditions [7-10]. But there is a common problem with these datasets, the data cannot cover all the colour attributes, i.e., lightness, chroma and hue, and also the cross-term effects.

To develop a comprehensive colour contrast model, a series of visual experiments have been conducted to investigate the simultaneous contrast effect including lightness, chroma and hue using Albers' pattern. In the previous researches carried out by the authors, a modification to CAM16 which named CC_Z model was proposed to predict contrast effects [11].

In this study, in order to verify the prediction performance of CC_Z model and compare it with the other models, a web-based experiment was conducted in eight universities from four countries (China, Japan, Korea and United Kingdom). It is not all the experiments can be done online, using uncontrolled display and viewing condition. The hypothesis is that most of laptop computer displays are similar to sRGB display. Most importantly, the categorical judgement on colour difference was designed to estimate two pairs of colours shown on the display at the same time, the inaccuracy of colorimetry can be partly ignored. The web-based experiment is convenient and large-scaled. All observers did their experiments at home to avoid the influence of the outbreak caused by COVID-19.

An independent and comprehensive dataset considering three colour attributes (lightness, chroma and hue) and cross-term effects was accumulated for verifying the prediction performance of colour appearance models on simultaneous colour contrast effect using categorical judgement method. Wu and Wardman's model (designated as CC_W model) which is based on CIECAM02 using Hunt94 model's colour contrast adaptation functions [12-14] and CC_Z model were tested using the web-based dataset.

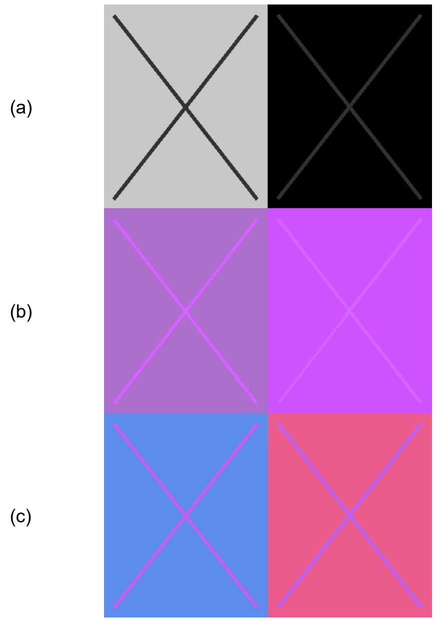


Figure 1. *Simultaneous colour contrast effect, the colours of the crosses in each diagram are the same. (a) lightness contrast; (b) chroma contrast; (c) hue contrast.*

Experimental

Colour selection

To considering the colour distribution in hue circle of test colours within the gamut of the sRGB colour space, five hue angles and three chroma levels (high C, medium C and low C, labelled as *hC*, *mC* and *lC*) were selected. Figure 2 shows the coordinates of 15 test colours in CIELAB a^*b^* plane, the grey shaded area region is the gamut of sRGB colour space. The five hue angles were selected to be located between unitary hues which were derived from previous studies. Table 1 lists the L^*, C^*_{ab}, h_{ab} values of the test colours.

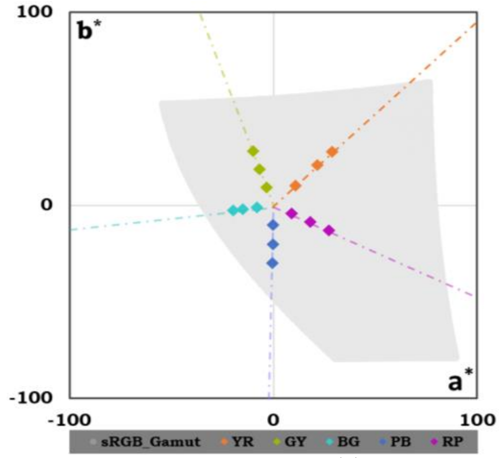
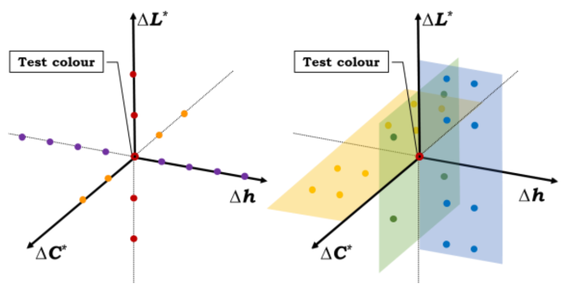


Figure 2. *The test colours plotted in CIELAB a*b* plane.*



(a) (b)

Figure 3. *Illustration of the background selection of a certain test colour. (a) single attribute effect; (b) cross-term effects.*

Table 1. The CIELAB coordinates for the 15 test colours.

	L^*	C^*_{ab}	h_{ab}
YR	50	15	44
	50	30	44
	50	40	44
GY	50	10	110
	50	20	110
	50	30	110
BG	50	8	188
	50	15	188
	50	20	188
PB	50	10	269
	50	20	269
	50	30	269
RP	50	10	335
	50	20	335
	50	30	335

The backgrounds were generated by taking the test colours as a centre, and divided into six parts according to the colour attributes, including lightness, chroma, hue and three cross-terms, i.e., lightness and hue, chroma and hue, lightness and chroma. Figure 3 illustrates the background selection of a certain test colour including single attribute effect and cross-term effects. Table 2 lists the CIELAB coordinates for six parts of the background colours for each test colour. The colours of the left and right backgrounds were randomly selected from the table, and formed 102 combinations for each test colour. This results in a total of 1,530 combinations, i.e., 15 test colours x 102 backgrounds.

Table 2. The CIELAB coordinates for background colours for each test colour.

Parts	Backgrounds		Combinations
L	ΔL^* = ±20, ±10		6
C	hC: ΔC^*_{ab} = -12, -6, +3, +6 mC: ΔC^*_{ab} = -12, -6, +6, +12 lC: ΔC^*_{ab} = -6, -3, +6, +12		6
H	Δh_{ab} = ±120, ±90, ±60, ±30		28

C&H	hC: ΔC^*_{ab} = -12, -6, +3, +6;
	mC: ΔC^*_{ab} = ±12, ±6;
	lC: ΔC^*_{ab} = -6, -3, +6, +12;
		Δh_{ab} = -60, -30	28

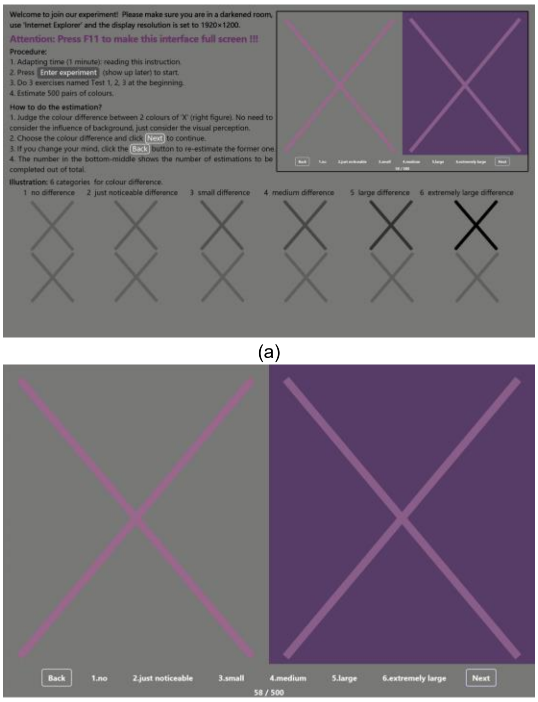
L&H	ΔL^* = ±20, ±10;	Δh_{ab} = +60, +30	28

L&C	hC: ΔC^*_{ab} = -6, +3;
	mC: ΔC^*_{ab} = ±6;
	lC: ΔC^*_{ab} = -3, +6;
		ΔL^* = ±10	6

Total	102 combinations		

Procedure

The experiment was conducted online. Observers accessed to the experimental interface and made it full screen using their own computer. The sRGB was used as a standard colour space in this experiment, which is based on the monitor characteristics expected in a dimly lit office, and has been standardised by the IEC. This colour space has been widely adopted by the industry, and is used universally for CRT, LCD and projector displays.



(a)

(b)

Figure 4. *Experimental interface. (a) Interface for adaptation; (b) Interface for estimation.*

Observers were asked to adapt in a darkened room for more than one minute reading an instruction (see Figure 4a) on the display (CCT=6500K, L^*=50). Then, a double-crosses image was presented and observers were instructed to evaluate the colour difference between two test colours of ‘X’ on the left and right. Figure 4b shows the interface for estimation. The RGB values of two test ‘X’ are the same, but the appearances are different because of the effect of the backgrounds. Six categories which including ‘1’ for ‘no difference’, ‘2’ for ‘just noticeable difference’, ‘3’ for ‘small difference’, ‘4’ for ‘medium difference’, ‘5’ for ‘large difference’ and ‘6’ for ‘extremely large difference’ were employed for visual assessment of colour difference. Once observers confirm the estimation, they have to click ‘Next’ to continue. And if they change their mind, they are allowed to click ‘Back’ to re-estimate the former one. The number in the bottom-middle shows the number of estimations to be completed out of total.

At the beginning, each observer conducted three exercises to familiarise with the operation. After that, each observer estimated 500 pairs of colour combinations, including 450 combinations randomly selected from 1,530 combinations and 50 repeats.

Overall, 126 normal colour vision observers participated in the experiment including 63 males and 63 females. In total, 63,000 estimates were accumulated, i.e., 500 combinations × 126 observers.

Result & Discussion

Observer variation

The STRESS value calculated from Equation (1) was used to indicate the disagreement between two sets of data compared.

$$STRESS=\left(\frac{\sum_{i=1}^{n}(A_i-FB_i)^2}{\sum_{i=1}^{n}F^2B_i^2}\right)^{1/2}\times 100\ ,\ F=\sum_{i=1}^{n}A_i^2/\sum_{i=1}^{n}A_iB_i \qquad (1)$$

where n is the number of sample pairs and F is a scaling factor to adjust A and B data sets on to the same scale. The percent STRESS values are always between 0 and 100. Values of STRESS near to zero indicate better agreement between two sets of data. The inter-STRESS value was calculated between mean of all the observers and each individual observer’s results. And intra-STRESS value was calculated from the repeating groups. Table 3 shows inter- and intra- observer variation as STRESS.

The results are comparable to former colour difference experiment, e.g., inter-observer variability of the Xu *et al.*’s experiment ranged from 19 to 26 with a mean of 21 [15]. It indicates that the web-based method is reliable for this experiment while offering convenience and large scale.

Table 3. The inter- and intra- observer variation as STRESS.

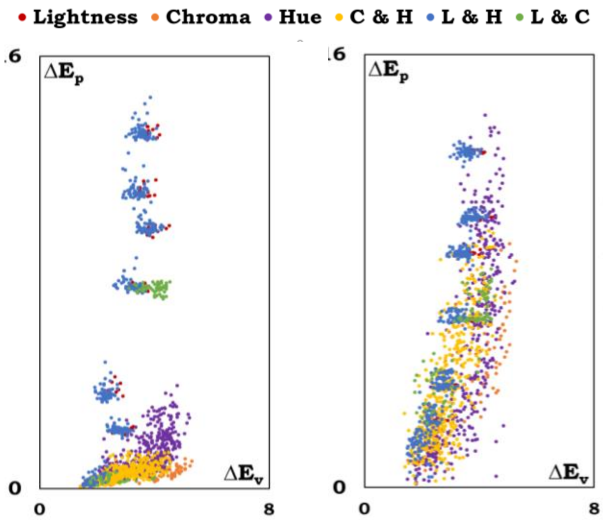
	Inter-	Intra-
All the observers (126 observers)	32	28
Colour science group (17 observers)	28	23

Furthermore, the observers’ experience had an impact on the results. The results of the observers with a background in colour science were also investigated. The inter- and intra-STRESS were induced to 28 and 23 respectively.

Testing CCW contrast effect model

Wu and Wardman proposed a modified CIECAM02 colour appearance model named CCW model to predict simultaneous contrast effect. The structure is a development from Hunt94. In the Hunt94 colour appearance model, the simultaneous contrast and assimilation effects are predicted using a modified hyperbolic function to modify the reference white cone signals, shown in Equation (2), where R'_w, G'_w, B'_w and R_w, G_w, B_w are the cone signals of the modified reference white and original reference white; R_{ind}, G_{ind}, B_{ind} and R_b, G_b, B_b are the cone signals of the induction colour and background, respectively. The value of ρ depends on the size and geometrical shape of the induction colour and varied between -1 and 0 for simultaneous contrast and between +1 and 0 for assimilation. The ρ values in CCW model are chosen as -0.4 for lightness and -0.05 (one-eighth of that for lightness) for hue.

$$\begin{aligned}
R'_w &= \frac{R_w\left[(1-\rho)P_R+(1+\rho)/P_R\right]^{1/2}}{\left[(1+\rho)P_R+(1-\rho)/P_R\right]^{1/2}}\\
G'_w &= \frac{G_w\left[(1-\rho)P_G+(1+\rho)/P_G\right]^{1/2}}{\left[(1+\rho)P_G+(1-\rho)/P_G\right]^{1/2}}\\
B'_w &= \frac{B_w\left[(1-\rho)P_B+(1+\rho)/P_B\right]^{1/2}}{\left[(1+\rho)P_B+(1-\rho)/P_B\right]^{1/2}}\\
&\text{with } P_R=\frac{R_{ind}}{R_b},\ P_G=\frac{G_{ind}}{G_b},\ P_B=\frac{B_{ind}}{B_b}
\end{aligned} \qquad (2)$$



(a) (b)

Figure 5. The plot of the visual results versus predictions of (a) CCW model and (b) CCZ model for six parts of results.

Figure 5a shows the prediction performance of CCW model for six parts (lightness, chroma, hue, lightness and hue, chroma and hue, lightness and chroma) individually. The visual results ΔE_v were plotted versus the colour difference between two predictions of left and right crosses ΔE_p.

It can be seen that CCW model gives a good performance on lightness contrast, but the predictions on hue is unsatisfactory. It may be caused by the structure of the model, because CCW used Hunt94 model’s colour contrast adaptation functions. Simultaneous contrast effect is too complicated to be predicted just by altering the reference white in a colour appearance model. On the other hand, the magnitude of the six types of contrast effects should be corrected. And the predictions of chroma and cross-term effects should be integrated into the model, because they are proved to have a significant impact.

Testing CC_Z contrast effect model

A modification to CAM16 colour appearance model, named CC_Z, was proposed in previous studies. Figure 6 shows the flow chart of the modelling. Lightness and chroma contrast are modelled by a sigmoidal function, while hue colour contrast is modelled as a sine function, as given in Equation (3).

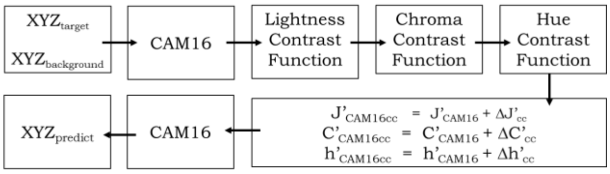


Figure 6. *The flow chart of CC_W model.*

$$\Delta J'_{cc} = \frac{16.0067}{0.0837 + e^{-0.0240 \times \Delta J'_{b-t}}} - 13.4455$$
$$\Delta C'_{cc} = \frac{9.7536}{0.4396 + e^{-0.1232 \times \Delta C'_{b-t}}} - 4.343 \quad (3)$$
$$\Delta H'_{cc} = 0.4408 \times \Delta H'_{b-t} \times e^{-0.001 \times (\Delta H'_{b-t})^2}$$
$$with\ \Delta H = 2 \times (C_1 C_2)^{0.5} \sin(\frac{\Delta h}{2})$$

where $\Delta J'_{b-t}$ is the lightness differences between background and test colour, $\Delta J'_{cc}$ is the visual lightness shift, $\Delta C'_{b-t}$ is the chroma differences between background and test colour, $\Delta C'_{cc}$ is the visual chroma shift, $\Delta H'_{b-t}$ is the hue differences between background and test colour, $\Delta H'_{cc}$ is the visual hue shift.

Note that the hue metric differences $\Delta H'_{cc}$ and $\Delta H'_{b-t}$ are determined from the hue angle differences $\Delta h'_{cc}$ and $\Delta h'_{b-t}$, using Equation (3) to make the same visual scale as the lightness and chroma differences.

Figure 5b shows the prediction performance of CC_Z model for six parts (lightness, chroma, hue, lightness and hue, chroma and hue, lightness and chroma) individually. The visual results ΔE_v were plotted versus the colour difference between two predictions of left and right crosses ΔE_p.

It can be seen that CC_Z model performs well on all of the types of contrast effects, especially the lightness and chroma contrast. Although the result is slightly scattered for the hue contrast, it still gives a good consistency. Table 4 shows the STRESS values between predicted results and visual results for each background part.

Table 4. The STRESS values predicted results and visual results for each background part.

	L	C	H	C&H	L&H	L&C
STRESS	31	29	41	35	34	15

Comparison of CC_Z model and CC_W model

STRESS and R (correlation coefficient) were used to calculate the agreement between predicted results ΔE_p and visual results ΔE_v. Table 5 shows the STRESS values and R values of two models. The prediction performance of CC_Z model is improved significantly.

Table 5. The STRESS and R values between predicted results and visual results of CC_Z and CC_W models.

	CC_Z	CC_W
STRESS	41	75
R	0.68	0.28

Conclusion

In the previous investigations carried out by the authors, a modification to CAM16 which named CC_Z model was proposed to predict contrast effect on lightness, chroma and hue. In order to verify the prediction performance of CC_Z and compare with the other models, a web-based experiment was conducted in eight universities from four countries (China, Japan, Korea and United Kingdom). An independent and comprehensive dataset considering all of the colour attributes (lightness, chroma, hue and cross-terms) was accumulated for verifying the prediction performance of colour appearance models on simultaneous colour contrast effect using categorical judgement method.

The small observer variation indicates that the web-based method is robust while offering convenience and large scale.

The CC_Z model derived by the authors and the CC_W model proposed by Wu and Wardman using Hunt94 model's colour contrast adaptation functions were tested. The results showed although the latter gave a good performance on lightness contrast, the predictions on hue, chroma and cross terms were unsatisfactory. CC_Z performed well on all of the types of contrast effects, especially the lightness and chroma contrast. Although the result was slightly scattered for the hue contrast, it still gave a good consistency.

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