https://doi.org/10.2352/issn.2694-118X.2020.LIM-29

Modelling and modification of simultaneous lightness contrast effect using the Albers' pattern

Yuechen, Zhu[1], Ming Ronnier, Luo[1,2*]
[1]State Key Laboratory of Modern Optical Instrumentation; Zhejiang University, Hangzhou, China
[2]School of Design, University of Leeds, Leeds LS2 9JT, UK
[*]Corresponding author: m.r.luo@zju.edu.cn

Abstract

Experiments were carried out to investigate the simultaneous lightness contrast effect on a self-luminous display using simultaneous colour matching method. The Albers' contrast pattern named 'double-crosses' was used. The goals of this study were to model lightness contrast effect and modify it in the CAM16 colour appearance model. Five coloured targets were studied, and 41 test/background combinations were displayed on a calibrated display. Twenty normal colour vision observers performed colour matching in the experiment. In total, 820 matches were accumulated. The result shows present CAM16 has an unsatisfactory prediction for the effect, especially in the positive region which means the background is brighter than the target. Two models were established based on the visual data, i.e., with and without modification to the lightness difference in CAM16 space. Both of the models predict the effect with high accuracy and reliability.

Introduction

Simultaneous colour contrast effect is an important visual perception phenomenon that happens when two adjacent colours influence each other, changing human perception of these colours. It can be observed with different lightness, chroma and hue [1]. Previous investigations have shown that the appearance of colour considered moves toward the opposite colour of the surrounding colours, following the opponent colour theory [2-3]. And the effect is usually studied in a centre-surround paradigm, also called test/background paradigm [3-6]. The phenomenon is illustrated by Albers' pattern [7] in Figure 1, the tristimulus values of the cross ('X') in each diagram are the same, (a) lightness contrast, a dark background induces a colour to appear lighter, (b) chroma contrast, a saturated background induces a colour to appear less saturated, (c) hue contrast, a red background induces a colour to appear bluish. It can be found that the lightness contrast performs a significant effect and lightness is very important in image processing. Thus, the lightness contrast effect was studied in this study. Albers' pattern in the shape of the double crosses was used in the present experiment.

The mechanism of human vision is an interdisciplinary filed, including optics, biomedicine, mechanics, chemistry and electronics. Thus, the mechanism of simultaneous contrast effect is complex, various colour appearance models (CAMs) which are used to predict the colour appearance under a wide range of viewing conditions have been developed to solve the problems. The contrast effect was first modelled in Hunt94 colour appearance model [8-11], which was the first relatively comprehensive colour appearance model. And nowadays, CIECAM02 [12] is widely used as a universal colour appearance model for scientific researches and industrial applications. However, it has been found that computational failures can occur in certain cases such as during the image processing of cross-media colour reproduction applications. Thus, CAM16 is in the process to replace CIECAM02 with a simpler structure [13]. The CAM16 already took lightness contrast effect into consideration, but the prediction performance was proved to be unsatisfactory. The goals of this study were to model lightness contrast effect with high accuracy and also modify it in the CAM16 colour appearance model.

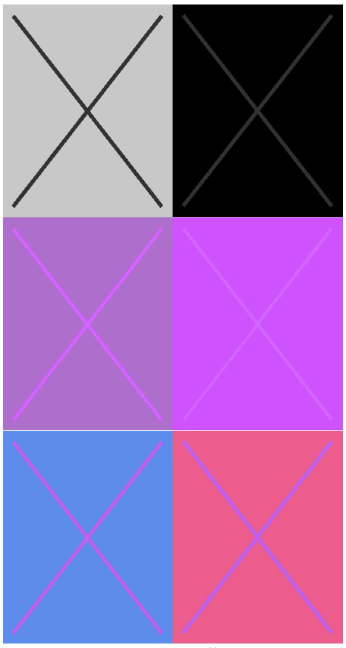

Figure 1. *Simultaneous colour contrast effect, the colours of the crosses in each diagram are the same. (a) lightness contrast; (b) chroma contrast; (c) hue contrast.*

Experiment

Apparatus

The experiment was conducted on an EIZO-CG243W display (size: 24.1", luminous level: 125 cd/m^2) in a darkened room. The display provides a large colour gamut (Adobe RGB coverage: 99%), and it was calibrated using the GOG model and the CIE 1964 10° Colour Matching Functions (CMFs) [14]. Typically, it had a uniformity of 0.91 ΔE^*_{ab} between the middle and the other 8 surrounding regions on the display. It was characterized using a GOG model [15], which gave a mean ΔE^*_{ab} of 0.72 to predict the 24 colours on X-rite 24 ColorChecker target.

Colour stimulus

Five target colours (Red, Yellow, Green, Blue, Magenta) were selected considering the colour distribution in hue circle.

The L^*, C^*_{ab}, h_{ab} and L (cd/m^2) values of the target colours are given in Table 1. Figure 2 shows the coordinates of target colours in CIELAB a^*b^* plane. The lightness and chroma of each target colours were set to L^*=50 and C^*_{ab}=30 to prevent the results from being out of gamut.

The test 'X' of each coloured target 'X' (Red, Yellow, Green, Blue, Magenta) was against seven grey backgrounds differed in lightness (L^* of 0, 20, 40, 50, 60, 80, 100). This results in a total of 41 combinations for each observer, i.e., 5 targets x 7 backgrounds + 6 repeats. Note that the repeats were randomly selected from 35 combinations.

Table 1. The CIELAB coordinates for the 5 target colours.

Target colour	L^*	C^*_{ab}	h_{ab}	L (cd/m^2)
Red	50.0	30.0	7.4	23.1
Yellow	50.0	30.0	79.9	23.1
Green	50.0	30.0	139.5	23.1
Blue	50.0	30.0	236.4	23.1
Magenta	50.0	30.0	301.9	23.1

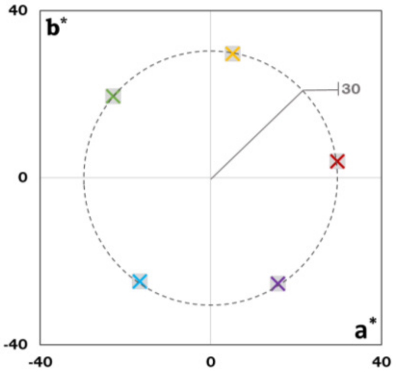

***Figure 2.** The target colours plotted in CIELAB a*b* plane.*

Procedure

Twenty observers participated in the experiment including ten males and ten females. They all passed the Ishihara Colour Vision Test with a normal colour vision, and were trained to understand the concept of colour attributes and experimental instruction. They had a mean age of 23.5 ranged from 19 to 30.

(a) **(b)**

***Figure 3.** Experimental setting. (a) Experimental situation; (b) Operational interface.*

Figure 3 shows the experimental setting. Observers sat at a distance of 80 cm away from the monitor. They first adapted to the darkened condition for one min viewing a grey background (CCT: 6500K, luminance level: 23 cd/m^2, L^*: 50) on the display. A double crosses image (see Figure 2(b)) was presented on the display and the observers then adjusted the lightness, chroma and hue of the test cross on the right via a keyboard in CIELAB colour space to match the colour of the reference cross on the left until they looked visually the same. Once the observer confirmed the well-matched colour, the next randomly generated combination was presented. The background on the left was fixed (CCT: 6500K, luminance level: 23 cd/m^2, L^*: 50), and the lightness (L^*) of the background on the right changed ranging from 0 to 100.

In total, 820 matches were accumulated, i.e., (5 target colours × 7 backgrounds + 6 repeats) × 20 observers.

Results

Observer variation

Mean Colour Difference from the Mean (MCDM) were calculated to represent the observer variation of the results. Table 2 summarizes the MCDM values. All colour differences were calculated using CAM16-UCS colour space [13]. The intra-observer variation describes the repeatability between the single observer's two repeats while the inter-observer variation describes the consistency between all observers. The overall MCDM was found to be 4.2 $\Delta E'_{Jab}$ and 2.5 $\Delta J'$ for inter-observer variations. The intra-observer variations are 2.0 $\Delta E'_{Jab}$ and 1.3 $\Delta J'$.

Figure 4 presents the inter-observer variation of each target. The degree of observer consistency is considered to be highly satisfactory.

Table 2. MCDM values for characterizing the inter- and intra-observer variations.

	Inter-	Intra-
$\Delta E'_{Jab}$	4.2	2.0
$\Delta J'$	2.5	1.3

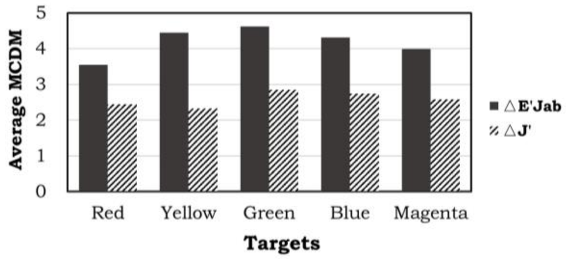

***Figure 4.** The average MCDM of each target for characterizing the inter-observer variations.*

Modelling the simultaneous lightness contrast effect based on the CAM16 lightness difference

As for the present CAM16 already included function to consider the lightness contrast effect. The data was used to verify the prediction performance of CAM16 first. In the computation, the luminance of reference white (L_w) was set to 125 cd/m^2, the adaptive luminance (L_a) was set to the 23 cd/m^2 which is consistent to the luminance of reference background, while the background luminance factor (Y_b) was set to different luminance factors of individual test backgrounds. The relationship of L_a and Y_b can be calculated by Equation (1).

$$Y_b = 100 \times \frac{L_a}{L_w} \quad (1)$$

To reveal the contrast effect, the visual results were expressed as each test/background combination. The reference background on the left was always set to the neutral colour of

L^*=50, the differences in lightness $\Delta J'_v$ represents the visual lightness shifts between the results of test/background and the target/reference (target/L^*=50). The differences in lightness $\Delta J'_{b-t}$ was the lightness differences between test background and target colour (the results of target/L^*=50).

Figure 5 shows the plot of $\Delta J'_v$ against $\Delta J'_{b-t}$ for all the five series of target colours, the colour coding scheme of the dots corresponding to the target colour of the series, i.e., Red, Yellow, Green, Blue and Magenta.

The result showed the lightness contrast correction of CAM16 works well in negative region (the third quadrant), but fails in positive region (the first quadrant). Thus, a modification was proposed in this study to improve the performance of CAM16. There is a clear trend, i.e., a darker background will make centre brighter, and the results of each target consistent with each other very well. So, the trend in the positive region was modelled by a linear function ($\Delta J'_{LC1}$), as given in Equation (2).

$$\Delta J'_{LC1} = 0.3797 \times \Delta J'_{b-t} \quad , \quad \text{for } \Delta J'_{b-t} > 0 \qquad (2)$$

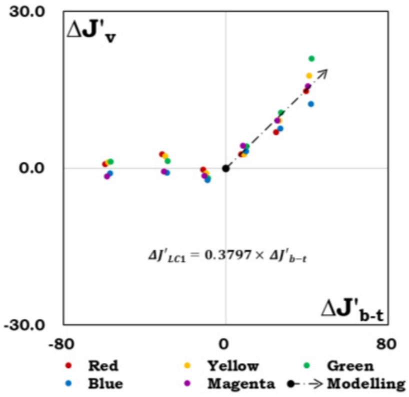

Figure 5. The prediction performance of lightness contrast function in CAM16 and the modelling of CAM16.

The model was fitted by minimizing the colour difference between visual colour shift ($\Delta J'_v$) and $\Delta J'_{LC1}$ (Equation (2)) using a root mean square. The graph of the fitted linear function is also plotted in Figure 5. It can be seen that the function fitted well to all the data points, having a lightness difference of 1.98 and a correlation coefficient of 0.94. Figure 6 shows the prediction performance of revised CAM16 ($\Delta J'_{LC1}$). After the modification, the model is well fitted to the visual data, the colour differences between predicted results and visual results are very small, i.e., all the points spread around the horizontal axis.

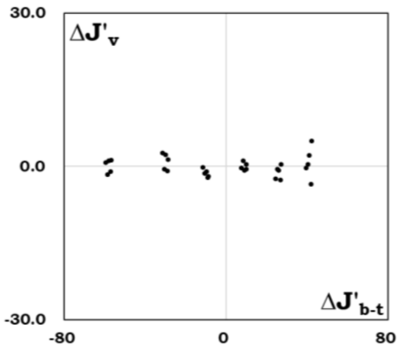

Figure 6. The prediction performance of revised CAM16 ($\Delta J'_{LC1}$).

Modelling the simultaneous lightness contrast effect without the lightness correction of CAM16

As mentioned earlier, the present CAM16 has an unsatisfactory prediction for lightness contrast effect, especially in the positive region. To avoid the over correction of CAM16, a model without the lightness correction of CAM16 was established.

Note that, the luminance of reference white (L_w) was set to 125 cd/m^2, the adaptive luminance (L_a) was set to the 23 cd/m^2 and the background luminance factor (Y_b) was set to 18, the parameters were fixed to remove the lightness correction of CAM16. The relationship of L_a and Y_b can also be calculated by Equation (1).

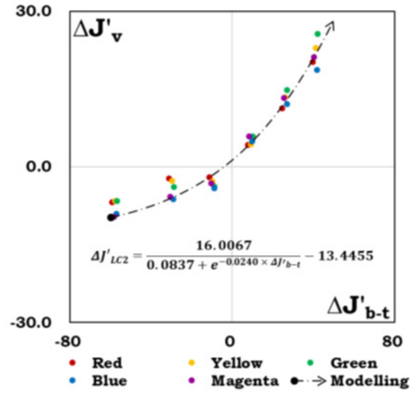

Figure 7. The results without the lightness contrast correction of CAM16 and modelling.

Figure 7 shows the plot of $\Delta J'_v$ against $\Delta J'_{b-t}$ for all the five series of target colours, the trend is more significant than that of Figure 5. The trend was modelled by a hyperbolic function, as given in Equation (3).

$$\Delta J'_{LC2} = \frac{16.0067}{0.0837 + e^{-0.0240 \times \Delta J'_{b-t}}} - 13.4455 \qquad (3)$$

The model was also fitted by minimizing the colour difference between visual colour shift ($\Delta J'_v$) and $\Delta J'_{LC2}$ (Equation (3)) using a root mean square. The curve of the fitted hyperbolic function is also plotted in Figure 7. It can be seen that the model fitted well to all the data points, having a lightness difference of 1.70 and a correlation coefficient of 0.99.

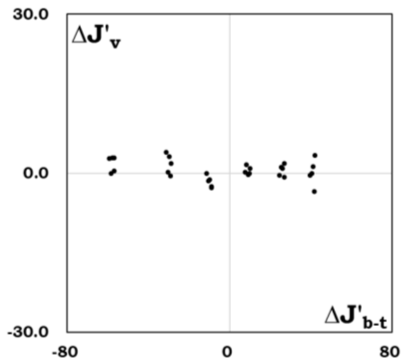

Figure 8. The prediction performance of model without the lightness contrast correction of CAM16 ($\Delta J'_{LC2}$).

Figure 8 shows the prediction performance of the new model without the lightness contrast correction of CAM16 ($\Delta J'_{LC2}$). After the modification, the model is also well fitted to the visual data, all the points are also close to the horizontal axis. The performance of $\Delta J'_{LC2}$ is slightly better than $\Delta J'_{LC1}$. The remaining discrepancy was due to different colour centres. However, the effect is small.

Reliability and performance of the models

Table 3 shows the colour difference of inter-observer variation and the prediction errors of the models proposed in this study in terms of $\Delta J'$. As for the $\Delta J'$ of the models are smaller than that of inter-observer variation, the models show high accuracy and reliability.

Table 3. Colour difference of inter-observer variation and prediction errors in terms of $\Delta J'$.

	Inter-observer	Before modelling	CAM16	$\Delta J'_{LC1}$	$\Delta J'_{LC2}$
$\Delta J'$	2.5	10.6	7.4	2.0	1.7

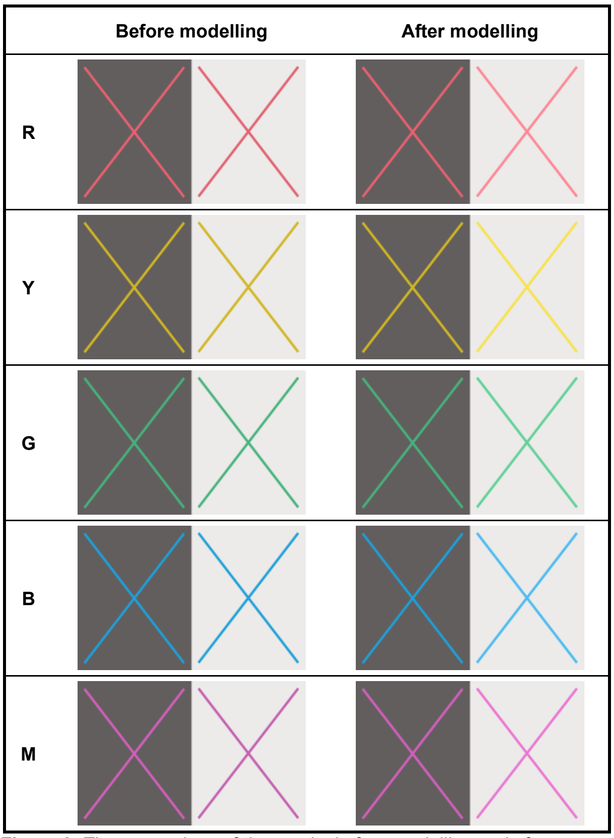

Figure 9. *The comparison of the results before modelling and after modelling.*

The prediction performances were very similar between two models, so a comparison of the results before modelling and after modelling without lightness contrast correction in CAM16 was also illustrated in Table 3 and Figure 9. It revealed that there is a significant improvement which means accurate models to predict simultaneous lightness contrast effect were successfully proposed.

Conclusion

Visual experiments were carried out to investigate the simultaneous lightness contrast effect on a self-luminous display using simultaneous colour matching method. The Albers' contrast pattern named 'double-crosses' was used. The goals of this study were to model lightness contrast effect and modify it in the CAM16 colour appearance model. Five coloured targets were studied, and 41 test/background combinations were displayed on a calibrated display. Twenty normal colour vision observers performed colour matching in the experiment. In total, 820 matches were accumulated.

The result suggests that the present CAM16 has an unsatisfactory prediction for predicting the effect, especially in the positive region which means the background is brighter than the target. Two models were established based on the visual data, i.e., one is a modification to CAM16 which already considering the lightness contrast effect, the other is a new model to predict the effect without the lightness correction of CAM16. The performances of them are very similar, the new model without the lightness correction of CAM16 outperforms slightly.

Acknowledgement

The work is supported by National Natural Science Foundation of China (Grant number: 61775190).

References

[1] M. R. Luo, Encyclopaedia of Colour Science and Technology, (Springer, Berlin, 2015).

[2] D. Jameson, L. M. Hurvich, "Theory of brightness and color contrast in human vision", Vision Research, 4(1-2), 135-154 (1964).

[3] M. R. Luo, X. W. Gao, "Quantifying colour appearance. part V. simultaneous contrast", Color Research & Application, 20(1), 18-28 (1995).

[4] R. C. Wu, R H. Wardman, "Lightness and hue contrast effects in surface (fabric) colours", Color Research & Application, 32(1), 55-64 (2007).

[5] R. C. Wu, R H. Wardman, M. R. Luo, "A comparison of lightness contrast effects in CRT and surface colours", Color Research & Application, 30(1), 13-20 (2010).

[6] R. C. Wu, R H. Wardman, "Proposed modification to the CIECAM02 colour appearance model to include the simultaneous contrast effects", Color Research & Application, 32(2), 121-129 (2010).

[7] J. Albers, Interaction of color, (Yale University Press, 1975).

[8] R. W. G. Hunt, "A model of colour vision for predicting colour appearance", Color Research & Application, 7(2), 95-112 (1982).

[9] R. W. G. Hunt, "Revised colour-appearance model for related and unrelated colours", Color Research & Application, 16(3), 146 - 165 (1991).

[10] R. W. G. Hunt, "An improved predictor of colourfulness in a model of colour vision", Color Research & Application, 19(1), 23-26 (1994).

[11] R. W. G. Hunt, M. R. Luo, "Evaluation of a model of colour vision by magnitude scalings: discussion of collected results", Color Research & Application, 19(1), 27-33 (1994).

[12] CIE 159:2004, A colour appearance model for colour managmeng systems: CIECAM02, (CIE, Vienna, 2004).

[13] C. Li, Z. Li, Z. Wang, Y. Xu, M. R. Luo, G. H. Cui, M. Melgosa, M. H. Brill, M. R. Pointer, "Comprehensive color solutions,

CAM16, CAT16 and CAM16-UCS”, Color Research & Application, 42(6), 703-718 (2017).

[14] P. W. Trezona, R. P. Parkins, “Derivation of the 1964 colorimetric standards”, Color Research & Application, 23(4), 221-225 (1998).

[15] L. Xu, M. R. Luo, “Comparison Between Models, Measurement Instruments, and Testing Datasets for Display Characterization”, Lecture Notes in Electrical Engineering, 13-20 (2018).