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A Revised Formulation Based on CIECAM16 for Cross-Media Colour Reproduction via Real Scene Experiment

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Abstract

In order to reproduce the colour appearance between real scene and images on self-luminous display. This study conducted a series of psychophysical experiments using threshold method. Three types of real scenes were built up in a lighting room, including painting, fruit and vegetable, skin colour chart. Sixteen adapting conditions were designed including four CCTs (3000K, 4500K, 6500K, 8000K) and 4 luminance levels (10lux, 100lux, 500lux, 1000lux). Four displays with different sizes were studied. The result indicated that the colour appearance of real scene and the image on the display were different, especially for low CCT and luminance level. The contents of scene and size of display didn't show a significate impact. The prediction performance of CIECAM16 was tested, and a revised formulation was proposed with high accuracy.

Instruction

With the rapid development of digital imaging technology, cross-media colour reproduction (CMCR) has become a key issue, and colour appearance match plays an important role in this field of research [1].

Colour appearance model is a mathematical model to predict the colour appearance in different lighting and viewing conditions on different media, which is widely used in both academia and industry [2-3]. Recently, International Commission on Illumination (CIE) recommended CIECAM16 to become a common model [4-5].

Over the decades, many psychophysical experiments were conducted to establish the dataset and implement the colour appearance reproduction. The most widely-used dataset is the LUTCHI dataset [6-7], which was obtained by a large-scale experiment divided into 23 phases according to various viewing parameters. LUTCHI dataset was used for the development of the CIE colour appearance models. Huang et al. [8] studied the impact of different viewing light illuminance on CMCR between display and printed samples using colour matching method. The results showed that the saturation of the matched colours on the monitor increased with the increasing of the illuminance of the light. Lu et al. [9] used memory matching and pair comparison methods to investigate CMCR performances of CIECAM02 between print samples viewed in a cabinet and reproduced samples presented on a self-luminous display. The results indicated that the colour samples reproduced by parameter 'dim' performed well in all three conditions, while the performance of parameters 'dark' and 'average' are dependent on the lightness and chroma of colour.

But these studies only include colour patches with simple pattens, which may have problems in predicting images in real scene. Xu et al. [10] conducted experiment to find the best viewing condition parameters for CIECAM02 when comparisons were to be made between a real indoor lit scene and its reproduction on a computer display. The results showed that the 'dim' and 'dark' surround parameters used in CIECAM02 always give similar performance when used to match the real scene and perform better than the 'average' surround parameter when rendering the real lit lighting environment. But Xu's study only verified the performance of CIECAM02, rather than modified the model.

In this study, a series of real scene experiments were carried out, and a revised formulation based on CIECAM16 for cross-media colour reproduction was proposed.

Method

Apparatus

The experiment was conducted in a lighting room controlled by ten LED light sources (see Figure 1). A 11-channel LED tuneable lighting device, the Thouslite LEDcube was used as the light source. It can accurately reproduce a measured or imported spectrum and keep same illuminant properties during illuminant switch without warm up time.

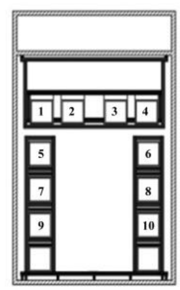


Figure 1. *The illustration of lighting room.*

Four displays were selected, including Apple Pro Display XDR (32 inches), EIZO CG243W (24.1 inches), Huawei MatePad (10.4 inches), Huawei Mate40 Pro (6.76 inches). Apple Pro Display XDR was used as a standard display in this study.

A Konica Minolta CS2000A spectroradiometer was used to calibrate the illumination conditions and the display. CIE 1931 standard colorimetric observer was used to calculate the XYZ values.

Adapting conditions

Sixteen adapting conditions were designed including four CCTs (3000K, 4500K, 6500K, 8000K) and 4 luminance levels (10lux, 100lux, 500lux, 1000lux). Table 1 summarised the light quality parameters of each adapting condition, the error of CCT is less than 73K, and the error of D_{uv} is less than 0.0059.

Real scenes and image processing

Three types of real scenes were built up, containing painting, fruit and vegetable, skin colour chart (see Figure 2). Note that all the scenes contained a Macbeth ColorChecker Chart (MCCC) for subsequent analysis.

Original images of the real scenes were first captured using a Nikon Z6 digital camera under a standard condition (6500K, 500lux). The white balance was set to 6500K, and the other parameters were kept the same among each scene (such as exposure, ISO speed, f/number, shutter speed). A camera characterization model was implemented using a polynomial regression technique with a precision of 1.5 ΔE^{*}_{ab} averaged from the 24 test colours of the MCCC. Each original image transformed from camera image in RGB format to image in CIE XYZ tristimulus values on a pixel-by-pixel basis.

(a) (b) (c)

Figure 2. *Three types of real scenes, (a)painting, (b)fruit and vegetable, (c)skin colour chart.*

An image rendering database was built up using the CIECAM16 model (see Figure 3). Each original image was then processed to give 513 images with different white points ($X_wY_wZ_w$), including 27 CCTs (ranged from 2700K to 8100K with a step equal to 200K) and 19 luminance levels (k ranged from 0.2 to 2.0 with a step equal to 0.1), note that k is luminance factor, 'k=1' means the lightness of each pixel is the same as the original image. The XYZ data were processed via the forward CIECAM16 model to predict the perceptual attributes under current standard condition (6500K, 500lux). Then, using the reverse CIECAM16 model, the attributes were transformed to XYZ tristimulus data for target viewing conditions. Finally, the XYZ values were transformed to RGB values on a display via the Gain-Offset-Gamma (GOG) model. The colours were clipped in the RGB colour space if they were out of colour gamut.

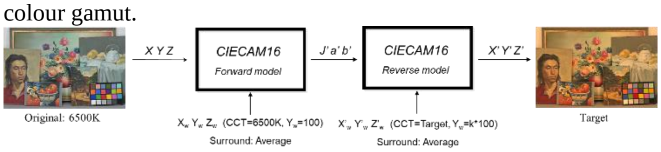


Figure 3. *Image processing of the experimental database.*

Table 1. The light quality parameters of adapting conditions.

	L(cd/m^2)	CCT(K)	D_{uv}
1	3.1	7927	-0.0057
2	31.8	8002	0.0026
3	159.6	7996	0.0043
4	319.1	7966	0.0037
5	3.3	6457	0.0016
6	33.1	6511	0.0038
7	159.9	6463	0.0059
8	319.1	6490	0.0054
9	3.1	4540	0.0056
10	32.3	4489	-0.0002
11	159.4	4531	0.0017
12	318.6	4528	0.0014
13	3.2	3004	-0.0058
14	32.1	3022	0.0031
15	158.7	3004	0.0002
16	318.5	2989	-0.0004

Procedure

Observers were asked to do adaptation for two minutes by looking around the neutral wall and the objects in the real scene. The next step was 'Rough selection', 20 images differed in CCT (CCT=3500K, 4500K, 5500K, 6500K, 7500K) and luminance (k=0.5, 0.9, 1.3, 1.7) were presented simultaneously (see Figure 4), observers were asked to choose one initial image (labelled as 'CCT_i, k_i') which was most similar to the scene on the display. When they finished the selection, the program automatically found 49 images which were close to the initial image in the image rendering database (7 CCT: $CCT_i \pm 600$, ± 400, ± 200, +0; 7 k: $k_i \pm 0.3$, ± 0.2, ± 0.1, +0). Each image was shown in the centre of the display in a random order, the size of the image was maximized to occupy the full field of view of the observers. The remaining part of the display was set to a colour which was as same as the white wall of the real scene to stabilize the adaptation (see Figure 5). Observer compared the images on the display with the real scene, and a threshold method was used for observers to judge each image as 'matched or not matched', this step was 'Fine selection'. Each observer had his/her own random sequence in terms of test images, lighting conditions and real scenes.

Figure 4. *The experimental interface of 'Rough selection'.*

Figure 5. *The experimental interface of 'Fine selection'.*

Experiments

Experiment 1: Real scene & Standard display

Experimental setup

All the three types of real scenes and sixteen adapting conditions were studied. And Apple Pro Display XDR was used as a standard display in this part. This results in a total of 2,499 evaluations for each observer, i.e., (4 CCTs x 4 luminance levels +1 repeat lighting condition) x 3 real scenes x 49 evaluations.

Observers

Twenty normal colour vision observers between 22 and 28 years of age (mean = 25.0, std = 1.7) participated in the experiment including ten males and ten females. In total, 49,980 evaluations were accumulated.

Results

Because the images were generated on a pixel-by-pixel basis and each image contained a MCCC, the CIE XYZ tristimulus values of No.21 patch (natural grey) of each image were measured to represent its colorimetric values. Thus, for each experimental setting, observer evaluated 49 images corresponding to different XYZ values. By averaging the XYZ values of the images judged by 'matched', the results of each experimental setting were obtained.

Observer variation

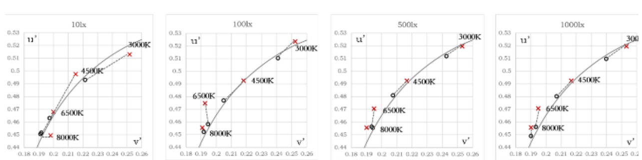
Mean Colour Difference from the Mean (MCDM) were calculated to represent the observer variation of the result. Table 2 summarizes the MCDM values. All colour differences were calculated using CIELAB colour space. The inter-observer variation describes the consistency between all observers. The MCDM values were ranged from 5.9 to 8.2 ΔE^*_{ab}. It can be found that the results of skin colour chart gave a high consistency, and the overall results were comparable to similar studies [10].

Table 2. The inter observer variation characterized by MCDM for each type of real scene.

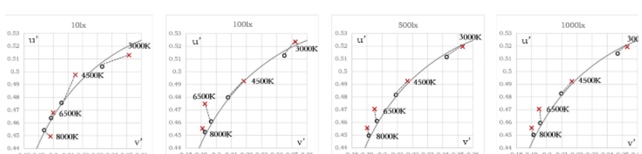
	painting	fruit and vegetable	skin colour chart
ΔE^*_{ab}	8.2	7.6	5.9

Averaged visual results of evaluation experiment 1

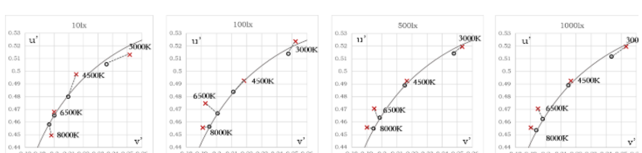
Firstly, the averaged results were plotted in CIE1931 *u'v'* plane (see Figure 6). The red crosses are the chromaticity coordinates of the adapting conditions of the real scene, and the black circles are the chromaticity coordinates of the visual results on the display. The dotted lines between them represent the appearance shift between display and real scene. The shorter the dotted line is, the closer visual perception of the display is to the real scene. The results showed that the visual results of the display under low CCT are quite different from the real scene, especially for low luminance. And the results of three types of scenes showed high consistency, which indicated that the contents of the scene didn't impact the direction and magnitude of the appearance shift. Thus, the averaged results of three scenes were used in subsequent analysis.



(a) painting



(b) fruit and vegetable



(c) skin colour chart

***Figure 6.** Averaged results of experiment 1 in CIE1931 u'v' plane, '×': adapting conditions '○': visual results.*

Testing the performance of CIECAM16

The visual results were also used to test the performance of CIECAM16. Table 3 showed the CCT and luminance of No.21 patch predicted by CIECAM16. It can be found that there is a big deviation in the prediction of luminance. And CIECAM16 should be revised especially for the low CCT under low luminance. The predicted images of CIECAM16 and the averaged visual results were also compared in Figure 7, taking 3000K&10lux, 4500K&100lux, 8000K&1000lux as examples.

Table 3. The prediction performance of CIECAM16 in terms of CCT and luminance of No.21 patch.

CIECAM16		Visual results	
CCT	$L(cd/m^2)$	CCT	$L(cd/m^2)$
3410	0.36	3849	17.12
5088	0.35	5928	21.38
7496	0.38	7249	19.38
9747	0.36	7819	21.84
3274	5.55	3231	58.33
5096	5.77	5344	47.80
7483	5.83	6974	56.06
9627	5.88	7970	55.16
3278	32.49	3234	112.02
5172	33.41	5081	106.44
7644	34.26	7174	106.96
9681	33.41	8003	110.90
3257	70.13	3266	137.78
5181	71.93	5082	147.43
7704	73.65	7276	150.02
9861	74.39	8387	154.56

(a) 3000K&10lux

(b) 4500K&100lux

(c) 80000K&1000lux

***Figure 7.** Comparison of the predicted images of CIECAM16 and the averaged visual results.*

Experiment 2: Real scene & Test display

Experimental setup

According to the above, the contents of the scene had no significate influence, and the results of 'skin colour chart' showed highest stability. Thus, only 'skin colour chart' was used in this experiment, and sixteen adapting conditions were kept the same. And three sizes of displays were used, including EIZO CG243W, Huawei MatePad and Huawei Mate40 Pro. This results in a total of 2,499 evaluations for each observer, i.e., (4 CCTs x 4 luminance levels +1 repeat lighting condition) x 1 real scenes x 3 displays x 49 evaluations.

Observers

Twelve normal colour vision observers participated in each experiment including six males and six females. In total, 29,988 evaluations were accumulated.

Results

Observer variation

Mean Colour Difference from the Mean (MCDM) were calculated to represent the observer variation of the result. The inter-observer variation describes the consistency between all observers. The MCDM values were ranged from 5.2 to 6.9 ΔE^{*}_{ab}.

Averaged results of evaluation experiment

The averaged results (XYZ values) were transformed to CCT (see figure 8) and luminance (see Figure 9). It can be found that the size of display didn't show a significate impact. And the visual results of the display under low CCT are quite different from the real scene, especially for low luminance.

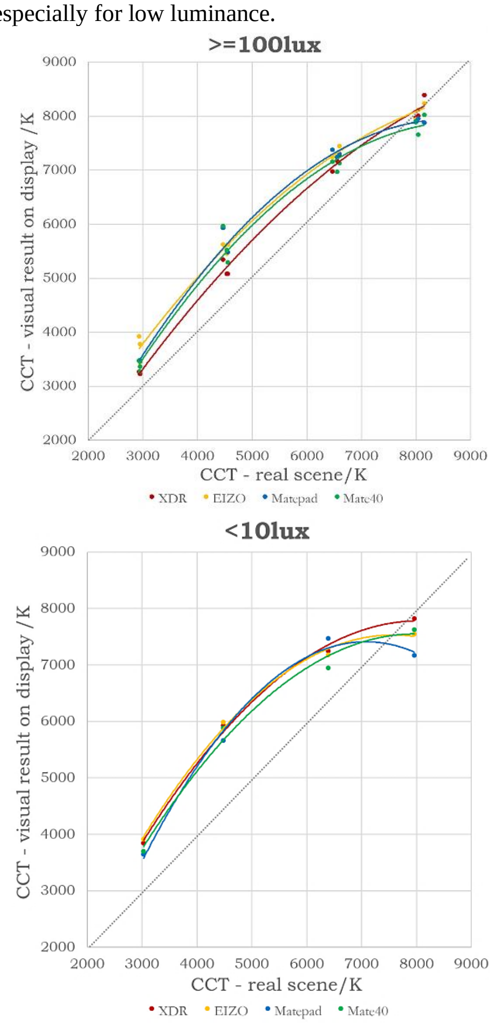


Figure 8. *Averaged results in terms of CCT of experiment 2.*

In addition, the visual results of luminance on the display were much higher than real scene. It is important to note that the luminance range of four displays are very different, so the maximum luminance is taken as a variable (see Figure 10). The results showed a power function distribution, and the coefficient was related to the maximum luminance of the display.

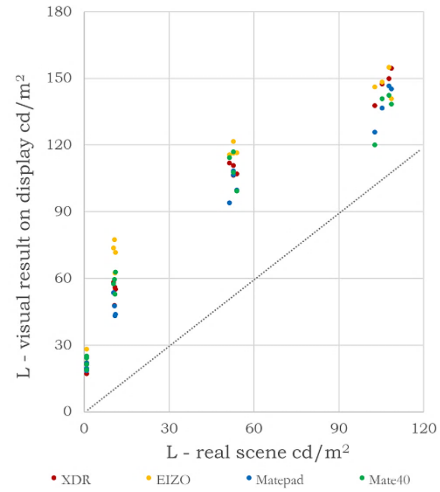


Figure 9. *Averaged results in terms of luminance of experiment 2.*

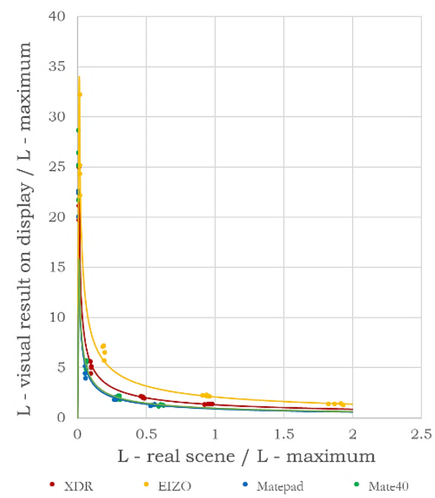


Figure 10. *Averaged results in terms of luminance of experiment 2 (take maximum luminance of each display as a variable).*

Propose a formulation to revise CIECAM16

As for the data showed a great consistency between different experimental settings, such as contents of the real scene and the size of the display. A revised formulation was proposed with high accuracy based on the averaged data from experiment 1 and 2.

The CCT and luminance (L) were modelled separately, as given in Equation (1) and Equation (2), CCT_v is the CCT of visual results on the display, and CCT_s is the CCT of the real scene, L_v is the luminance of visual results on the display, and L_s is the luminance of the real scene, L_{max} is the maximum luminance of the display. Table 4 shows the accuracy of the formulation.

$$\begin{aligned} &for\ L \geq 100lux, \\ &\quad CCT_v = -0.00011528 * {CCT_s}^2 + 2.1653 * CCT_s - 1978.3 \\ &for\ L < 100lux, \\ &\quad CCT_v = -0.0001783 * {CCT_s}^2 + 2.711 * CCT_s - 2766.6 \end{aligned} \quad (1)$$

$$L_v/L_s = \left(66.105 * {L_{max}}^{-0.676}\right) * (L_s/L_{max})^{-0.6} \quad (2)$$

Table 4. Accuracy of the formulation characterized by R^2.

	CCT Equation (L>=100lux)	CCT Equation (L<00lux)	L Equation
R^2	0.987	0.986	0.973

Conclusion

A series of psychophysical experiments using threshold method were conducted to reproduce the colour appearance between real scene and images on self-luminous display. Three types of real scenes were built up in a lighting room, including painting, fruit and vegetable, skin colour chart. Sixteen adapting conditions were designed including four CCTs (3000K, 4500K, 6500K, 8000K) and 4 luminance levels (10lux, 100lux, 500lux, 1000lux). Four displays with different size were studied. The result indicated the colour appearance of real scene and the image on the display were different, especially for low CCT and luminance level. The contents of scene and size of display didn't show a significate impact. The prediction performance of CIECAM16 was tested. It can be found that there is a big deviation in the prediction of luminance, and CIECAM16 should be revised especially for the low CCT under low luminance. Finally, a revised formulation was proposed with high accuracy.

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Author Biography

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