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A new corresponding color dataset covering a wide luminance range under high dynamic range viewing condition

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Abstract

An experiment was carried out to investigate the change of color appearance for 13 surface stimuli viewed under a wide range of illuminance levels (15-32000 lux) using asymmetrical matching method. Addition to the above, in the visual field, observers viewed colours in a dark (10 lux) and a bright (200000 lux) illuminance level at the same time to simulate HDR viewing condition. The results were used to understand the relationship between the color changes under HDR conditions, to generate a corresponding color dataset and to verify color appearance model, such as CIECAM16.

Introduction

In recent years, people acquire information largely through displays. With the rapid development of display technology and image processing technology, people have a great demand for high quality display, especially HDR technology. As we all know, HDR images file is a special graphics file format, each pixel of it not only have the ordinary RGB information, but also the actual brightness information. Therefore, compared with ordinary images, HDR images can provide more dynamic range and image details, which can better reflect the visual effects in the real environment.

However, the dynamic range of the real scene is always far beyond the dynamic range of the display, so how to correctly map the stored brightness information is crucial. The ITU has established two photoelectric conversion curves for HDR: One is Dolby’s Perceptual Quantizer (PQ) curve [1], and the other is BBC’s Hybrid-Log Gamma (HLG) curve [2].

Color reproduce is also important. Although CIE XYZ chromaticity system can quantitatively represent a color, it cannot accurately represent the actual color perception of human eyes. In addition to the color stimulus itself, the external observation environment will also have an impact on the color perception of human eyes. Therefore, it is necessary to introduce a color appearance model to describe the color perception of human eyes in a complex lighting environment or in a specific observation background. Usually, researchers uses color samples or images to collect corresponding colors data, which is called Psychophysical experiments.

CIE recommended CIECAM02 [3] to supersede CIECAM97s [4]. It is a model of color vision capable of predicting color appearance under different viewing environment, which introduced a chromatic adaptation model CAT02 [4]. In 2016, Li et al. [5] modified the model structure on the basis of CIECAM02, simplified the original model, and proposed a new color appearance model, CIECAM16.

The color appearance values obtained in CIECAM16 are J (lightness), C (chroma), Q (brightness), M (colorfulness), S (saturation) and h (hue). Among them, brightness and colorfulness reflect the absolute intensity of the color stimulus perceived by the observer; lightness and chroma are relative values of the absolute intensity of the color stimulus perceived by the observer compared to the perfectly diffuse reflector.

The goal of the present research is to accumulate reliable experimental data of corresponding colors and test the accuracy of color appearance model CIECAM16. The experiment was carried out on the high dynamic range experimental platform. Color matching as one of the psychophysical experiments was adopted to collect matching data of 5 achromatic samples and 8 chromatic samples under 6 illuminance levels by 10 observers.

Experimental

Viewing devices

The experimental environment is composed of three illumination Boxes (IBs), named IB1 to IB3. IB1 can be adjusted within the range of 15 ~ 200000lx. IB2 and IB3 were set at 10 lx and 200000 lx, respectively. Figure 1 shows the experimental situation. Observers viewed the three IBs at the same time. This arrangement of three IBs was intended to form an HDR viewing environment.

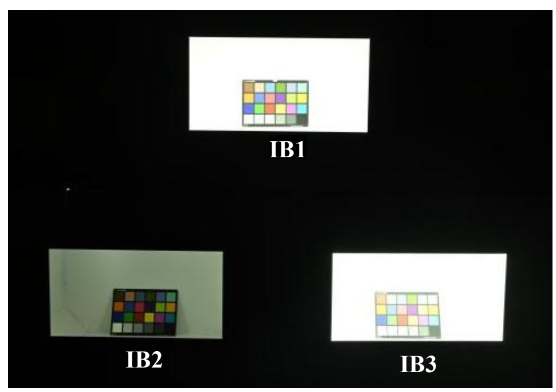


Figure 1. *HDR Illumination Boxes*

Table 1 shows the white and black colors in the bottom left and right of X−Rite Macbeth ColorChecker Chart (MCCC) in IB1 within the full range of illuminance with the Correlated Color Temperature (CCT), color deviation from the blackbody locus (Duv) and Contrast which is a ratio of lux levels between the white and the black in the MCCC. It can be seen the illuminance range to cover a wide range and contrast, CCT and Duv to be highly stable.

Table 1: HDR box's condition under different illuminance levels

Lux	White (cd/m²)	Black (cd/m²)	Contrast	CCT (K)	Duv
15	4.7	0.2	26	5989	0.0022
100	30.6	1.2	26	5987	0.0012
1000	333.1	13.0	26	5996	0.0018
10000	3100	122.2	25	6001	0.0005
32000	9895	391	25	6019	-0.0002
100000	30510	1213	25	6068	-0.0010
200000	60520	2410	25	6143	-0.0017

It was determined to apply 6 illuminance levels in the experiment: 15, 100, 1000, 3150, 10000 and 32000 luxs. The display used in the experiment was an Apple Pro Display XDR, which was set to a peak luminance of 500 cd/m^2.

***Figure 2.** 13 test samples from NCS Album*

They were selected from the NCS Album specified in terms of blackness, chromaticness and hue. E.g., 2020-G50Y means a color to have blackness of 20, chromictness of 20 and a hue including 50% of green and 50% of yellow. Figure 2 shows 13 stimuli used in the experiment, including 8 chromatic colors, respectively 3040-R50B, 5020-R50B, 3020-B50G, 3040-B50G, 2020-G50Y, 3050-G50Y, 2040-Y50R and 6020-Y50R, and 5 achromatic colors, 2500-N, 5000-N, 6500-N, 7500-N, and 8500-N.

These colors were selected to give a reasonable coverage of color gamut and hue angles as possible. Besides, efforts were made to select colors with moderate range of chromaticness and darkness. So, the patches under very high illuminance level in IB1 can be matched on XDR display.

Figure 3 shows that the experimental situation. Asymmetrical matching method was used in the experiment. The background of the display was black, while samples in IB1 were against a white background. The reason to set a black background on the display was to avoid the large variation of glare on the background of the display caused by the nonuniform lighting environment. Using a black background, the matching results under all different levels can be directly compared to show the trend of shift of color appearance.

Observers

In total, 10 observers participated in the experiment, including 4 females and 6 males. Their ages ranged from 22 to 27 years old, with an average of 23.7 years old. Each observer in the experiment passed the Ishihara color vision test. All observers had color science background.

Procedure

The experiment was divided into 3 sessions. Each session took about 30 minutes and included 2 illuminance levels. In each level, observers matched 13 stimuli, taking about 30 minutes. For each level, observers took a one-minute adaptation. The whole experiment took about 30 hours (10 observers × 6 illuminance levels × 30 minutes).

The experiment was conducted in a dark room. Before the experiment, each observer was given the instruction of the experiment. Then, a short training was given to familiarise with the color control using keyboard.

Observers sat about 1.5 meters away from the back wall of the IB1. The size of the sample was 4^{o} viewing field. The seat of observer was adjusted to have the same line of sight between the observer's eyes and samples.

The initial color of the matching on the display was gray, which was set to L*=50, a*=0, and b*=0 in the experiment, meaning that it is half the maximum brightness of the display. In addition, the initial color was different from any of the 13 stimulus colors used in the experiment, ensuring that the observer was not affected by the initial color.

***Figure 3.** Experiment environment*

In the real experiment, the experimenter randomly choose a illuminance level of IB1, and observers were asked to adapt to the environment for 1 minute. Subsequently, observers were asked to match the test samples which was randomly placed in IB1. For color samples, observers were instructed to make adjustments using L^*, C^*_{ab}, h_{ab} and a^*, b^* controls for chromatic and achromatic colors, respectively. Two X-rite ColorChecker Charts were placed in IB2 and IB3, so that the same bright and dark colors on the charts appear in the observer's field of view, resulting a high-dynamic range environment.

Results

The matching results were recorded in RGB values and these were measured using a Konica-Minolta CS2000 tele-spectroradiometer. The results were transformed to XYZ values for CIE 1964 standard colorimetric observer.

Inter-observer variation

Inter-observer variation was first analyzed. It was reported in terms of Mean of Color Difference from the Mean (MCDM) in CIELAB units. Tables 2, 3 and 4 list the inter- observer variation between observers, for all samples in each illuminance level and for each stimulus, respectively. Table 2 showed that the overall variation to have a mean of 6.2 ranged from 4.9-8.5 CIELAB units.

Note one of the observers, Observer 2, was removed due to very poor performance. Table 3 shows a clear trend that observers were more consistent for matching the darker stimuli. From Table 4, it can be seen that observers performed matching on achromatic colors more precisely than that of chromatic colors. In addition, observers were less consistent to match the lighter than darker stimuli. Figures 4a and 4b plot the MCDM values against L^* and C^*_{ab} respectively. It can be clearly seen observer consistency reduced for lighter color stimuli, respectively.

Note that observers did respond they could not produce a satisfactory match for the darker stimuli. However, the above MCDM values showed a more observer consistency for the darker shades. This could be attributed limited color range they can select on the display. The present MCDM values are also bigger than those of earlier experiments. This could be attributed to the asymmetrical matching environment, including different backgrounds (white and black), different media (surface and self-luminous), and different illuminance difference between the two fields.

Table 2: MCDM for each observer (remove Ob2).

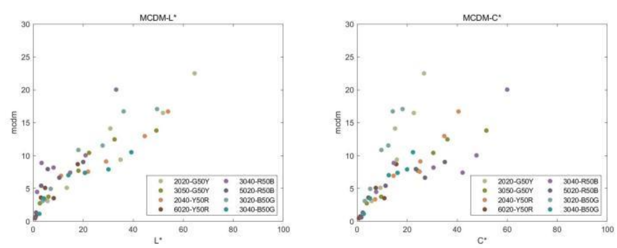
1	3	4	5	6	7	8	9	10	Mean
6.0	6.1	4.9	5.0	5.4	8.5	6.6	5.4	7.3	6.2

Table 3: MCDM for each luminance level

15lx	100lx	1000lx	3160lx	10000lx	32000lx
1.74	3.20	6.13	6.33	8.35	11.1

Table 4: MCDM for each stimulus

chromatic colors		achromatic colors	
2020-G50Y	11.79	2500-N	7.64
3050-G50Y	8.49	5000-N	3.59
2040-Y50R	9.44	6500-N	1.63
6020-Y50R	3.70	7500-N	1.17
3040-R50B	9.84	8500-N	0.51
5020-R50B	5.17	Mean	2.91
3020-B50G	10.71		
3040-B50G	6.25		
Mean	8.17		



(a) **(b)**

Figure 4. *MCDM values plotted against (a) L*; and (b).C*$_{ab}$*

Corresponding colors

The results of the matching results were reported in terms of XYZ tristimulus values for the stimuli measured on display and in IB1. The results in this type are known as corresponding colors, two sets of tristimulus values giving the same appearance. In this study, a pair of corresponding color was formed one against a white background and the other against black background, both under different illuminance levels.

The luminance value in terms of cd/m^2 was first analyzed. These were transformed from illuminance to luminance by dividing π. Figure 5 shows the plot of corresponding log10(luminances) between the matched and target stimuli. It shows the change of luminance for each color (see each horizontal locus). Each best fitted line close to vertical direction represents the full range of colors from the highest to the lowest illuminance levels studied. It can be found that the trends of color change are consistent and a similarity for both chromatic and achromatic stimuli.

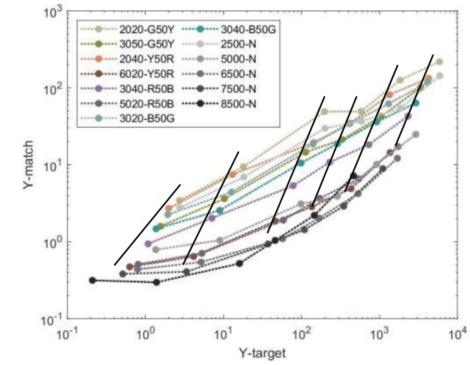


Figure 5. *Plot of corresponding log$_{10}$(luminance) values between the target and the visual results*

Figure 6 shows the matching results plotted in u'v' chromaticity diagram. Each target color stimulus, measured under different luminance levels in IB1 condition, are located at one chromaticity, this is expected that all stimuli having same saturation. Just like an object illuminated by daylight at varying illuminance levels. Their chromaticity values will be unchanged. For the matched results on the display, stimuli at different luminance levels do still situate close to each other. It is expected that their results will be more scattered. However, 3 darker matched stimuli (6020-Y50R, 5020-R50B, 3040-B50G) did show larger color shift away from the target stimuli and also had larger scatter than the target chromaticity coordinates. As explained earlier, this could be due to out of gamut of the display.

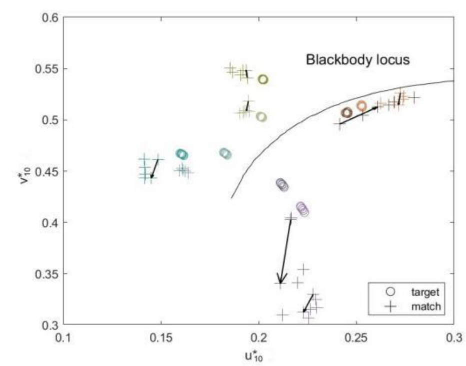


Figure 6. *The experimental results are plotted in CIE $u'_{10}v'_{10}$ plane.*

CIECAM16's Performance

CIECAM16 is a model of color vision to predict color appearance under different viewing conditions. It is widely used for color reproduction, i.e., the same appearance to be reproduced under different conditions, such as illuminant, illuminance levels,

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background luminance factor, surround conditions. The target results (in XYZ) were inputted to the forward CIECAM16 model to predict the color appearance in terms of lightness (J), chroma (C) and hue (h) under the white background. The reverse model was then used to transform these attributes to XYZ values corresponding to the black background condition at the luminance of peak display white, 500 cd/m^2. Again, the log-log (luminance) are plotted in Figure 7.

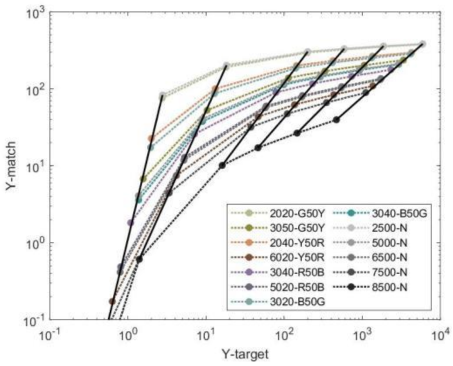


Fig. 7 *Plot of corresponding log$_{10}$(luminance) values between the target and the CIECAM16 predicted results*

For a perfect agreement between the model predicted and visual results, Figures 5 and 7 , should be very similar. It can be seen that there is a large discrepancy between them. The largest discrepancy is the model predicted a large difference of luminance range from brightest to the darkest by a factor of 2 log units.

Figure 8 shows the plot of the visual and target results in CIECAM16 a'b' plane, drawn in crosses and open circles respectively. It can be seen that in general, there are systematic hue shifts for all colours except the orange (Y50R) colors.

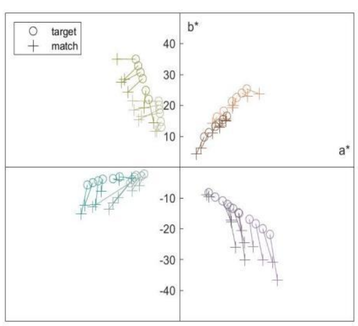
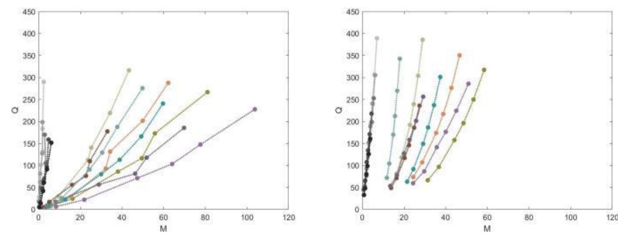


Fig. 8. *The experimental results are plotted in CIECAM16 a'b' plane*

Figures 9a and 9b show the color matching and the CIECAM16 predicted results respectively plotted in CIECAM16 Brightness (Q) and colorfulness (M) plane. The Q and M scales were developed from the Lv and Luo's work [6]. They conducted an experiment to develop two-dimensional color appearance scales including whiteness, blackness, vividness and depth. 80 stimuli having a large range of luminance from 5 to 4200 cd/m^2 were used. Their new scales were developed based on the absolute scales of CIECAM16 brightness and colorfulness and gave accurate prediction to the visual data.

An expected, a clear trend can be seen in Figure 9a, i.e. an increase of Q and M with an increase of illuminance level. This is known as Hunt effect [7]. Also, the pattern of color shifts represent the two-dimensional color appearance scale of vividness, a radiation from the black point. Figure 9b represents the CIECAM16 trends. It can be seen that the slope of color changes between those in Figures 9a and 9b are quite different. Also, CIECAM16 loci do not converge to the black point.



(a) Visual results (b) Predicted results

Figure 9. *Plot of (a) visual and (b) CIECAM16 results in Q-M plane*

Conclusions

A color matching experiment was conducted to match surface patches ranged from 15 to 32,000 lux levels on a display in HDR viewing condition. A corresponding color dataset was established. The results were used to show various visual effects via various plots, including log-log (luminance), CIE u'v', CIECAM16 a'b' and QM. Various effects were identified such as dynamic luminance effect, Hunt effect.

New experiments will be conducted to make symmetrical matching and magnitude estimation in more illuminance range.

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