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New colour appearance scales under high dynamic range conditions

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Abstract

New colour appearance scales close to daily experience and image quality enhancement are highly desired including whiteness, blackness, vividness and depth. This article describes a new experiment to accumulate the data under HDR (high dynamic range) conditions. The data were then used to test the performance of different colour appearance scales such as CIELAB and CAM16-UCS plus the recent extension by Berns' Vab, Dab*. The results showed those Berns' scales gave a reasonable performance. However, it was found no scale is capable of predicting colour appearance data covering a wide dynamic range. New scales were developed based on the absolute scales of brightness and colourfulness of CAM16-UCS and gave accurate predictions to the data.*

Introduction

The conventional colour appearance scales based on Munsell colour order system [1, 2] have been widely used including lightness, chroma and hue. Almost all colour spaces and appearance models include these scales. Colour appearance models, such as CIECAM02 [3] and CAM16 [4], also include absolute scales brightness and colourfulness to reflect the viewing conditions. However, these scales only correspond to one dimension. In real life, these are impractical. For example, colour appearance of objects changes according to different lighting intensities, i.e. same objects viewed under sunlight are brighter and more colourful and becomes dimmer and less colourful when view under the shadow. This is known as Hunt effect. The effect can be modelled by the vividness scale, Vab* proposed by Berns [5]. When doing painting, it is typical by mixing solid pigment with white base. The more coloured pigment is added, the colour becomes darker and more colourful. This is a scale of saturation or depth, Dab* proposed by Berns [5]. Cho et al carried out experiments to assess colour samples by the British and Korean observers [6] and the visual results were used to test different colour models and to develop new scales based on CIELAB [7] and CAM02-UCS [3]. They also found the opposite of depth and vividness perception is whiteness and blackness perception respectively, which are the main attributes of the NCS system. With the demand for high image quality, these colour scales should be valuable to enhance image quality. An experiment was conducted here to 1) prepare stimuli of high dynamic luminance range from 100 to 4500 cd/m^2, 2) perform visual assessments using Chinese observers, 3) compare the scales with those developed by Berns and Cho et al, and 4) develop new scales to consider HDR luminance range.

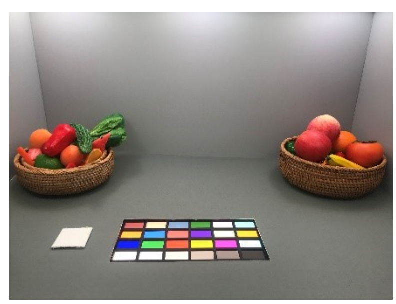
Methods

Light settings

Figure1. shows the experimental situation. The experiment was carried out in a viewing cabinet. The background colour had a L* of 44. Two multi-channel LED illumination systems supplied by the Thouslite Ltd. were used. One was used in the viewing cabinet having a CCT of 6500K. Its spectral power distribution (SPD) is given in Figure 1.1.

Stimuli

A test chart included 24 coloured filters which were illuminated by a backlit LED lighting transmitter. A mask having the same background colour had the same size as each stimulus with 2^o field of view. Observers only viewed one stimulus at a time. Each stimulus (or a colour filter) had 5 luminance levels ranged from 93, 255, 580, 1400 to 4616 cd/m^2 defined by measuring the white colour in the bottom left corner of the chart (see the below of Figure 1). Two fruit baskets were placed inside the adapting field to make the whole scene as a nature environment. All stimuli appeared like surface colours. In addition, a reference white was placed beside the test stimuli, having x, y, L values of [-1.54, 2.05, 92.83].



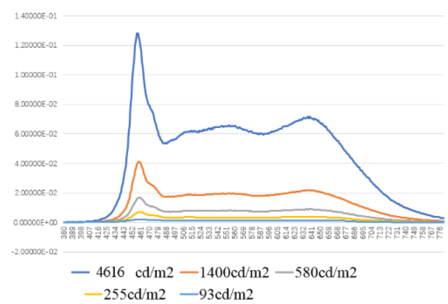


Figure 1*. The experimental condition (above) and the SPD of the 5 luminance levels (below).*

Sixteen stimuli from the 24 colours in the chart were used in the experiment. There were 80 test stimuli, i.e. 16 stimuli x 5 luminance levels. . Figure 2 shows the distribution of all samples in CIELAB a*-b* and L*- Cab* planes under D65/10^{o} conditions and all stimuli were measured using a JETI 1211 tele-spectroradiometer, whose spectral range was from 250 to 1000 nm at a 5 nm interval. Note only 16 colours were plotted and they were normalized to their corresponding white at luminance of 580 cd/m^2. The geometry of illumination and receiving is 0^{o}/45^{o}. When performing colour measurement, the light in the viewing booth was on. This would ensure the measurement results correspond to the observer's viewing condition.

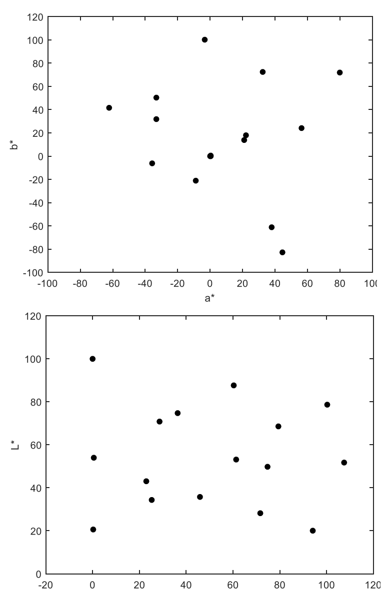


Figure 2*. The distribution of samples in CIELAB a*-b* (above) and L*- Cab* plane (below) under 4616cd/m^2*

Observers

Twenty observers (10 females and 10 males) took part in the experiment. All of them had normal colour vision tested by Ishihara colour vision test and received a training session to explain each impression.

Experimental procedure

Observers were asked to adapt in the viewing environment for one minute looking around the inside of viewing cabinet, such as the fruits, the background before the experiment. Four colour appearance scales were assessed: whiteness, blackness, vividness and depth. During the experiment, observers assessed stimulus separately one at a time. The alternative forced choice method was used to ask observers to judge the stimulus in question to be close to white or not a white, black or not a black, vivid or not vivid, deep or not deep respectively.

Results

The experimental results were processed, to transform the raw data in terms of "yes" and "no" to percentage. Those were than transformed to z-score.

Testing performance of color appearance scales

The visual results of whiteness, blackness, vividness and depth at 5 luminance levels were used to test 8 different scales: CIELAB L*, Berns' vividness and depth, and saturation (s), colourfulness (M), lightness (J) and brightness (Q) of CAM16-UCS. When calculating using CAM16-UCS lightness (J), CIELAB and its extended scales, all colours in each luminance level were treated separately. These scales were calculated to refer to a reference white (bottom left of the colour chart (see Figure 1 (left)). For CAM16-UCS s, M, Q scales, these were reported in terms of absolute value.

Figure 3.1-3.4 show the plot of the correlation coefficients of 8 scales against the visual whiteness, blackness, vividness and depth results respectively. In each plot, each model had 5 luminance levels together with the combined data (named Total). The correlation coefficient was used to indicate the performance of each scale. A better scale should have a larger (positive) or a smaller (negative) correlation coefficient.

The results are summarized below:

- For estimating whiteness results (Figure 3.1), Dab*(-0.82) performed the best, followed by s scale (-0.68).
- For predicting blackness results (Figure 3.2), lightness scales (L*, J) and brightness scale (Q) performed better (-0.72 to -0.77), followed by Vab* (-0.67).
- For vividness results (Figure 3.3), M performed the best (0.81), followed by Cab* (0.76) and Vab* (0.76).
- Finally, for predicting depth results(Figure 3.4),, the lightness L* and brightness Q performed the best (-0.84), followed by J (-0.82).
- Note that Berns' depth and vividness only gave reasonable accurate prediction. All scales could not give an overall good performance across all luminance levels. In general, the luminance levels for 580 and 255 cd/m^2 gave better performance than the others. Because the model scales were mainly derived from the data accumulated in this range.

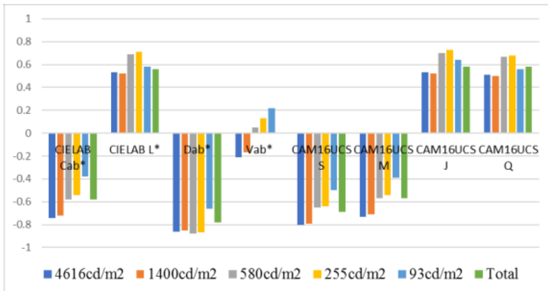


Figure 3.1*Correlation coefficients (r) of Whiteness results versus different models*

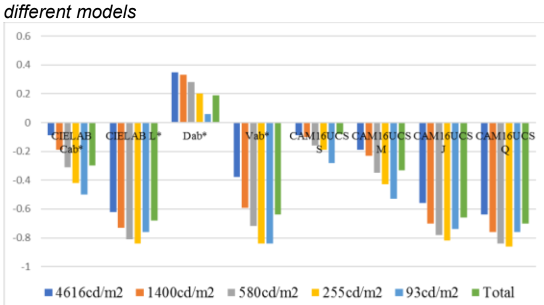


Figure 3.2 *Correlation coefficients (r) of Blackness results versus different models*

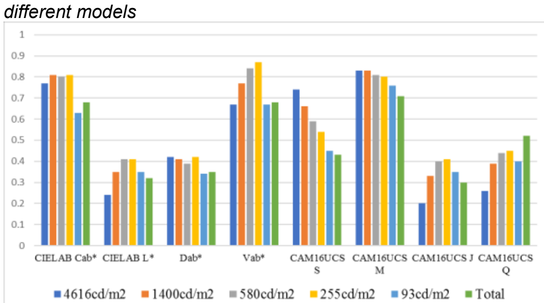


Figure 3.3 *Correlation coefficients (r) of Vividness results versus different models*

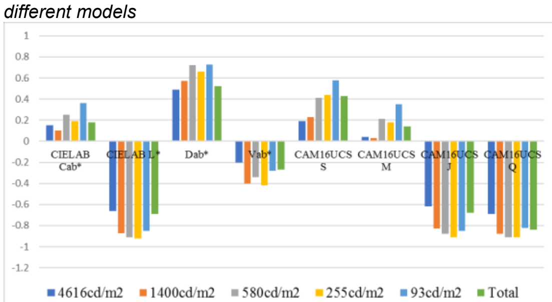


Figure 3.4 *Correlation coefficients (r) of Depth results versus different models*

New ellipsoid model

Similar to the work by Cho et al. [7], the ellipsoid-based models (Vividness (V), Depth (D), blackness (K), whiteness (W)) were developed based on CAM16-UCS using distance metric as given in Equation (1). The centre of the ellipsoid can be considered to be the strongest perception, e.g. the most vivid. The boundary of the ellipsoid indicates the 50% of vividness intensity.

$$(V, D, K \text{ or } M)\ scales = k_M + k_L\sqrt{(Q-Q_0)^2 + k_A(a'-a_0')^2 + k_B(b'-b_0')^2} \quad (1)$$

Table.1 All coefficients of Equation (1)

Scale1	k_1	k_2	k_3	k_4	Q_0	a_0'	b_0'
V	-18	0.21	72	65	0	0.40	-5.9
D	-347	1.1	0.01	5.3	300	-3.6	-1.1
K	82	-0.2	17.5	12.3	0	-2.5	-8
M	114	-0.4	13.5	17.7	300	-0.7	-5.3

Note that Cho et al. used lightness scale in Equation（1）and CAM16-UCS brightness and colourfulness scales were used here. This would allow changes in colour appearance at different luminance levels to be considered. In other words, this would consider HDR viewing conditions.

Figure 4 plots the new models' predictions against visual results. It can be seen that the scattering of the data points was quite small, i.e. the data from different luminance levels are not distinguishable. The results in term of correlation coefficient from the new scales are summarized in Figure 4 (a) arranged in the same way as Figures 4 (a) to 4 (d). In general, the visual data versus V, D, K, M scales had quite small scattering, or models to have a good fitting to the visual data. This proved that new models about colour appearance scales which can cover a wide dynamic range can fit visual data covering a wide range very well.

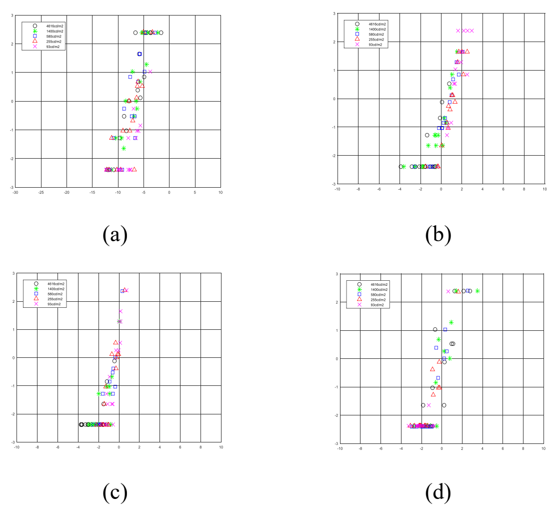


***Figure** 4. The plot of visual data (z-scores) versus the predictions from the new vividness (V), Depth (D), Blackness (K) and whiteness (W) scales.*

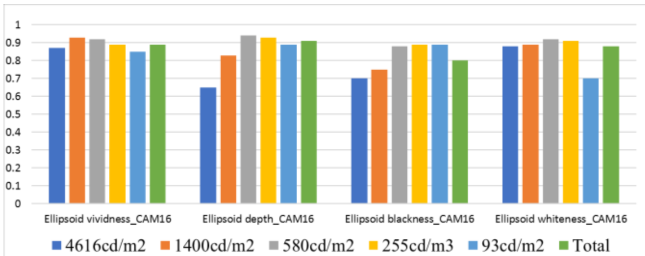


***Figure** 5. Correlation coefficients (r) of V, D, K, M results versus V, D, K, M scales separately.*

Conclusions

The studies carried out the physics experiment on the colour appearance of the high dynamic range and the results were used to test CIELAB Cab*, CIELAB L*, Berns' vividness, depth and CAM16-UCS. All of these models can't predict the colour perception under HDR conditions very well. Based on it, the studies develop new models about colour appearance attributes which can cover high dynamic range.

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Author Biograph

Xi Lv received her BSc and Master degree from College of Optical Science and Engineering, Zhejiang University, Hangzhou, China. She is supervised by Professor Ming Ronnier Luo since 2018. Her research interests include colour appearance modelling.