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# Two-dimensional models to predict a new colour appearance dataset

***Molin Li, Ming Ronnier Luo;State Key Laboratory of Extreme Photonics and Instrumentation, Zhejiang University; Hang Zhou, China;***

## Abstract

*An experiment was carried out to study the two-dimensional (2D) colour appearance scales including whiteness, blackness, vividness, and depth. Forty samples were used to be assessed by 10 observers under a 6000K illuminant at 10, 100, 1,000 to 10,000 $cd/m^2$. These data were used to develop new 2D scales and compared with the existing ones. It comes out the CAM6-UCS and sCAM based scales performed the best. The sCAM is a colour appearance model based on the Simple Uniform Colour Space (sUCS). Its structure will also be introduced.*

## Introduction

In colour science, colour is defined by three one-dimensional scales, lightness, chroma and hue such as the Munsell spacing [1]. However, two-dimensional scales are frequently used in real life, such as vividness and depth which are closely related to our visual experience. For example, when a colour is illuminated by a high luminance light source, it can be observed the colour of an object to increase vividness from shadow to highlight regions, resulting in an increase of both lightness and chroma. Depth is widely experienced in the colour design or colorant industry, when the concentration of the colorants increases, it would result in a deeper colour, and also its lightness decreases and chroma increases. These concepts were introduced by Berns [2], who also proposed $V^*_{ab}$ and $D^*_{ab}$ based on CIELAB spacing [3].

The whiteness and blackness scales are adopted by the NCS system [4]. These terms are widely used by the designers and colorant users, because of their associations with adding white and black colorants for colour mixing, respectively. From our experience, by adding white colorant, the mixture would appear whiter, or an increase of lightness and reduction of chroma. So, the whiteness of the colour is increased. Conversely, an increase of blackness by adding black colorant to a mixed colour, it would reduce lightness and increase chroma. So, there is an increase of blackness of the colour.

From the Cho et al's study [5,6], Korean and British observers were used to accumulate data and derive models. It was found people from the two ethnicity groups agreed well with each other. Their results also indicated the whiteness and depth perceptions had strong inverse correlation and can be considered opposite end of the same scale, and also for blackness and vividness, as illustrated in Figure 1, where chroma and lightness are the one-dimensional scales in the x- and y-axes, respectively, and the two two-dimensional scales are whiteness-depth and blackness-vividness, respectively. These scales give a good representation of the object changing colour appearance in real world and have importance in the processing for image applications.

In 2020, International Commission on Illumination (CIE) has established a Technical Committee (TC) 1-99 with aims to accumulate experimental data and to propose the 2D scales for industrial applications. The present work was designed to achieve these aims.

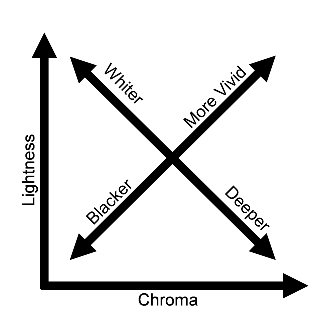
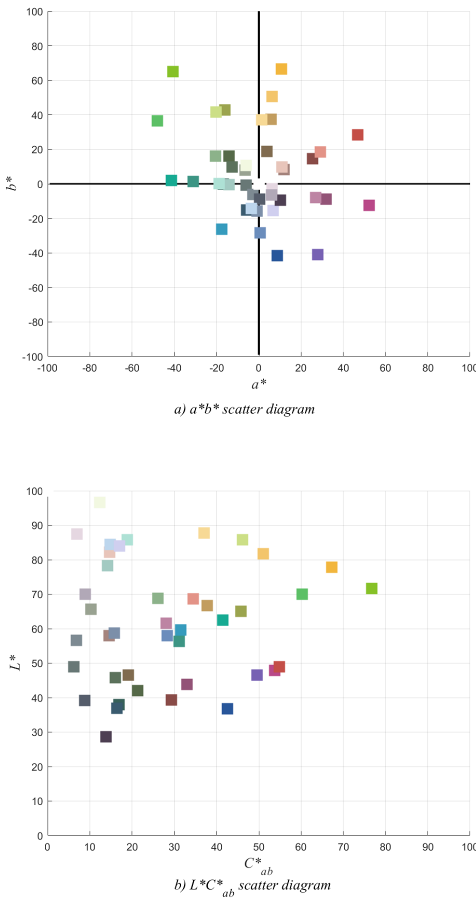



***Figure 1.*** *The relationship between one- and two-dimensional scales.*

## Experimental

Figure 2 shows the 40 experimental samples selected from the NCS atlas. They were evenly distributed in CIELAB space. Ten normal colour vision observers according to Ishihara test took part to estimate the magnitude of 4 two-dimensional scales, vividness, blackness, whiteness and depth. The experiment was conducted at a high dynamic range lighting cabinet from 0 to 20,000 cd/m$^2$, with a mid-grey background $[66, -1.6, 3.4]$ for $L^*$, $a^*$, $b^*$ values. All the test colours were assessed under a 6000K light source at 4 luminance levels, 10, 100, 1,000 and 10,000 cd/m$^2$.




*a) a*b* scatter diagram*

*b) L*C*ab scatter diagram*

***Figure 2.*** *Sample distribution in a) $a^*b^*$ and b) $L^*C^*_{ab}$ planes.*

Prior to the experiment, each observer was given an extensive training session to use magnitude estimation technique to scale 2D scales studied here. They were first learned the one-dimensional scales by showing hue pages in the Munsell Atlas. This was then followed by the hue circle, together with the whiteness and blackness concepts using the NCS Atlas. The definitions of the 2D colour appearance scales are also given:

***Vividness (V)*** is an attribute as the distance from a neutral black to the colour in question.

***Depth (D)*** is an attribute as the distance of colour from neutral white.

***Whiteness (W)*** is a scale as the degree to which an area appears to contain white. It is an NCS scale (see earlier) and is defined as the resemblance to pure white.

***Blackness (K)*** is a scale that describes the amount of black present in an area. It is also an NCS scale, defined as the resemblance of pure black.

Subsequently, some test colours were provided for them to assign numbers to the 2D scales studied. Note that 2D scales have a fixed anchor point and open-end in both ends of the scale, i.e. a reference white as 0 for scaling depth and 100 for scaling whiteness. In addition, an imaginary black was used as anchor point as 100 for scaling blackness and 0 for scaling vividness.

# RESULTS

## *Observer Variations*

Data analysis were first carried out using the mean data to represent all 10 observers. The inter- and intra-observer variations were calculated in terms of the standard residual sum of squares (*STRESS*) [7] to indicate the degree of agreement. For a perfect agreement between two sets of data, the *STRESS* value is zero. It can be considered as % disagreement. For inter-observer variation, observers exhibited the highest consistency for Vividness ($V$) and Depth ($D$) with a *STRESS* value of 20, followed by Whiteness ($W$) and Blackness ($K$) with a *STRESS* value of 25. Across all luminance levels, observer accuracy was consistent with a mean score of 24, varying between 22 and 25. For intra-observer variability, the data indicated the following scores: Vividness ($V$) had a variation of 10.1, Depth ($D$) had a variation of 12.8, Whiteness ($W$) had a variation of 14.9, and Blackness ($K$) had a variation of 14.4, reflecting a consistent pattern among observers with mean variability ranging from 10.1 to 14.9.

## *Developing new 2D scales*

The mean results from the 10 observers were used as the raw data. New 2D scales were developed based upon the ellipse model in CAM16-UCS lightness ($J'$) and chroma ($M'$) space. The 4 scales are named $V_{\text{CAM16-UCS}}$, $D_{\text{CAM16-UCS}}$, which were derived to fit the present experimental results. In addition, the relationships of

$W_{\text{CAM16-UCS}} = 100 - D_{\text{CAM16-UCS}}$ and $K_{\text{CAM16-UCS}} = 100 - V_{\text{CAM16-UCS}}$, found by Cho et al. [5, 6], were applied as Whiteness and Blackness scales, respectively.

$$\begin{aligned} W_{\text{CAM16-UCS}} &= 100 - D_{\text{CAM16-UCS}} \\ &= 100 - 1.44\sqrt{(100-J')^2 + 1.56(M')^2} \end{aligned} \tag{1}$$

$$\begin{aligned} K_{\text{CAM16-UCS}} &= 100 - V_{\text{CAM16-UCS}} \\ &= 100 - \sqrt{(J')^2 + 2.6(M')^2} \end{aligned} \tag{2}$$

The CAM16-UCS [8]was chosen because it is the most uniform colour space tested by Luo and Xu [16], i.e., it gave the most accurate prediction, over 13,800 pairs of samples, including three groups of colour difference datasets (named large colour difference (LCD) [6601 pairs] and small colour difference-surface (SCD-surface) [4927] and -display (SCD-Display) [2272]). In addition, the model is based on CIECAM16 [8, 9] which is the current CIE recommendation and is capable of accurately predicting the LUTCHI colour appearance data [10–13]. In other words, the model is capable of not only predicting colour difference accurately but also taking into account different viewing conditions.

### *Testing 2D scales' performance*

All the available 2D scales were tested using the present and NCS datasets. Firstly, the Berns's $V^*_{ab}$ and $D^*_{ab}$ [2] scales were included in the test as given in Eqs. 3 and 4, respectively.

$$V^*_{ab} = \sqrt{L^{*2} + C^{*2}_{ab}} \tag{3}$$

$$D^*_{ab} = \sqrt{(100-L^*)^2 + C^{*2}_{ab}} \tag{4}$$

Although his scales do not include the whiteness and blackness scales, the reverse rule is again applied, i.e. $W = 100 - D^*_{ab}$ and $K = 100 - V^*_{ab}$.

The $J_{HK}$ equation (see Eq.7) derived by Hellwig and Fairchild [14] based on CIECAM16 was also tested. The subscript of HK means Helmholtz-Kohlrausch [15] effect, which is a visual phenomenon as explained by the equation, i.e. a colour would appear lighter ($J_{HK}$), with an increase of modified chroma ($C$), while the colour's lightness ($J$) remains unchanged.

The revised definitions of Colorfulness and Chroma are given below:

$$M = 43N_c e_t \sqrt{a^2 + b^2} \tag{5}$$

$$C = 35 \cdot \frac{M}{A_v} \tag{6}$$

$$J_{HK} = \sqrt{J^2 + 66C} \tag{7}$$

The other sets of 2D scales were fitted to the NCS sample set based on sCAM [16] as given in Eqs. 8 and 9, respectively.

$$\begin{aligned} W_{\text{sCAM}} &= 100 - D_{\text{sCAN}} \\ &= 100 - 1.3\sqrt{(100-I_a)^2 + 1.6(C)^2} \end{aligned} \tag{8}$$

$$\begin{aligned} K_{\text{sCAM}} &= 100 - V_{\text{sCAM}} \\ &= 100 - \sqrt{(I_a)^2 + 3,0(C)^2} \end{aligned} \tag{9}$$

where $I_a$ and $C$ are the sCAM lightness and chroma. The full sCAM model is given in the Appendix.

Note Simple Colour Appearance Model (sCAM) is based on Simple Uniform Colour Space (sUCS). sUCS has great accuracy in predicting three groups of colour difference datasets [16]. Its performance is similar to CAM16-UCS except that it performed slightly worse than CAM16-UCS in the SCD-surface group. However, its constant hue perception character is much more linear than that of CAM16-UCS and the same performance as the IPT [18]. For the sCAM, it predicts equally well to the CIECAM16 using the LUTCHI data, especially performing the best for its brightness subset. Finally, the sCAM model has a simple structure like IPT or CIELAB, and has low computational cost.

All the above scales were tested using the present 2D and the NCS datasets. The scales' performance are summarized in Figures 3 and 4 in *STRESS* units for predicting the Vividness and Blackness, and Depth and Whiteness, respectively. They were arranged together.

Testing all scales using the present dataset, Figure 3 clearly shows CAM16-UCS performed the best and the other scales gave similar performance. In Figure 4, for the Depth scales, CAM16-UCS and sCAM performed the best and gave equal performance. However, sCAM performed the best amongst all whiteness scales.

Testing all scales using the NCS dataset, CAM16-UCS performed the best for the blackness data (see Figure 5). Both CAM16-UCS and sCAM gave similar performance and they outperformed $J_{HK}$ and Berns's scales (see Figure 6).

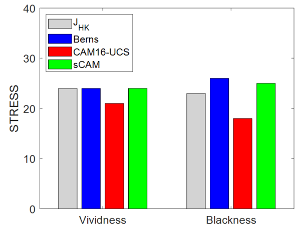



*Figure 3.* *2D scales' performance in predicting the present vividness and blackness visual results*

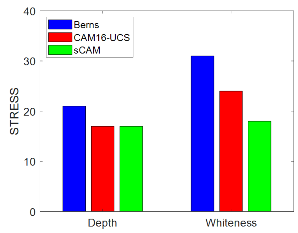



*Figure 4.* *2D scales' performance in predicting the present depth and whiteness visual results*

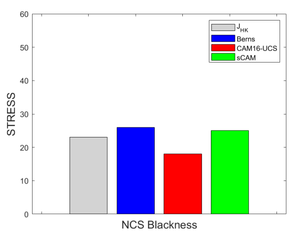



*Figure 5.* *2D scales' performance in predicting the NCS blackness visual results*

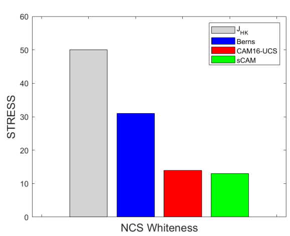



*Figure 6.* *2D scales' performance in predicting the NCS whiteness visual results*

The scattering diagrams were also plotted between the visual results against different scales' predictions. They are given in Figures 7 - 10. It can be found that the degree of scattering in general agrees well with the *STRESS* values reported in Figures 3 - 6. Overall, the newly developed 2D scales based on CAM16-UCS gave the best performance and were followed by those based on sCAM.

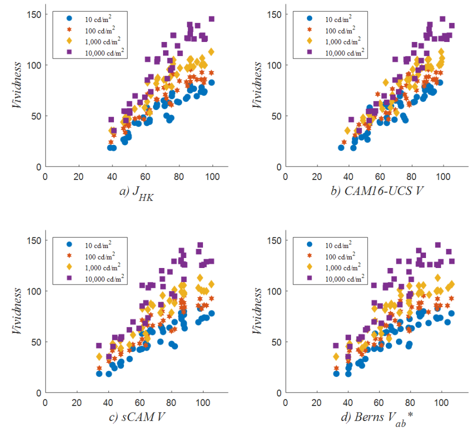



*Figure 7.* *Plots of the present vividness visual results vs the 4 scales' predictions,* a) $J_{HK}$, b) $CAM16-UCS$, c) $sCAM$, *and* d) $Berns$.

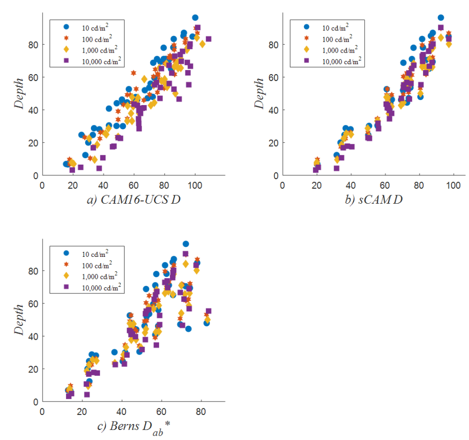



*Figure 8.* *Plots of the present depth visual results vs the 3 scales' predictions,* a) $CAM16-UCS$, b) $sCAM$, *and* c) $Berns$.

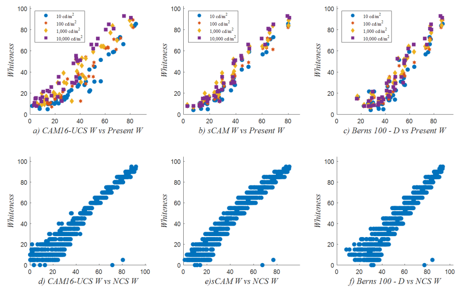


***Figure 9.*** *Plots of the present and NCS whiteness visual results vs the 6 scales' predictions, $a$) CAM16-UCS vs Present, $b$) sCAM vs Present, $c$) Berns vs Present, $d$) CAM16-UCS vs NCS, $e$) scAM vs NCS, $f$) Berns vs NCS.*

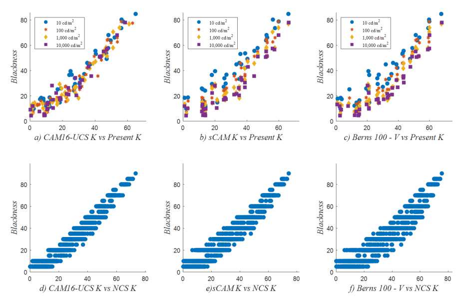


***Figure 10.*** *Plots of the present and NCS blackness visual results vs the 6 scales' predictions, $a$) CAM16-UCS vs Present, $b$) sCAM vs Present, $c$) Berns vs Present, $d$) CAM16-UCS vs NCS, $e$) scAM vs NCS, $f$) Berns vs NCS.*

## Conclusions

Two-dimensional colour appearance scales have been realized to be closely associated with the illumination of light on object colours. These visual phenomena could be valuable to many applications such as colour designers and engineers to control colorants in colour mixing, or image quality to manipulate images in real-world conditions. In this paper, an experiment was conducted to assess vividness, depth, whiteness, and blackness scales by 10 observers under a wide luminance range from 10 to 10,000 cd/m$^2$ at 6000K in a lighting cabinet. The results were used to test all available scales, including the newly developed scales based on CAM16-UCS. It was found that the newly developed 2D scales performed the best, followed by those based on sCAM. The latter model has recently been introduced. Efforts were also spent to introduce many new features of the model.

## Appendix sCAM Structure

The following is the $c$ and $F_M$ parameters used in sCAM.

| Surround | $c$ | $F_M$ |
|---|---|---|
| Average | 0.52 | 1.0 |
| Dim | 0.5 | 0.95 |
| Dark | 0.39 | 0.85 |

$$z = 1.48 + \sqrt{\frac{Y_b}{Y_w}} \tag{10}$$

$$F_L = 0.171 L_A^{\frac{1}{3}} \left( \frac{1}{1 - 0.4934 e^{-0.9934 L_A}} \right) \tag{11}$$

$$\mathbf{XYZ}_{D65} = \mathrm{CAT}_{16}\left(\mathbf{XYZ}, \mathbf{XYZ}_w, L_A, F\right) \tag{12}$$

$$\mathrm{ICh} = \mathrm{sUCS}(\mathbf{XYZ}_{D65}) \tag{13}$$

$$I_a = 100 \left( \frac{I}{100} \right)^{cz} \tag{14}$$

$$Q = I_a \left( \frac{2}{c} F_L^{0.1} \right) \tag{15}$$

$$M = C \left( \frac{F_L^{0.1} e_t F_M}{I_a^{0.27}} \right) \tag{16}$$

$$e_t = 1 + 0.06 \cos(110 + h) \tag{17}$$

## Appendix sUCS Structure

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.4002 & 0.7075 & -0.0807 \\ -0.2280 & 1.1500 & 0.0612 \\ 0 & 0 & 0.9184 \end{bmatrix} \begin{bmatrix} X_{D65} \\ Y_{D65} \\ Z_{D65} \end{bmatrix} \tag{18}$$

$$T' = \begin{cases} T^{0.43} & \text{if } T \geq 0, \\ -(-T)^{0.43} & \text{if } T < 0 \end{cases} \tag{19}$$

where $T$ is $L$, $M$, or $S$ response.

$$\begin{bmatrix} I \\ a \\ b \end{bmatrix} = \begin{bmatrix} 200/3.05 & 100/3.05 & 5/3.05 \\ 430 & -470 & 40 \\ 49 & 49 & -98 \end{bmatrix} \begin{bmatrix} L' \\ M' \\ S' \end{bmatrix} \tag{20}$$

$$C = \frac{1}{0.0252} \ln\left(1 + 0.0447\sqrt{a^2 + b^2}\right) \tag{21}$$

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## Author Biography

*Molin Li received his BS in Optoelectronic Information Science and Engineering from Shenzhen University in 2017 and is currently pursuing his PhD in Optical Engineering at Zhejiang University since 2021. His primary research interests are in the areas of uniform color spaces and color appearance models.*

*Ming Ronnier Luo is a Professor at the College of Optical Science and Engineering, Zhejiang University (China). He was Ex-Vice-President and Ex-Director of Division 1 (Colour and Vision) of the International Commission of Illumination (CIE). His main research areas include colour science, imaging science, and LED illumination. He has published over 650 scientific papers. He is a Fellow of the Society for Imaging Science and Technology (IS&T), and the Society of Dyers and Colourists (SDC). He was the recipient of the AIC 2017 Judd Award for lifetime achievement, and of the 2020 Newton Award for outstanding contribution to colour science from the Colour Group of Great Britain.*