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Reversible Colour Appearance Scales for Describing Saturation, Vividness, Blackness, and Whiteness for Image Enhancement

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Abstract

New reversible saturation, vividness, blackness and whiteness models were developed based on a visual data. The aim of this study is to develop a model that can be applicable to imaging devices and to enhance the images by controlling one of the scales. It was found that the models gave good predictions with the NCS (Natural Colour System) data. The newly developed models are applicable to colour image evaluation and image enhancement.

Introduction

Many models for saturation have been developed. CIE developed a CIELUV saturation [1] model which consists of lightness and chroma. Lübbe [2] developed a theoretical model based on the CIELAB. Nayatani [3-5] developed saturation model in several versions. Hunt and Luo [6] introduced a saturation model which includes cone response for long, medium and short wavelengths. In Juan and Luo's study [7], they found that saturation is a difficult attribute to scale for dark colour samples. The obtained data were used for deriving CIECAM02. Fairchild and Heckaman [8] proposed a saturation model which is based on the CIELUV system.

There were few studies carried out for vividness. In Fedorovskaya *et al.*'s study [9], vividness was considered as colourfulness. In Kim *et al.*'s study [10], vividness was developed for applying colour laser printed images. Berns [11] introduced a vividness model which includes L*, a* and b* attributes.

Blackness is a very important attribute when setting up a black point for displays or printers. There were very few studies for developing blackness models. On the other hand, there were some experimental studies on blackness perception. In Bode *et al.*'s study [12], they used black print pastes. It was found that bluish black was found to be the blackest one. Westland *et al.* [13] carried out psychophysical experiment by ranking 100 printed black samples and introduced a blackness model. Adams [14] developed blackness (s^+), whiteness (w^+) and chromaticness (c^+) models based on the NCS. The key point is that when you add all three attributes it makes 100. Also, Adams [15] developed a CIELAB version of model based on symmetries and the attributes of lightness and chroma. In Clonts *et al.*'s study [16], they found that the perceived blackness is influenced by lightness and chroma. The blackest colour was found to be in the region of cyan and blue. The least black was found to be in the region of purple. Tao *et al.* carried out a blackness perception using Chinese and British observers with Munsell samples [17]. The samples were displayed on a LCD monitor. The result showed that there was little effect on culture and gender between the two countries. Haslup *et al.* [18] also carried out a blackness perception to see the effect of hue. Bluish black or greenish black were found to be the blacker than yellowish or reddish blacks. The result agreed with Clonts *et al.*'s result.

In addition, there were a few studies in developing whiteness model. The whiteness models were developed for evaluating textiles, paper, coatings and plastics [19-21]. The disadvantage of this model is that the model is limited to certain region. Nayatani and Sakai [22] developed a whiteness model. The model is based on the CIELUV system. As mentioned earlier, Adams developed a whiteness model based on the CIELAB which considers the concept of the NCS.

The previous models mentioned above are complex, restricted to certain region of colours, applications or viewing conditions. Thus, simple and reliable models are required to be used in real life and widely used in applications. Models such as saturation and vividness are important for image quality and enhancement. Whiteness model is important to evaluate the white materials, cosmetic products, textiles, papers and plastics. Blackness model is needed to set up black point for displays and colour printers. Also, the models are important for high contrast ratio and enhancing image quality. Thus, the present study aims to develop reliable and simple four types of models (i.e. saturation, vividness, blackness and whiteness) based on psychophysical data (or visual data).

The authors' previous study [23] developed four types of models (i.e. saturation, vividness, blackness and whiteness) according to the above aims. The advantage of these models is that they can be used to estimate the quality of images in imaging device. The difference with the present models is that the authors' previous models do not consider reversible model. Thus, the new model considers the aims that the model can be reversible. This means that the new model can be applied to imaging device.

Development of reversible models

Forward model

The experimental data were obtained from the authors' previous experiment [23] by 68 British and 64 Korean observers. A psychophysical experiment for saturation, vividness, blackness and whiteness were carried out using 120 NCS colour samples. The Torgerson's laws of categorical judgement [24] were applied to transfer the obtained data to z-score values. The data were ranged between -3 to 3.

In this study, four new models such as saturation (S), vividness (V), blackness (B) and whiteness (W) were developed based on the experimental data. The new models were ranged between 0 and 100. The models are given in Equation (1). The models were developed by optimizing the r value between predicted value and the visual data. The parameters were obtained by fitting the visual data to the predicted value.

In the authors' previous study [23], the visual data of British and Korean observers obtained from the psychophysical experiment were compared against the predicted value of the existing model. For saturation, the British data showed better correlation with the predicted value of the CIELAB lightness ($r = 0.58$) and chroma ($r = -0.64$) than the Korean data ($r = 0.32$ and $r = -0.71$), respectively. On the other hand, for vividness, the Korean data showed better correlation with the predicted value of the CIELAB chroma (r = 0.60), the CIECAM02 chroma (r = 0.61) and the CIECAM02 colourfulness (r = 0.61) than the British data (r = 0.34, r = 0.41 and r = 0.41), respectively. Thus, the saturation model was developed based on the British data. The Korean data was not included because the correlation coefficient seemed to show low value with the predicted value of lightness and chroma, respectively. The vividness model was developed based on Korean data which showed better correlation than the British data. But for developing blackness and whiteness models, British and Korean data were used because both data showed good correlation with the predicted value of the existing models such as lightness. Figure 1 shows the data plot between the visual data and the model predictions of each attribute. It can be seen that the visual data fit well with each model.

$$
\begin{aligned}
S &= \left(\frac{C^*}{0.52L^*+0.49C^*+0.001} - 0.1\right) \times 94.3262411348 \\
V &= (C^* - 0.03) \times 1.35135135135 \qquad (1) \\
B &= -1.4975664545L^* - 0.0748783227a^* \\
&\qquad + 0.0748783227b^* + 136.2785473605 \\
W &= 1.3100436681L^* + 0.0873362445a^* \\
&\qquad - 0.4366812227b^* - 36.506550218
\end{aligned}
$$

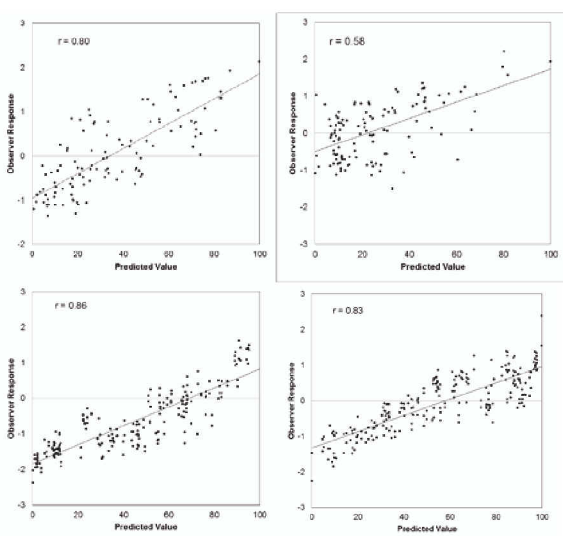


Figure 1. Visual data plotted against the predictive values of the new models

Testing models using psychophysical data

The previously developed models which were mentioned earlier were tested using the visual data. The visual data consist of British and Korean observer data. In addition, the author's previously developed models and the present models were also tested to compare the performance. This is to see their relationship with the present experimental data. Berns' Depth, Vividness and Clarity models were tested because these models predict similar to the present models. Lightness and chroma models of the CIELAB and the CIECAM02, and saturation models of the CIELUV, the CIECAM02, Fairchild and Lübbe were tested. In addition, theoretical saturation scale (s_{ab}) which is based on the concept of the CIELUV saturation was also tested. Some of the existing models which were mentioned earlier were not tested because there were different kinds of models such as Hunt and Nayatani's models. The CIE whiteness index was not tested because this model was restricted to a certain region of colours. Nayatani and Sakai's whiteness (w) and blackness (bk) models were not tested because they were not consistent in terms of the definition of the original concept. This means that each colour could only be either whiteness or blackness having either be zero. The models were tested using the present experimental data in terms of correlation coefficient and were summarized in Table 1. These tested results can investigate the interrelationship between the existing models and the experimental data obtained by naive observers. Testing the existing and new models using the visual data of saturation, Berns' depth (r = 0.80) outperformed among the models, followed by the new blackness (r = 0.67), and lightness of the CIELAB (r = -0.66) and the CIECAM02 (r = -0.65). However, the CIELUV saturation (r = 0.53) and Fairchild's saturation (r = 0.44) did not seem to predict well with the visual data. For vividness, Berns' clarity (r = 0.61) performed the best among the models. However, Berns' vividness (r = 0.16) and the newly developed vividness (r = 0.44) showed poor correlation with the visual data. For blackness, Berns' vividness (r = -0.89) outperformed among the models, followed by newly developed blackness (r = 0.86) and the lightness of the CIELAB (r = -0.85) and the CIECAM02 (r = -0.84). For whiteness, new whiteness (r = 0.83) and blackness (r = -0.83) models outperformed among the models, followed by the lightness of the CIELAB (r = 0.82) and the CIECAM02 (r = 0.81).

Table 1. r value between models and visual data

r	Saturation	Vividness	Blackness	Whiteness
CIELAB chroma C_{ab}*	0.44	0.44	-0.23	-0.16
CIELAB lightness L*	-0.66	0.01	-0.85	0.82
Berns depth D_{ab}*	0.80	0.25	0.64	-0.79
Berns vividness V_{ab}*	-0.47	0.16	-0.89	0.72
Berns clarity T_{ab}*	0.33	0.61	-0.32	-0.03
CIELAB saturation s_{ab}*	0.64	0.42	0.02	-0.43
Lübbe saturation s^+	0.63	0.40	0.05	-0.36
CIELUV saturation s_{uv}	0.53	0.37	0.02	-0.43
CIECAM02 colourfulness M	0.51	0.49	-0.20	-0.21
CIECAM02 chroma C	0.51	0.49	-0.20	-0.21
CIECAM02 lightness J	-0.65	0.03	-0.84	0.81
CIECAM02 saturation s	0.62	0.43	0.002	-0.39
Westland Blackness B3	0.17	-0.33	0.77	-0.48
Fairchild's saturation S	0.44	0.29	-0.04	-0.28
Reversible saturation	0.63	0.40	0.06	-0.43
Reversible vividness	0.44	0.44	-0.23	-0.16
Reversible blackness	0.67	-0.003	0.86	-0.83
Reversible whiteness	-0.61	-0.02	-0.74	0.83

Testing models using the NCS data set

The NCS which consists of whiteness, blackness and chromaticness is a widely used colour order system. The big advantage of this system is that it has the largest dataset. In this study, a total of 1749 NCS samples were used to test the existing and new models. This sample data from the 1st edition of the NCS Colour Atlas were measured by Juan. An X-Rite CE7000A spectrophotometer was used to measure the samples with setting the device as specular included, small aperture and UV included. The measured samples are formed as spectral reflectance. The reflectance data were transformed to the XYZ values of the CIE D65 and 1931 standard colorimetric observer.

Table 2. Correlation coefficient between predicted model and the NCS chromaticness data

Model	r
Cho et al.'s Ellipsoid-based saturation $_{\_CIELAB}$	0.71
Cho et al.'s Ellipsoid-based saturation $_{\_CIECAM02}$	0.74
Cho et al.'s Ellipsoid-based vividness $_{\_CIELAB}$	0.60
Cho et al.'s Ellipsoid-based vividness $_{\_CIECAM02}$	0.62
Cho et al.'s Hue-based chromaticness $_{\_CIELAB}$	0.98
Cho et al.'s Hue-based chromaticness $_{\_CIECAM02}$	0.98
Berns vividness V_{ab}*	0.24
Berns clarity T_{ab}*	0.70
Berns depth D_{ab}*	0.69
CIELAB chroma C_{ab}*	0.94
CIELAB (theoretical) saturation s_{ab}*	0.95
CIELUV saturation s_{uv}	0.71
Lübbe saturation S^+	0.94
CIECAM02 saturation s	0.95
CIECAM02 chroma C	0.98
CIECAM02 colourfulness M	0.98
Fairchild saturation S	0.80
Reversible saturation	0.94
Reversible vividness	0.94

Table 3. Correlation coefficient between predicted model and the NCS blackness data

Model	r
Cho et al.'s Ellipsoid-based blackness $_{\_CIELAB}$	0.97
Cho et al.'s Ellipsoid-based blackness $_{\_CIECAM02}$	0.97
Cho et al.'s Hue-based blackness $_{\_CIELAB}$	0.99
Cho et al.'s Hue-based blackness $_{\_CIECAM02}$	0.99
CIELAB lightness L*	-0.87
CIECAM02 lightness J	-0.86
Berns vividness V_{ab}*	-0.93
Berns clarity T_{ab}*	-0.70
Berns depth D_{ab}*	0.47
Westland Blackness B3	0.80
Reversible blackness	0.87

Table 4. Correlation coefficient between predicted model and the NCS whiteness data

Model	r
Cho et al.'s Ellipsoid-based whiteness $_{\_CIELAB}$	0.94
Cho et al.'s Ellipsoid-based whiteness $_{\_CIECAM02}$	0.96
Cho et al.'s Hue-based whiteness $_{\_CIELAB}$	0.99
Cho et al.'s Hue-based whiteness $_{\_CIECAM02}$	0.99
CIELAB lightness L*	0.85
CIECAM02 lightness J	0.86
Berns vividness V_{ab}*	0.56
Berns clarity T_{ab}*	-0.02
Berns depth D_{ab}*	-0.96
Westland Blackness B3	0.18
Reversible Whiteness	0.94

To see the predictive performance of the model, the correlation coefficient between the model prediction and the NCS data were calculated. It is noted that the models that are relevant to the tested dimensions were tested. For example, to see the whiteness and blackness predictive performance, saturation and chroma models were not included. Tables 2-4 summarize the results for the NCS chromaticness, blackness and whiteness, respectively. It can be seen that almost all of the models performed well. As shown in Table 2, Cho *et al.*'s hue-based chromaticness models (r = 0.98), and chroma (r = 0.98) and colourfulness (r = 0.98) of the CIECAM02 outperformed among the models together with the CIELAB chroma (r = 0.94), Lübbe's saturation (r = 0.94), saturation of the CIECAM02 (r = 0.95), the new saturation (r = 0.94) and vividness (r = 0.98) models. In Table 3, Cho *et al.*'s hue-based blackness (r = 0.99) models performed the best among the model followed by Cho *et al.*'s ellipsoid-based blackness (r = 0.97) models and Berns' vividness (r = -0.93). In addition, new blackness model predicted the NCS blackness data well having r value of 0.87. As shown in Table 4, Cho *et al.*'s hue-based whiteness (r = 0.99) models outperformed other models together with Cho *et al.*'s ellipsoid-based whiteness (0.94 and 0.96 for CIELAB and CIECAM02 versions, respectively) models and the new whiteness (r = 0.94) model. According to Tables 2 and 4, among the models, Cho *et al.*'s hue-based models outperformed. However, the disadvantages of these hue-based models are not reversible. It can estimate the quality of an image but it cannot be applied to imaging device. The newly developed models predict well with the NCS data. The advantage of the newly developed model is that it can be applied to imaging device because it is reversible.

Reverse model

The reverse models of L*, C*, a* and b* were calculated from the new models for image application as shown in Equation (2) respectively. It can be seen that if saturation changes, then lightness changes. This will also effect a* and b* values as well. If vividness change, then the chroma value changes. If blackness and whiteness change, then this will affect a* and b* values.

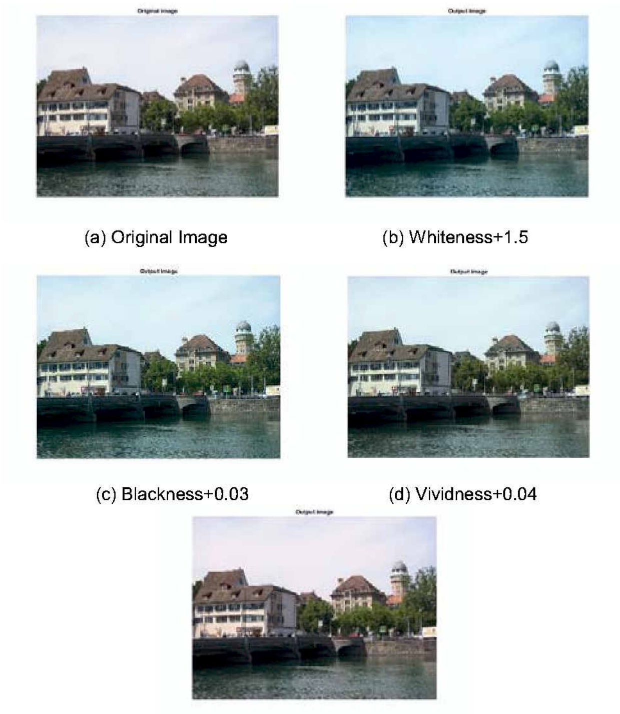
$$\begin{aligned} L^* &= (252.966C^* - 1.3818SC^* - 0.00282S \\ &\quad - 0.0266)/(1.4664S + 13.832) \\ C^* &= 0.74V + 0.03 \\ a^* &= -21.25L^* + 2170.5 - 16.69375B - 2.8625W \\ b^* &= -1.25L^* + 350.5 - 3.33875B - 2.8625W \end{aligned} \tag{2}$$

Application to Image

The reversible colour appearance scales are applicable to image enhancement. The average values of four colour appearance scales for an image may be computed pixel by pixel first using the forward models (Equation 1), and then the reverse models (Equation 2) should be applied to the image by slightly changing the average value of one of four scales. As an example, the value of 1.5 was added to the mean whiteness value for the original image in Figure 2 (a). The output image is shown in Figure 2 (b), and shows whiter than the original image. This also shows in applying blackness and vividness scales by adding 0.03 and 0.04, respectively as shown in Figures 2 (c) and (d). It looks slightly vivid than the original image. On the other hand, for saturation, the output image in Figure 2 (e) shows slightly reddish by adding 0.02 of the saturation to the original image.

Discussion and Conclusion

Four reversible models for saturation, vividness, blackness and whiteness were developed based on the visual data obtained from the authors' previous study. The difference with the other models is that it can be reversible. This means that the model can be applied to imaging devices. The newly developed model predicted well with the fitted data. Though saturation and vividness models showed low correlation with the visual data, the newly developed models showed very high agreements with the NCS data set. Finally, the new models can be used to enhance images by changing one of the four colour appearance scales.



(a) Original Image (b) Whiteness+1.5

(c) Blackness+0.03 (d) Vividness+0.04

(e) Saturation+0.02

Figure 2. (a) Input image and (b) to (e) are images that are enhanced images by changing one of four scales.

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