Alternatives to the Third Dimension of Colour Appearance

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Abstract

Colour appearance has been extensively studied. It was found that assessing the third dimension of colour appearance, such as chroma, colourfulness or saturation attributes, normally are more inconsistent than for other two dimensions (lightness and hue), even with experienced observers. Two psychophysical experiments were conducted to address the issue using British and Korean observers respectively. The following word scales to represent the third dimension were scaled by observers: 'bright', 'light-heavy', 'active-passive', 'fresh-stale', 'clean-dirty', 'clear', 'boring', 'intense-weak', 'saturated', 'vivid-dull', 'distinct-indistinct', 'full-thin', and 'striking'. All observers did not have any colour science background, nor did they receive any training about each word scale. Predictive models of saturation and of vividness were developed to fit the experimental results. They reflect novice observers' view of colour appearance.

Introduction

Colour appearance has been extensively studied over the years and many colour appearance models were developed to predict colour appearance for a wide range of viewing conditions, such as CIELAB[1] and CIELUV[1], Hunt model[2-4], CIECAM97s[5], CIECAM02[6] and CAM02-UCS[7]. Uniform colour space, such as CIELAB, CIELUV including simple chromatic adaptation transforms and predictors of lightness, chroma and hue, were also considered as colour appearance model.

Colour appearance is normally specified by three attributes such as hue, lightness and colourfulness (or chroma, chromaticness). It has been found, however, that the scaling of the latter attribute associated with "chromatic" attribute can be performed poorest among all colour appearance attributes although very experienced observers with sufficient understandings of these attributes. Even with well-trained observers, the visual results for colourfulness may still show poor data consistency comparing with the other two attributes.

The overall objectives of this study were, firstly, to understand and clarify the meanings of each "chromatic" attributes for Korean and British observers and, secondly, to seek an alternative to the third dimension of colour appearance that better reflects novice observers' view of colour appearance (i.e. without any trainings of colour appearance scaling). Finally, this study proposes a new model of saturation and a model of vividness, which may serve as an alternative to the third dimension of colour appearance with potential applications in various industries, or as an extension of the current colour appearance model such as CIECAM02.

Experimental methods

Two psychophysical experiments were carried out to assess the "chromatic" attribute (such as "vivid-dull") of colour stimuli using categorical judgement method[8]. Experiment 1 used Korean observers, whereas Experiment 2 used British observers. In both experiments observers gave responses on a six-point forced choice scale, such as "very dull", "dull", "a little dull", "a little vivid", "vivid" and "very vivid". Both British and Korean observers used their native languages to conduct the visual assessments (i.e. English and Korean, respectively) and that all observers were students at the University of Leeds, UK.

In both experiments, forty-eight 3x3 inch colour patches (paper cards), including randomly repeated (randomly selected from the 48), were used as the stimuli accessed by observers naive to colour appearance scaling. Figure 1 shows the colour distribution of 48 colour samples plotted in a_M-b_M diagram in CIECAM02 space. The colour samples were selected from the Natural Colour System (NCS) to cover a wide range of hue, chromaticness and blackness. Each colour patch was presented in a VeriVide viewing cabinet. The cabinet was covered with grey background (X=154.05, Y=159.40, Z=188.15 in cd/m^2 unit) illuminated by a D65 simulator, situated in a darkened room. The reference white in the viewing cabinet was measured X=491.95, Y=511.35, Z=557.20 in cd/m^2 unit. Observers were comfortably seated to view the colour patches at a distance of about 60 cm.

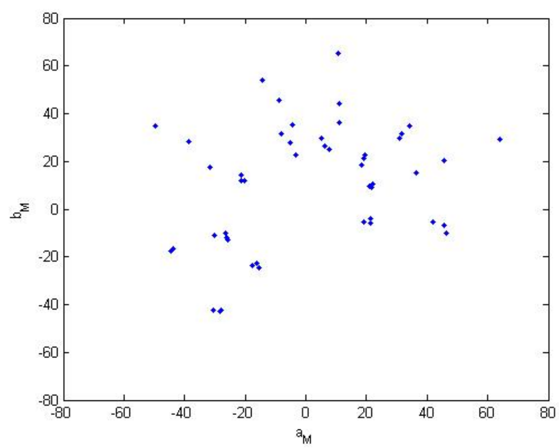

***Figure 1** Distribution of 48 NCS colour samples used in the experiment in aM-bM coordinate of CIECAM02 system*

Twenty-four Korean observers, 10 male and 14 female, participated in the first experiment. They were asked to rate each colour using 15 word scales: vivid-dull, distinct-indistinct, striking, intense-weak, full-thin, saturated-unsaturated, warm-cool, clean-dirty, clear, light-heavy, active-passive, fresh-stale, natural-unnatural, boring and bright.

Twenty-nine British observers, 14 male and 15 female, participated in the second experiment. The experimental setup and conditions were the same as the first experiment, except that the word scales used in Experiment 2 included only "saturated-unsaturated" and "vivid-dull". All Korean and British observers had normal colour vision and had no training session on the meaning of each word scaled.

Only two word-pairs, "saturated-unsaturated" and "vivid-dull" were used in Experiment 2 assessed only by British observers. There are two reasons for this. Firstly, *'Saturation'* has been studied and defined by the CIE International Lighting Vocabulary[9] and was adopted for the CIELUV space and the CIECAM02 colour appearance model. It is also used many colour order systems such as DIN [10], Oswald, Coloroid.

Secondly, regarding the "vivid-dull" scale, many efforts have been made in studying "vividness" for applications in image quality[11-13]. Colour vividness has been understood associated with colourfulness[14,15] in the field of image quality. The scale can be useful for image enhancement or gamut mapping. It was also adopted as one of the colour adjectives in ISCC-NBS[16] colour designation and PCCS[17] systems. Thus, the two word scales *"saturated-unsaturated"* and *"vivid-dull"* were selected for use in the second experiment.

Word scale translation

The 15 word scales were translated into Korean on the basis of a questionnaire survey conducted by 22 Korean participants. The 15 scales are summarised in Table 1.

Table 1 The 15 word scales used for Experiment 1

English	Korean
Bright	밝은
Light - heavy	가벼운 - 무거운
Active - passive	활기 있는 - 활기 없는
Fresh - stale	신선한 - 신선하지 않은
Clean - dirty	깨끗한 - 더러운
Clear	맑은
Boring	지루한
Natural - Not natural	자연적인 - 자연적이지 않은
Warm - cool	따뜻한 - 차가운
Intense - weak	강렬한 - 약한 (or 연한)
Saturated	포화된, 채도, 색의 순수한 정도
Vivid - dull	선명한 - 흐릿한
Distinct - indistinct	뚜렷한 - 뚜렷하지 않은
Full - thin	짙은 - 옅은
Striking	두드러진, 인상적인

Results

Factor analysis[17] was used to reveal underlying factors of each word scale. The 15 word scales were classified into two principal components. As shown in Table 2, *'bright', "light-heavy", "active-passive", "clean-dirty", 'clear'*, and *'boring'* were all highly correlated with Component 1; *"intense-weak"*, *"saturated"*, *"vivid-dull"*, *"distinct-indistinct"*, *"full-thin"*, and *'striking'* were highly correlated with Component 2.

Component 1 was found to be highly correlated with CIELAB metric lightness (L*), with a correlation coefficient of 0.59. Component 2 was correlated closely with CIE metric chroma (C_{ab}*), with a correlation coefficient of -0.86. The comparison results indicate that the word scales in Component 1 have a very high correlation with lightness, and the word scales in Component 2 were highly correlated with chroma. Among the 15 word scales, *'saturated'* shows the highest correlation coefficient 0.74 for chroma; and *"light-heavy"* shows the highest correlation coefficient 0.92 for lightness.

Table 2 Factor matrix of word scales for Korean Observers

	Component 1	Component 2
Bright	0.98	0.09
Light-heavy	0.96	-0.22
Active-passive	0.90	0.43
Fresh-stale	0.89	0.40
Clean-dirty	0.88	0.44
Clear	0.87	0.45
Boring	-0.86	-0.47
Natural-unnatural	-0.34	0.11
Warm-cool	-0.05	-0.02
Intense-weak	0.02	0.99
Saturated	0.22	0.92
Vivid-dull	0.48	0.86
Distinct-indistinct	0.49	0.86
Full-thin	-0.49	0.85
Striking	0.65	0.73

British observers scaled *"saturate-unsaturated"* and *"full-thin"* in Experiment 2. Figure 2 shows the correlation between *"saturated-unsaturated"* by British and 15 word scales by Korean, as presented on the basis of the factor plot generated according to Table 2. Among the 15 Korean word scales, *"full-thin"* was found to have the highest correlation with *'saturated'* by British observers with a correlation coefficient of 0.89. This value was higher than the correlation between *'saturated'* by British and *'saturated'* by Korean (r = 0.79). This result suggests that the English scale 'saturated' was better represented in Korean language by *"full-thin"* (짙은-옅은) than by *'saturated'* (포화된). Unsurprisingly, *"Full-thin"* by Korean shows a pattern similar to British result for *'saturated'* when compared with CIELAB chroma and lightness.

Figure 3 shows the correlation between *"vivid-dull"* by British and the 15 word scales by Korean. The *"vivid-dull"* by British observers was found to correlate most closely with *'striking'* by Korean, with a correlation coefficient of 0.90. This suggests that English scale *"vivid-dull"* was better represented in Korean language by *'striking'* (두드러진) than by *"vivid-dull"* (선명한-흐릿한) (r = 0.83).

The above results demonstrate that there may be some issues in translations, or there may be some impacts of cultural background on the meanings of the word scales used here. Note, however, that the correlation between the two observer groups in "saturated-unsaturated" ($r = 0.79$) and in "vivid-dull" ($r = 0.83$) are still fairly high, suggesting somewhat good agreement between the Korean and British results for these two scales.

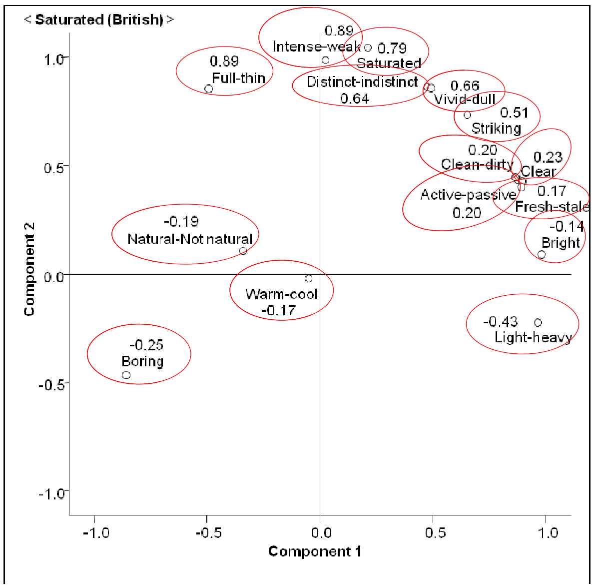

Figure 2 *Factor plot together with correlation coefficients between "saturate-unsaturated" by British observers and the 15 word scales by Korean observers*

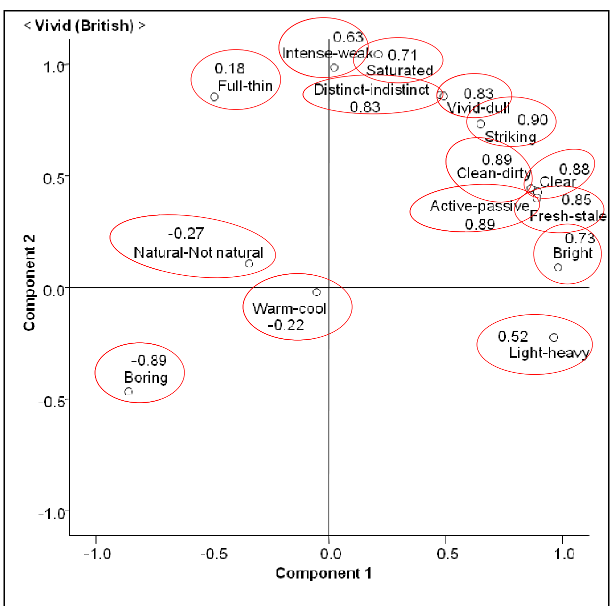

Figure 3 *Factor plot together with correlation coefficients between "vivid-dull" by British observers and the 15 word scales by Korean observers*

New model for saturation and vividness

Models of saturation and vividness were developed using the British data. The Korean data was not used because there was the uncertainty about the validity of the translations used in this study.

New saturation models, with three versions based on CIELAB, CIECAM02 and CAM02-UCS systems, were developed using existing colour emotion modelling techniques [18, 19]. The three equations are all in the form of a colour difference formula as illustrated in Equation (1):

$$\Delta E = \sqrt{\{k_L(L^* - L_o^*)\}^2 + \{k_A(a^* - a_o^*)\}^2 + \{k_B(b^* - b_o^*)\}^2} + k_M \quad (1)$$

where, L_o^*, a_o^*, b_o^* are the coordinates of the reference colour. In this case, the coordinates mean the least saturated colour in the CIELAB space in terms of L^*, a^* and b^* values. k_L, k_A, k_B are all constants representing the contribution of the three orthogonal CIELAB axes to the prediction, k_M: is also a constant. The negative value of k_M offset is used to fit in the visual result in the range from -3 to +3. For example of Saturation Model, the negative value means unsaturated colour and the positive value means saturated colour.

It is well known that the least saturated colour in the new model is likely to be white, which is high in lightness and low in chroma. For example, when dye a fabric or print ink on paper, the substrates are always a white. Thus, the reference colour was set to be white for all the three equations, as shown in Equations (2) to (4). The coefficients in each equation were determined using the Excel Solver tool to minimise the difference between observer response and predicted value.

$$S\_CHO_{ab^*} = -1.68 + 0.04\sqrt{(L^* - 100)^2 + 1.47(a^*)^2 + 0.65(b^*)^2} \quad (2)$$

$$S\_CHO_{CAM02} = -2.03 + 0.03\sqrt{(J - 100)^2 + 3.48(a_M)^2 + 2.33(b_M)^2} \quad (3)$$

$$S\_CHO_{CAM02-UCS} = -2.54 + 0.04\sqrt{(J' - 100)^2 + 5.96(a')^2 + 4.34(b')^2} \quad (4)$$

Observer response and the new saturation model based on the CIECAM02 system shows a high correlation coefficient 0.95 and a low root mean square (RMS) value of 0.24, as shown in Figure 4.

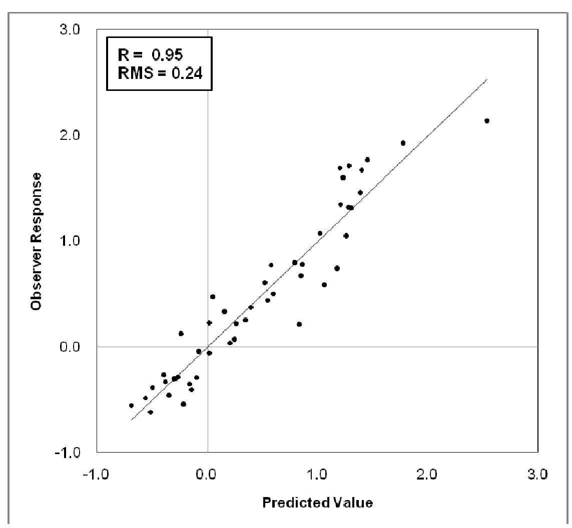

Figure 4 *Correlation between observer response and the predicted value of "saturated-unsaturated" based on CIECAM02*

Three versions of vividness model, based on the CIELAB, CIECAM02 and CAM02-UCS were also developed using the same method described above. The reference colour in the model (i.e. the least vivid colour) was assumed to be at a medium level of lightness. The Excel Solver tool found that the reference colour was at the lightness of 34, with slight differences in the other two coordinates for the three colour systems, as illustrated in Equations (5) to (7). All the three equations suggest the least vivid colour being a greyish yellow colour such as khaki.

$$V\_CHO_{ab^*} = -3.88 + 0.07\sqrt{(L^* - 34)^2 + 1.99(a^*)^2 + 1.22(b^* - 21)^2} \quad (5)$$

$$V\_CHO_{CAM02} = -3.39 + 0.07\sqrt{(J - 34)^2 + 1.67(a_M - 1)^2 + 0.96(b_M - 10)^2} \quad (6)$$

$$V\_CHO_{CAM02-UCS} = -5.09 + 0.08\sqrt{(J' - 34)^2 + 4.81(a' - 1)^2 + 2.92(b' - 5)^2} \quad (7)$$

The relationship between the observer response and the new vivid model based on the CIECAM02 system shows a high correlation coefficient 0.96 and a low RMS 4.14 as demonstrated in Figure 5.

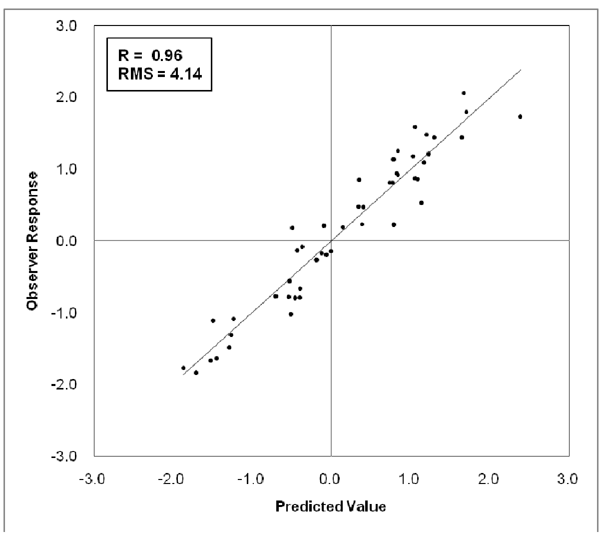

Figure 5 Correlation between observer response and the predicted value of "vivid-dull" based on CIECAM02

Discussion and conclusion

The experimental results may suggest some translation issues in this study, as "saturated-unsaturated" response given by British was correlated most closely with "full-thin" in Korean, instead of its corresponding translation; similarly, "vivid-dull" in English was correlated most closely with "striking" in Korean, instead of its corresponding translation. However, the correlation between the two observer groups in "saturated-unsaturated" (r = 0.79) and in "vivid-dull" (r = 0.83) are still fairly high, suggesting a good agreement between the Korean and British responses for these two scales.

Table 3 shows the correlation coefficients between observer response of "*saturated-unsaturated*" and those predicted by CIELAB L* and C*, CIECAM02 colourfulness, chroma, lightness and saturation, and CAM02-UCS colourfulness and lightness, respectively.

Comparing the observer responses "saturated-unsaturated" with colour appearance attributes predicted by existing colour models, it shows that CIECAM02 performed the best, i.e. high positive correlation (r = 0.94) followed by CIECAM02 saturation and fairly high negative correlation (r = -0.61) with CIECAM02 lightness. This suggests that CIECAM02 saturation works not only for well-trained observers, but it also applies well to naïve observers. Note that CIECAM02 was developed to fit the results from Juan and Luo's results at the University of Derby [20]. They extensively trained observer to scale saturation using the CIE definition [9]. This implies that two sets of results agree very well.

CIELAB chroma also shows higher correlation with Korean response than with British response, with correlation coefficients of 0.72 and 0.62, respectively. CIELAB lightness has a fairly high negative correlation with British response of -0.61. However, Korean data shows a low correlation coefficient of -0.22. CIECAM02, colourfulness, chroma, saturation and lightness all show higher correlation with British response than with Korean response. Also, CAM02-UCS results show a pattern a similar to CIECAM02 results. Among all the attributes in the table, CIECAM02 saturation shows the highest correlation with British response, with a correlation coefficient of 0.94.

Table 3 Correlation coefficients of Korean and British observers' saturation responses with existing colour appearance values in terms of chroma, lightness, colourfulness, saturation in CIELAB, CIECAM02, CAM02-UCS systems

Saturation		Korean	British
CIELAB	Cab*	0.72	0.62
	L*	-0.22	-0.61
CIELUV	S	0.67	0.67
CIECAM02	M	0.82	0.83
	C	0.82	0.83
	J	-0.19	-0.61
	S	0.80	0.94
CAM02-UCS	M'	0.82	0.84
	J'	-0.23	-0.62

Figures 6 and 7 plots CIELUV predictions against Korean and British observers responses, respectively.

Figures 8 and 9 are the same as Figures 6 and 7 except the predictions are from CIECAM02 Saturation. It can be found that the degree of scattering in agreement with the statistic figures in Table 3. Without a doubt, CIECAM02 saturation has the least scattering than CIELUV. In addition, British results agreed better by CIECAM02 than Korean Observers.

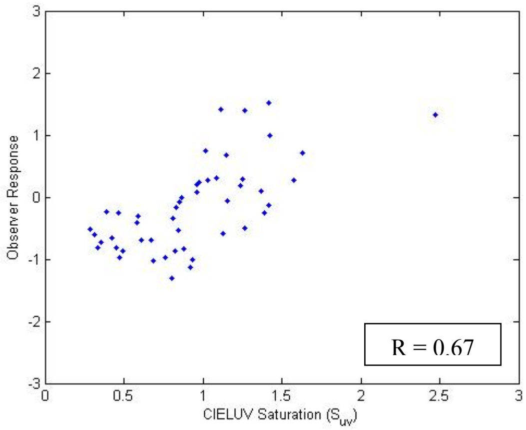

Figure 6 *Correlation between Korean observer response "saturated-unsaturated" and CIELUV saturation (Suv)*

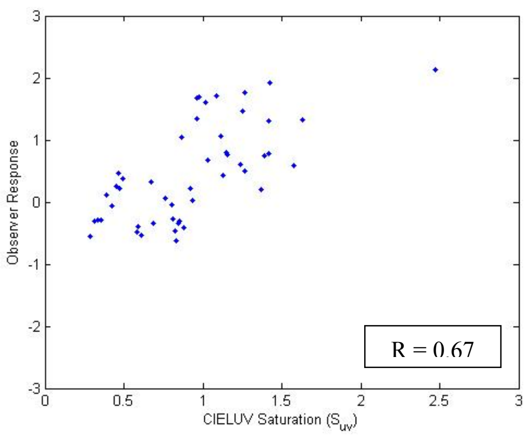

Figure 7 *Correlation between British observer response "saturated-unsaturated" and CIELUV saturation (Suv)*

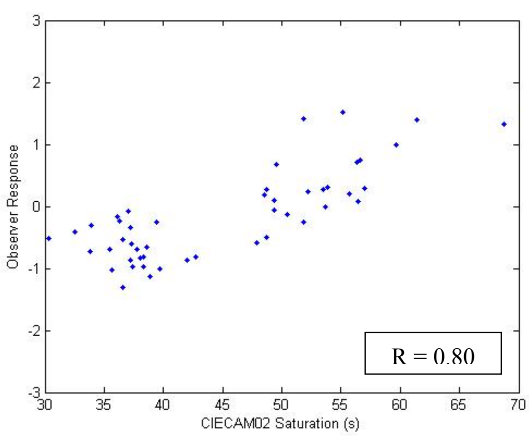

Figure 8 *Correlation between Korean observer response "saturated-unsaturated" and CIECAM02 Saturation (s)*

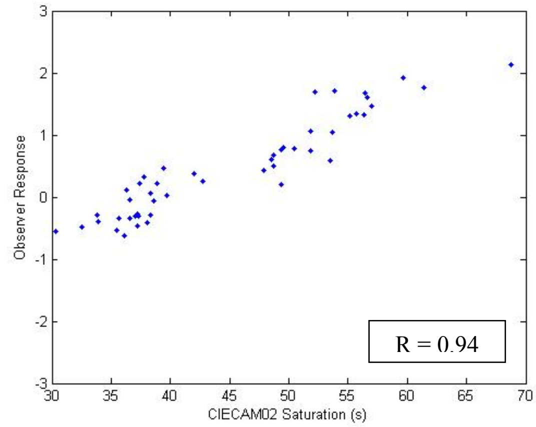

Figure 9 *Correlation between British observer response "saturated-unsaturated" and CIECAM02 Saturation (s)*

Table 4 shows the results in correlation coefficients between the visual results and different models' predictions. It clearly shows that vividness has low correlation with lightness.

Comparing the observer responses "vivid-dull" with colour appearance attributes predicted by existing colour systems, CIELAB chroma shows higher correlation with Korean results than with British results, with correlation coefficients of 0.74 and 0.52, respectively. Both Korean and British results show a low linear relationship with the CIELAB lightness, with correlation coefficients of -0.01 and 0.29. CIECAM02 lightness and CAM02-UCS lightness share the same trend in terms of correlation with the "vivid-dull" response. For CIECAM02 colourfulness and chroma, and CAM02-UCS colourfulness, Korean results shares the same trend as British results, with the same set of correlation coefficients, 0.82 for Korean and 0.67 for British, respectively. Overall, vividness results correlate reasonably well with chroma or colourfulness predictions for all models. Also, they fit better to Korean than British results.

Table 4 Correlation coefficient of Korean and British observers' vivid result in terms of chroma, lightness, colourfulness, saturation in CIELAB, CIECAM02, CAM02-UCS

Vivid		Korean	British
CIELAB	Cab* (Chroma)	0.74	0.52
	L* (Lightness)	-0.01	0.29
CIECAM02	M (Colourfulness)	0.82	0.67
	C (Chroma)	0.82	0.67
	J (Lightness)	0.03	0.29
	s (Saturation)	0.71	0.46
CAM02-UCS	M' (colourfulness)	0.82	0.67
	J' (Lightness)	-0.01	0.27

Conclusion

New saturation and vividness scales were developed here. The former model proposed shows a new approach for describing saturation attribute in the form of a colour difference formula with a reference colour (i.e. the least saturated colour) being white. The new saturation model also has a high correlation with the observer response (r = 0.95 for British data). In addition, the CIECAM02 saturation scale performed equally well without additional modifications. It was developed based on the earlier Juan and Luo's experiment. This suggests that saturation can be accurately scaled by different observer groups (experienced and inexperienced observers) based on completely different scaling techniques. Note that the selected colour samples in the present study did not cover the achromatic and highly greyish colour regions. These colours are currently under investigation.

Finally, a new vividness scale was also developed. It can be used to extend the colour appearance models such as CIECAM02. It should be able to apply for imaging works such as image enhancement, gamut mapping.

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