Individual Differences in the Assessment of Colour Saturation

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Abstract

The aim of the study is to investigate perceived saturation by looking into individual observer's response. To achieve this, a psychophysical experiment was conducted in which 39 untrained British and Korean observers participated. According to the experimental results, British observers were classified into three subgroups. The three subgroups show different trends of perceived saturation against CIECAM02 values. Korean observers were also classified into three subgroups, each showing a distinct pattern of saturation response. It was found that among the 6 subgroups of observer, only one subgroup agreed well with the CIECAM02 saturation, i.e. only 10% of the observers agreed closely with the CIE definition of saturation. The other observers showed different understandings of saturation; some regarded white, a light grey or medium grey as the least saturated among all colour samples, while some regarded black as the most saturated among all colour samples. The results seem to imply an impact of background colour on the perceived saturation, which however will require further verification in future studies.

Introduction

Saturation has been defined by the CIE International Lighting Vocabulary as the colourfulness of an area judged in proportion to its brightness [1]. This definition was adapted to CIELUV systems [2], the Nayatani et al model [3], the Hunt model [4], CIECAM97s [5], CIECAM02 [6], and CAM02-UCS [7]. Note that Juan et al. [8] performed a large scale psychophysical experiment for assessing saturation using magnitude estimation method. The visual results were used to develop CIECAM02 and CAM02-UCS. In Juan et al.'s study, observers reported that it was a difficult task to assess saturation and the results showed poorer data consistency than other scales such as colourfulness, lightness and hue. This was the case even for observers having a sufficient understanding of the CIE definition of saturation [8].

In an attempt to understand why there are such difficulties in the assessment of saturation, we looked into individual observer's visual data in the present study. We assumed that the difficulties in conventional assessment of saturation were due to a wide diversity in the observer's "natural understanding" of saturation. Thus, untrained observers (i,e. those without any knowledge of the CIE definition of saturation) were recruited to participate in a visual assessment of saturation for colour patches presented in a viewing cabinet. The words could have some problems with the translation. It could not be exactly the perfect word to translate due to the cultural difference. The experimental results were analysed using the principal component analysis method to classify the observers into subgroups according to their patterns of response. Models of saturation developed for each subgroup can help to clarify the individual differences in the assessment of saturation.

Experimental methods

A psychophysical experiment was carried out to scale saturation using a categorical judgement method [10]. A panel of 20 Korean (10 male and 10 female) and 19 British observers (10 male and 9 female) took part in the experiment. The experimental results obtained from Korean and British observers were then compared to see whether there was any cultural effect on scaling saturation. During the experiment, each observer assessed the saturation of 45 colour patches using a six-point scale from 1 (low saturation) to 6 (high saturation). All observers passed the Ishihara test for colour deficiency. The observers were all students of the University of Leeds, UK during the experiment. For Korean observers, the word 'saturation' was translated into '포화된' for the purpose of observer instructions, as was also used in the authors' previous study [9].

Forty-five 3 by 3 inch NCS (Natural Colour System) colour patches, together with 20 replicated (i.e. randomly selected from the 45 colours), were used as the stimuli. Observers were naive to colour appearance scaling and received no training session of colour appearance before starting the experiment. The colour samples covered a wide range of hue, chromaticness and blackness in the NCS space, as shown in Figure 1. Some of the colours were also used in the authors' previous study [9]. The experiment was conducted in a darkened room.

Each sample was presented against a grey background (X=154.05, Y=159.40, Z=188.15) in a VeriVide viewing cabinet illuminated by a D65 simulator.

The viewing distance was 60 cm. The adopted white of this study was X=491.5, Y=511.35 and Z=557.20 in cd/m^2. The experimental procedures were the same as those used in the authors' previous study [9]. The observer response (i.e. the "saturation" scale value for each colour sample, in terms of the z-score) was obtained using the categorical judgement method. [10]

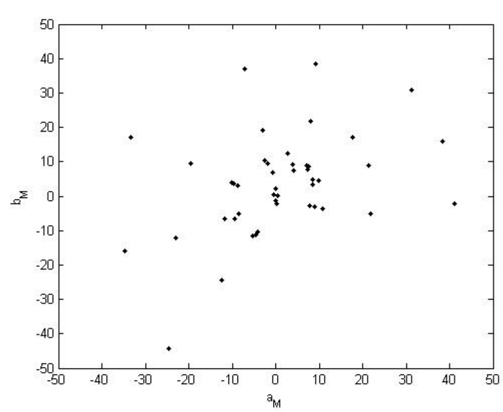
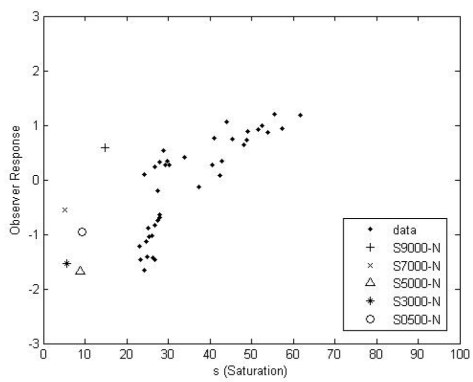


Figure 1 *$a_M b_M$ plane of colour samples in CIECAM02 space*

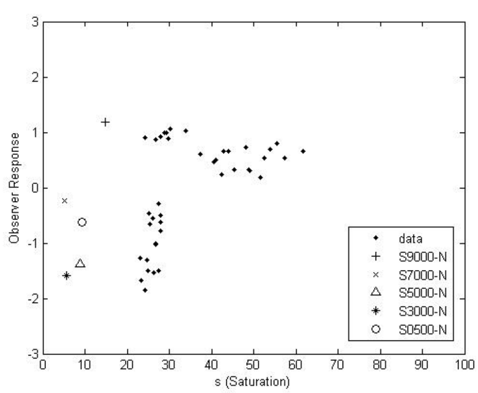
Results

To compare the observer response and the corresponding saturation values predicted by existing colour appearance models, the observer data were plotted against CIECAM02 saturation, as shown in Figure 2(a) for British observers and the Figure 2(b) for Korean observers. Note that the CIECAM02 saturation scale was developed on the basis of Juan et al.'s data [8], for which the observers were trained according to the CIE definition of saturation.

As shown in both graphs, achromatic colours are represented by special symbols. For example, a "plus" sign represents a dark grey (or called "black" in this study), with an NCS specification of S9000-N, meaning the colour has a blackness of 90 and a chromaticness of 0. Among these achromatic colours, the light grey seems to be the lowest in colour saturation for British observers, as shown in Figure 2 (a). For Korean observers, in the other hand, the medium grey seems to have the lowest saturation, as shown in Figure 2(b). The black colour (represented by the "plus" sign) seems to be the most saturated among the achromatic colours for both British and Korean observers, as shown in both graphs. This is followed by dark grey, white, medium grey and light grey. This trend seems to be shared by both British and Korean observers. For chromatic colours, i.e. those shown as dots, British data seem to have a better correlation with CIECAM02 saturation than Korean data.



(a)



(b)

***Figure 2** (a) Correlation between 'Saturation' by British observers and the CIECAM02 saturation; (b) correlation between 'Saturation' by Korean observers and the CIECAM02 Saturation*

Principal component analysis (PCA) [10] was used to classify the observers into subgroup according to their saturation response. As a result, British observers were classified into three subgroups each highly correlated with component 1, 2 and 3. For each observer, the highest component loadings are highlighted in grey, as shown in Table 2. As such, observer highly correlated with component 1 include observers 6, 9, 13, 21, 22, 26, 29, 31, 33, 35 and 36, called Group A; Those highly correlated with component 2 are observers 16, 27, 28 and 37 called Group B; Observers 10, 25, 30 and 38 are highly correlated with component 3, and are called Group C. Component 1 shows an eigenvalue of 12.31, 1.54 for component 2 and 0.95 for component 3.

Table 1 Component matrix of British observers based on the saturation response

	Component 1	Component 2	Component 3
Obs6	0.81	0.23	0.18
Obs9	0.67	0.46	0.45
Obs10	0.12	0.41	0.70
Obs13	0.80	0.40	0.17
Obs16	0.30	0.74	0.34
Obs21	0.68	0.25	0.47
Obs22	0.68	0.55	0.29
Obs25	0.29	0.08	0.83
Obs26	0.89	0.14	0.06
Obs27	0.30	0.81	0.26
Obs28	0.54	0.66	0.35
Obs29	0.77	0.50	0.21
Obs31	0.77	0.27	0.41
Obs30	0.36	0.30	0.70
Obs33	0.65	0.53	0.27
Obs35	0.65	0.31	0.41
Obs36	0.634	0.633	0.25
Obs37	0.47	0.53	0.45
Obs38	0.08	0.21	0.67

The observer response of each colour sample, calculated for each of the three groups were plotted against CIECAM02 saturation, as shown in Figure 3 (a) to (c) for Groups A to C, respectively. The graphs show that CIECAM02 agrees in general for most of the chromatic colours but there are some differences between the three observer groups in the achromatic colours, i.e. the least saturated colours seem to be different for the three groups of observers. For Group A, the observers seem to regard the light grey as the least saturated colour. For Group B, both the light grey and white were seen as the least saturated. For Group C, the observers seem to regard the medium grey as the least saturated colour. Note that only Group B shows a high correlation between the observer response and CIECAM02 saturation. These results suggest that during the experiment, there were at least three kinds of definition of saturation, for each of which the least saturated colour was located in the colour space somewhere between white and medium grey.

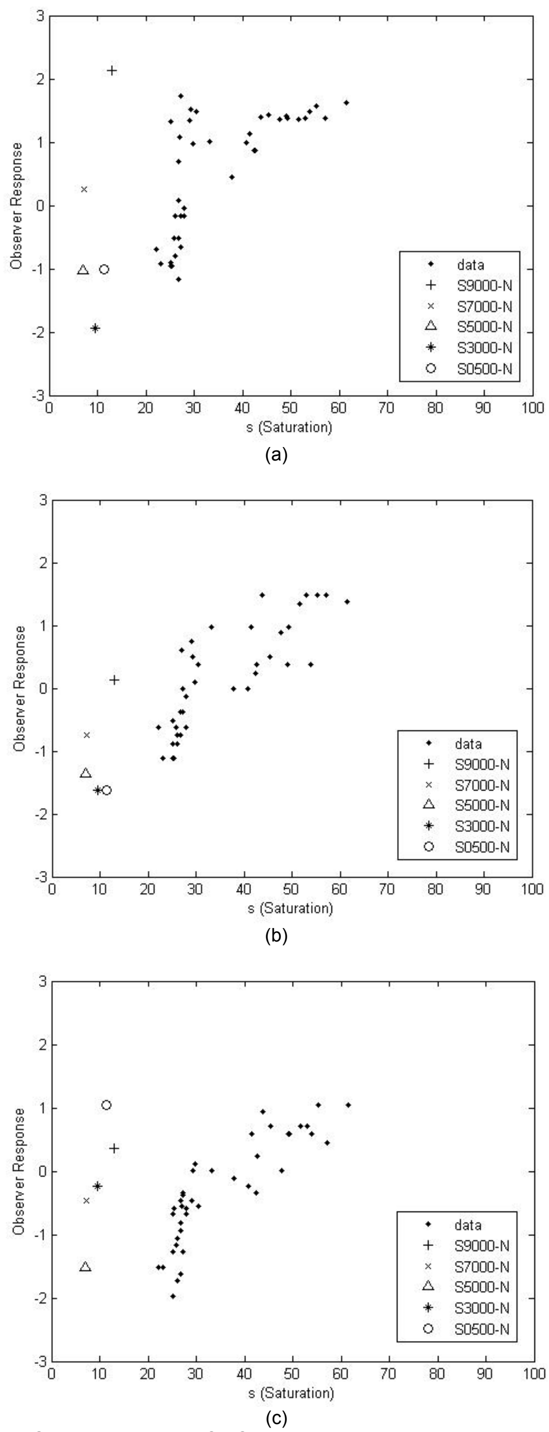


Figure 3 *Correlation between CIECAM02 saturation and British observers (a) Group A, (b) Group B and (c) Group C*

The comparisons between the three observer groups were also made using predictive models developed on the basis of observer response for each group. Each model was based on CIECAM02 values, taking into consideration one of the typical model frameworks of colour emotion [11, 12], in the form of a modified colour difference formula:

$$\Delta E = k_0 + k_1\sqrt{(J - J_0)^2 + k_A(a_M - a_0)^2 + k_B(b_M - b_0)^2} \quad (1)$$

where J_0, a_0, b_0 are coordinates of the reference colour (i.e. either the least or the most saturated colour). Coefficients k_A and k_B are constants representing the contribution of a_M and b_M, compared to J, to the prediction. k_0 and k_1 are constants for the purpose of scaling.

Equations (2) to (4) are saturation models based on a Group A to C of British data, with correlation coefficients of 0.96, 0.92 and 0.91, respectively. The high correlation coefficients indicate that the predicted values stand for the majority of total variance of the observer response.

$$S_{BA\_CIECAM02} = -2.93 + 0.07\sqrt{(J - 76)^2 + 0.83(a_M - 2)^2 + 1.09(b_M + 4)^2} \quad (2)$$

$$S_{BB\_CIECAM02} = -2.55 + 0.04\sqrt{(J - 83)^2 + 4(a_M - 1)^2 + 2.11(b_M - 1)^2} \quad (3)$$

$$S_{BC\_CIECAM02} = -1.98 + 0.06\sqrt{(J - 50)^2 + 1.31(a_M - 5)^2 + 0.74(b_M + 3)^2} \quad (4)$$

The reference colours shown by the three models suggest the least saturated colours for the three subgroups of British observers, i.e. pinkish/purplish greys with a high or medium lightness. The further away from the reference colour, the more saturated the colour in question will tend to appear.

Using the same method (i.e. PCA) as described above, the Korean observers were also classified into three subgroups. Group A is highly correlated with Observers 2, 4, 7, 8, 12, 15, 23, 24 and 39; Group B is highly correlated with Observer 1, 5, 14, 17, 18, 19, 20, 32 and 34; Group C is highly correlated with Observer 3 and 11 shown in Table 2. The eigenvalue of component 1 is 11.20, 2.25 of component 2 and 1.51 of component 3.

Table 2 Component matrix of Korean observers based on the saturation response

	Component 1	Component 2	Component 3
Obs1	0.05	0.60	-0.27
Obs2	0.83	0.42	0.03
Obs3	0.53	0.18	0.70
Obs4	0.80	0.31	0.26
Obs5	0.17	0.79	0.10
Obs7	0.64	0.23	0.40
Obs8	0.90	0.28	0.10
Obs11	0.21	0.02	0.86
Obs12	0.74	0.35	0.18
Obs14	0.37	0.75	0.10
Obs15	0.84	0.47	0.002
Obs17	0.55	0.64	-0.02
Obs18	0.33	0.67	0.08
Obd19	0.56	0.75	0.04
Obs20	0.37	0.72	0.08
Obs23	0.80	0.43	0.07
Obs24	0.65	0.20	-0.65
Obs32	0.22	0.73	0.22
Obs34	0.47	0.80	-0.01
Obs39	0.66	0.22	0.34

Figure 4 (a) to (c) show the observer response of each colour sample plotted against CIECAM02 saturation for the three subgroups of Korean observers. The graphs show that the least saturated colours for the three subgroups are either a light grey or a medium grey. Note that Figure 4 (c) shows a distinct pattern for the chromatic colours, illustrating a trend for highly saturated colours, the observer response tends to decrease as the CIECAM02 saturation value gets higher. This trend is different from both Figure 4 (a) and (b), in both of which the observer responses tends to increase as the CIECAM02 saturation value gets higher.

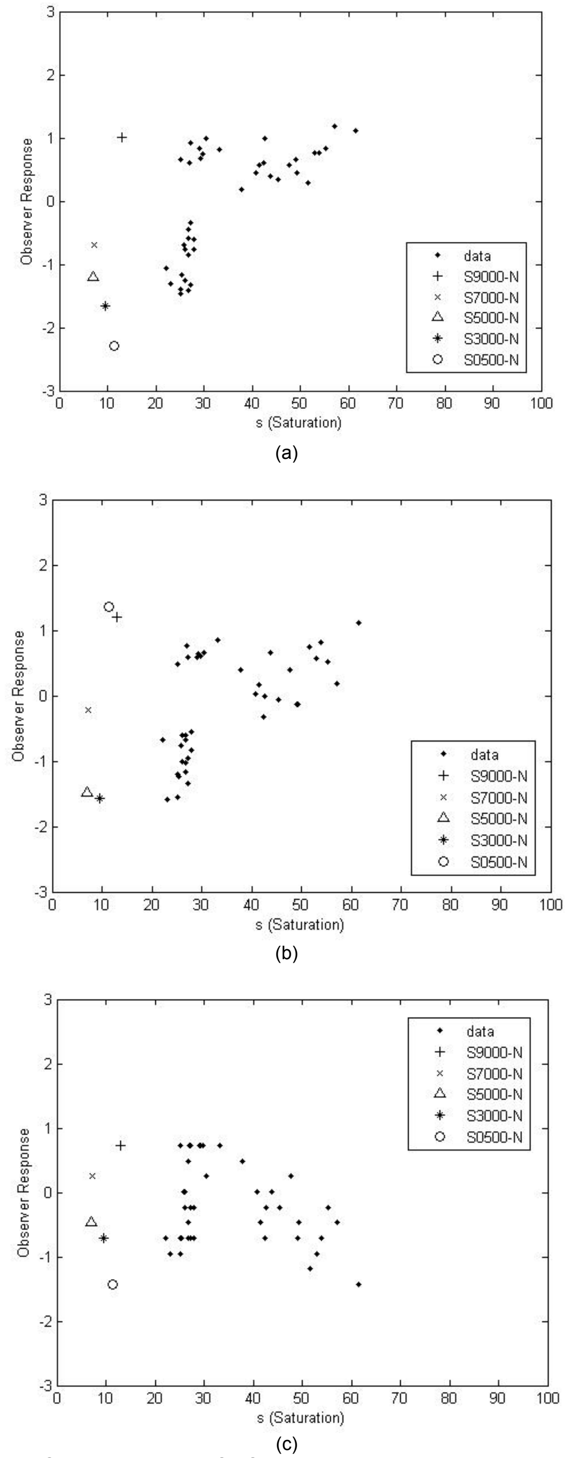


Figure 4 *Correlation between CIECAM02 saturation and Korean observers (a) Group A, (b) Group B and (c) Group C*

Eqs. (5) to (7) show the saturation models based on Group A to C of Korean data, with correlation coefficients of 0.97, 0.94 and 0.87, respectively. The high correlation coefficients indicate that the predicted values stand for the majority of total variance of the observer response. For Group A and Group B, the least saturated colours were light bluish grey (Eq 5) and a medium grey (Eq 6), respectively. The further away from the reference colour, the more saturated the colour in question will tend to appear. For Group C, the model shows that the most saturated colour is black, and that the further away from black, the less saturated the colour in question will tend to appear.

$$S_{Ka\_CIECAM02} = -3.36 + 0.06\sqrt{(J-85)^2 + 0.98(a_M+1)^2 + 1.15(b_M+7)^2} \quad (5)$$

$$S_{Kb\_CIECAM02} = -1.87 + 0.07\sqrt{(J-56)^2 + 0.38(a_M-1)^2 + 0.48(b_M-2)^2} \quad (6)$$

$$S_{Kc\_CIECAM02} = 1.3 - 0.03\sqrt{(J)^2 + 2.18(a_M-3)^2 + 1.09(b_M)^2} \quad (7)$$

Discussion and conclusion

Figures 2 (a)-(c) and 3 (a)-(c) show different trends of observer response in the assessment of saturation. This is reflected well by Equations (2) to (7). In particular, Equation (7) shows that Group C of Korean observers regarded black as the most saturated colour, and that the further away from black, the less saturated the colour in question will tend to appear. This trend is quite different from the other groups of observers, who tended to see a grey as the least saturated colour and that the further away from the grey, the more saturated the colour in question. The experimental results suggest a wide diversity in the assessment of saturation, not only between cultural backgrounds (British vs. Korean), but also between subgroups of the same cultural background.

Among the 6 subgroups of observers, only group B of British observers agreed well with CIECAM02 saturation. In other words, among the 39 observers only 10% of them agreed with the CIE definition of saturation, i.e. the colourfulness of an area judged in proportion to its brightness [1]. According to this definition [1], all achromatic colours have zero saturation because they all have colourfulness of zero. In the present study, the majority of observers showed different understandings of saturation; some regarded white, a light grey or a medium grey as the least saturated among all test colours, while some regarded black as the most saturated colour among all test colours.

We think the main reason for such diversities was perhaps that most observers when performing the visual assessment have tried to associate colour saturation with a cup of water with colorant fully dissolved. The reason for greys being regarded as the least saturated colour was perhaps due to the fact that the background colour used in the experiment was a grey. Thus, for the future studies, we suggest that the experiment uses different colours as the background to see whether and how the background colour can really affect the perceived saturation.

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