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How is colour harmony perceived by observers with a colour vision deficiency?

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Abstract

Judgements of colour harmony were made by observers, including some with normal colour vision and some with a colour vision deficiency. A set of colour pairs applied to food colourings was rated on a 1-10 scale of harmony, in two different locations, Norway and Taiwan. The results indicate that the harmoniousness of the colour pairs was rated slightly lower by the colour-deficient observers, but that other factors - the type of food object and the different nationalities of the observers - had a greater effect. It was also found that the results of showing deuteranope simulations of the colour pairs to normal observers did not agree with judgements made by those observers with an actual colour vision deficiency.

Introduction

Colour harmony is essentially the degree to which two or more colours seen in combination are judged to be pleasing. Colour harmony is not just an abstract perception, it also drives preferences and choices in many consumer areas including fashion, interior design, architecture and graphics. One subject of interest is the colour of food, where the palette of colours used by the chef plays an important role in how appealing the food is judged to be. The perceived colour harmony of food colours was investigated by Wei et al [1], and the role of colour in the appearance of food was studied by Hutchings [2], who noted that for people with colour vision deficiencies, the colour of food and whether they find it pleasing has not been extensively researched.

Colour vision deficiencies are most often a result of a mutation in a gene that encodes for retinal photopigments, resulting in a loss of discrimination between colours particularly in the red-green dimension. However, it has been found by Bonnardel [3] that dichromatic observers use the same colour names as those with normal vision, and Green [4] proposed that such observers may retain cognitive percepts for colour dimensions even in the absence of sufficient signal to noise to discriminate them in a given visual field. If this is the case, simulating the information loss by a dichromat may not, when presented to an observer with normal vision, predict how pleasing the individual colours and their combinations may appear to the dichromat.

Colour preferences are to some extent cultural, and a number of studies have found differences in the preferences for individual colours and for colour harmonies involving two or more colours [e.g. 5-10]. Nevertheless, models that predict the harmony of colour combinations have been derived from comprehensive experimental data based on judgements of colour patches, e.g. by Ou and Luo [8], Nayatani and Sakai [11], and Szabó et al. [12]. More recently, Ou et al [13] derived a model from psychophysical data from 12 regions in the world as a contribution to the work of CIE TC1-86 "Models of colour emotion and harmony"; this model is given below in eqn 1.

$$CH_U = CH_{\Delta H} + CH_{\Delta C} + CH_{\Delta L} + CH_{Lsum} \quad (1)$$

where

$$CH_{\Delta H} = -0.7 \tanh(-0.7 + 0.04\,\Delta H^*_{ab})$$

$$CH_{\Delta C} = -0.3 \tanh(-1.1 + 0.05\,\Delta C^*_{ab})$$

$$CH_{\Delta L} = 0.4 \tanh(-0.8 + 0.05\,\Delta L^*)$$

$$CH_{Lsum} = 0.3 + 0.6 \tanh(-4.2 + 0.028(L_1 + L_2))$$

In the current study, our objectives are to determine whether such a model can predict the colour harmony judgements of observers when applied to images of objects rather than colour patches; to compare the magnitude of cultural difference in such judgements; and to compare the judgements made by normal observers with those made by observers with a colour vision deficiency.

Experimental

A series of experiments was performed to explore the perception of colour harmony by normal and colour vision deficient (CVD) observers, using a subset of the sample pairs described in Ou et al [8]. The CIELAB coordinates of these 14 colours are given in Table 1, and illustrated in Figure 1. The different possible pair-wise combinations of the 14 colours gave rise to a total of 91 sample pairs. The CIELAB coordinates were converted to sRGB for viewing on a display.

Table 1 CIELAB coordinates of the 14 colours used in experiments 1 and 2.

	L^*	a^*	b^*	C^*_{ab}	h_{ab}
Red	35	46.4	23.2	51.8	27
Orange	56.7	30.6	52.1	60.4	60
Yellow	79.2	2.6	61.3	61.4	88
Green	34.1	-25.8	17	30.8	147
Cyan	34.6	-17.8	-8.9	19.9	206
Blue	35.8	-2.4	-33.4	33.5	266
Purple	35.7	36.9	-23.6	43.8	327

Pale red	79.8	21.9	10.9	24.5	26
Pale orange	79.6	13.1	22.2	25.8	59
Pale yellow	79.4	1.4	25.2	25.3	87
Pale green	79.5	-19.4	12.6	23.1	147
Pale cyan	80	-13.3	-5.9	14.5	204
Pale blue	80.6	-1.9	-24.3	24.4	265
Pale purple	80.3	19.5	-12.1	23	328

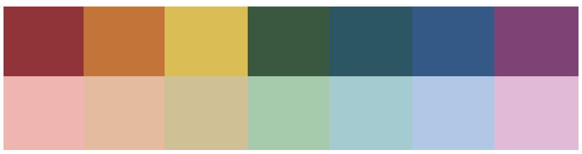

Figure 1. The 14 colours used in the two experiments

Experiment 1

The first experiment was designed to obtain data on the perceived harmony of simulated deuteranope colours to normal observers. The sample pairs described above were converted to a deuteranope simulation using the method described by Brettel et al [14], implemented using the proof viewing tool in Adobe Photoshop. The experiment was run as a web survey with no attempt to calibrate the users' displays. A total of 19 people with normal colour vision performed the experiment, ranging in age from 14 to 48. They judged the harmony of each pair on a 1-10 scale. The results are summarised in Table 6 below.

Experiment 2

In the second experiment the colours of the sample pairs were applied to images of food objects. Observers with both normal colour vision and a colour vision deficiency participated in two different locations, Norway and Taiwan.

Observers

A total of 43 observers participated in Experiment 2, of which 18 were in Norway and 25 in Taiwan, and 26 were male vs 17 female. All the observers took a screen-based colour vision test [15] based on a subset of the Ishihara colour plates. Twelve observers were classed as having a colour vision deficiency according to this test, and the deficiency types are shown in Table 2. The CVD observers were all male, with the exception of one female observer classed as weak deutan.

Table 2. Numbers of participants and types of colour vision deficiency

	Norway	Taiwan
Normal	12	19
Deutan	4	0
Weak or moderate deutan	1	5
Protan	1	0
Weak or moderate protan	0	1

Samples

Instead of presenting the sample pairs as uniform patches, the colours used in the first experiment were used to colorize food objects. Cupcakes and macaroons were selected as the food objects, on the basis that they are often coloured using food dyes and consumers are less likely to have expectations of the taste of the objects based on their colour. A pair of white-coloured cupcakes and a pair of macaroons were photographed under a diffuse illumination in a viewing booth. Colorizing was subsequently completed in L*, a* and b* channels, where the L* channel was left unchanged to permit realistic modelling and the a* and b* channels were filled with the intended colour of the given sample.

Setup

All the observations in Experiment 2 were conducted on the same computer, a Microsoft Surface Pro 20173 with a 12-inch display with a screen resolution of 2,736 x 1,824, calibrated to sRGB using the X-Rite i1Display Pro. The 182 images were saved in an array that was randomly shuffled, each image being selected and presented on screen in an image container using AJAX. Eventlisteners were added to each of the rating buttons, which stored the user input and then opened the next photo in the array. The experiment was presented to observers using the Opera web browser, who used the same 10-point scale to judge the magnitude of the colour harmony as in Experiment 1.

An example of the coloured food objects and the experimental interface is given in Figures 2 and 3.

Figure 2. Example of coloured food objects: a photograph of white cupcakes was colorized using the colours of the sample pairs.

Figure 3. Experimental interface

Results

Mean scores for all 91 sample pairs were computed for the two types of food objects (cupcakes and macaroons), and for normal vs CVD observers. These are shown in Table 3 with the standard deviations.

Table 3. Mean harmony scores and standard deviations for the two food objects for normal and CVD observers

	Normal		CVD	
	Mean	STD	Mean	STD
Cupcakes	5.71	0.99	5.63	0.56
Macaroons	5.17	1.02	4.59	0.59

It can be seen from Table 3 that colour harmonies on cupcakes were rated on average a little higher than on macaroons, but the differences between normal and CVD observers was small. Perhaps surprisingly, the results for CVD observers had smaller variances than those for normal observers.

A two-tailed t-test was performed on the data set to determine whether the differences shown in Table 3 were statistically significant. The results indicated that the differences between normal and CVD observers were not significant ($p=0.41$). However, the differences between Taiwanese and Norwegian observers with normal vision were significant ($p=0.003$).

In order to understand the relationship between the visual judgements of harmony and the colour difference between the sample pairs, the correlation coefficients between the visual judgements H_V and ΔE^*_{ab}, ΔL^*, ΔC^*_{ab} and ΔH^*_{ab} were calculated. These are shown in Table 4. It can be seen that all the components of difference are negatively correlated with visual harmony, suggesting that smaller differences (especially ΔL^*) tend to produce better perceived harmonies. The correlations for the CVD observers follow the same pattern as for normal observers, albeit mostly with lower magnitudes. The correlations for the two different food objects, cupcakes and macaroons, are in quite close agreement, mostly within 10% of each other, and this is also the case in Table 5 below.

Table 4. Correlation coefficients between experimental observations and components of colour difference between sample pairs

	Cupcakes		Macaroons	
	Normal	CVD	Normal	CVD
ΔE^*_{ab}	-0.63	-0.41	-0.60	-0.43
ΔL^*	-0.59	-0.29	-0.62	-0.31
ΔC^*_{ab}	-0.17	-0.25	-0.20	-0.22
ΔH^*_{ab}	-0.40	-0.29	-0.31	-0.28

Principles of colour harmony described by authors such as Itten [16] are widely used as a basis of tools which predict harmonious combinations of colours. Underpinning many of these principles is a difference in a single colour attribute, usually in either lightness or hue. A highly simplified model which incorporates this principle is shown in eqn 2.

$$H = (\Delta H^*_{ab} (1-\Delta L^*)+\Delta L^* (1-H^*_{ab}))^{1/3} + c \qquad (2)$$

where c is an arbitrary constant chosen to ensure $H>=0$.

CH_U values using the model of Ou et al [13] for the 91 sample pairs used in this study were calculated according to eqn 1, and the degree of fit with our data was found by computing correlation coefficients (Table 5). It can be seen that the correlations are poor, suggesting a fundamental difference in the perceived harmony of colour patches vs. the food objects used in the present study.

Calculating H values according to eqn 2 produces correlations which appear significantly better than the predictions of the Ou model, as shown in Table 5.

Although the chroma component of the difference between sample pairs was not positively correlated with H_V, it is commonly found that observers prefer samples with higher colourfulness. Vividness, defined as “an attribute of colour used to indicate the degree of departure of the colour of stimulus from a neutral black colour” [17], has been proposed as a useful component of colour appearance. Using the simplest formulation for vividness based directly on the eILV definition in Euclidean CIELAB space (eqn 3), (and noting that other formulas have been proposed for vividness) a combined vividness V_C for the two colours in each sample pair was computed according to eqn 4.

$$V_1 = (L_1^2 + C_1^2)^{0.5} \qquad (3)$$

$$V_2 = (L_2^2 + C_2^2)^{0.5}$$

$$V_C = (V_1^2 + V_2^2)^{0.5}$$

$$V_C = (L_1^2 + C_1^2 + L_2^2 + C_2^2)^{0.5} \qquad (4)$$

Where L_1 and L_2 are the L* lightness of the two colours in a given sample pair, and C_1 and C_2 are their C^*_{ab} chroma.

Finally the combined vividness term was added to H as shown in eqn 5.

$$HV_C = H + V_C$$

Correlation coefficients for V_C and HV_C are shown in Table 5, and it can be seen that both are positively correlated with the visual judgements.

Table 5. Correlation coefficients between experimental observations and predictions of a) Ou et al CH_U [15]; b) simple lightness/hue model H of eqn 2; combined Vividness Vc; and the sum of H and Vc

	Cupcakes		Macaroons	
	Normal	CVD	Normal	CVD
CH_U	-0.11	-0.11	-0.07	-0.16
H	0.63	0.36	0.61	0.40

Vc	0.60	0.30	0.55	0.28
HVc	0.76	0.40	0.71	0.40

These results suggest that observers prefer colour harmonies which use more vivid colours, and that the basic approach of constructing a harmony using either lightness difference or hue difference, gives an improved prediction of the results for the sample pairs used in this study. The simple models tested are not proposed for wider use, their purpose is simply to demonstrate whether the ideas behind them have validity. They could be refined with further work to give a better fit to the experimental data.

It is interesting to note that the correlations for the two different food objects, cupcakes and macaroons, are mostly within 10% of each other, suggesting that even though the magnitudes of harmony judgements differ between them the correlation with the models is independent of the type of food object.

CVD simulation

In order to determine how well the judgements V_{SIM} made by normal observers of the deuteranope-simulated colour patches agree with the judgements V_{CVD} of the observers with a colour vision deficiency of the same colours (applied to food objects), the correlation coefficient between the two sets of data was calculated and was found to be 0.002.

The judgements made by normal observers of the deuteranope-simulated colour pairs were further analysed in the same way as in the previous section and the results are shown in Table 6.

Table 6. Correlation coefficients between judgements made by normal observers of deuteranope-simulated colour pairs, and the attributes in Tables 4 and 5.

ΔE^*_{ab}	-0.33
ΔL^*	0.27
ΔC^*_{ab}	-0.22
ΔH^*_{ab}	-0.56
CH_U	-0.51
H	0.36
Vc	-0.44
HVc	-0.29

In Table 6 the values shown are the correlations between the scores from Experiment 1 (judgements of deuteranope-simulated pairs by normal observers), and the components of colour difference and the model predictions for the 91 sample pairs. It can be seen from Table 6 that these results are very different from those from actual observers with a vision deficiency (Tables 4 and 5). With the correlation between V_{SIM} and V_{CVD} being close to zero, these results strongly suggest that CVD simulations cannot be used to predict the degree to which colour combinations are pleasing to CVD observers.

Conclusions

Observers scaled the magnitude of colour harmony of 91 sample pairs in two different experiments. In the first, observers with normal colour vision judged sample pairs that had been processed to simulate the information loss experienced by dichromats; while in the second, both normal and colour vision deficient observers scaled the harmony of the 91 sample pair colours applied to food images.

One major limitation of the first experiment is that the types of vision deficiency were determined by a screen-based test which is yet to be verified; and in the case of the simulated images the type of simulation does not match the type or degree of deficiency of the majority of the observers. Nevertheless, it is clear from the results that the simulations do not enable normal users have the same experience of colour as that of a colour deficient observer.

In the second experiment the colours of the sample pairs were applied to food images, and the observations made in Experiment 1 repeated for normal observers and those with a colour vision deficiency. The results showed that the harmony judgements of these two groups were not significantly different, and that any differences between normal and colour deficient observers were less than the differences between the two food objects and between the two regions, suggesting that cultural associations have a greater influence on perceived harmony than vision differences.

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