Quantifying Colour Appearance for Unrelated Colour under Photopic and Mesopic Vision

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Abstract

This study investigates the colour appearance for unrelated colours with two sizes (0.5° and 10°) under photopic and mesopic vision[1]. The same test colours with different field sizes were assessed under four different luminance levels with reference white ranging from 60 to 0.1cd/m^2. Eight phases of psychophysical experiments were conducted to obtain visual data assessed by a panel of 9 observers. The results showed that brightness and colourfulness increased with luminance level. For photopic vision, brightness and colourfulness were relatively increased for large stimuli size. For the mesopic level (0.1 cd/m^2), the results were about 50% brighter and 60% more colourful for 10° stimuli than for 0.5° stimuli. The results were used to test two colour appearance models: CAM97u and CIECAM02. The latter model was revised for predicting unrelated colours. It was found that CAM97u predicted brightness visual results more accurately than CIECAM02 and opposite was found for predicting colourfulness visual results. For predicting hue visual results, CAM97u and CIECAM02 gave satisfactory predictions.

INTRODUCTION

In the real world, objects are normally viewed in a complex context. They are known as 'related' colours.[1] An 'unrelated colour'[1] is perceived by itself, and is isolated from any other colours. Typical examples of unrelated colours are signal light, traffic lights, and street lights viewed on a dark night. These colours are important in connection with safety issues (such as night driving). Almost all models for colour appearance have been developed to consider only related colours[2, 3, 4]. Hunt[5, 6] proposed a model to predict the colour appearance for both related and unrelated colours in different viewing conditions. At a later stage, he refined the original model to be used for unrelated colours, known as CAM97u[1]. However, there has been little data available to verify the performance of this model. The colour appearance models recommended by CIE such as CIECAM97s[2,3] and CIECAM02[7,8] are simplified models for practical application in which a version for unrelated colours is absent.

Normally an unrelated colour is seen against a dark field. It is known that the human eye has two kinds of retinal photoreceptors, the rods and the cones. They are not uniformly distributed on the retina. Outside the foveola, the light receptors are cones and rods; inside the foveola, only cones. In the area beyond about 40° from the visual axis, there are nearly all rods and very few cones[1]. The rods provide monochromatic vision under low luminance levels, known as the scotopic vision[1]. This low luminance is in operation when only rods are active, and the luminance level of stimuli is less than some hundredths of a cd/m^2. Between this level and a few cd/m^2, vision involves a mixture of rod and cone activities, which is referred to as mesopic vision[1]. It requires luminances of at least several cd/m^2 for photopic vision[1] in which only cones are active.

Although few researchers such as Kwak[9] performed studies for related colours with 2° and 10° viewing fields under mesopic vision. She concluded that it is insufficient to predict colour appearance simply using different colour matching functions. Thus, in this study, special efforts were made to investigate unrelated colours and different sizes of stimuli were used in photopic and mesopic vision. The results accumulated were used to test the colour appearance models, CAM97u and CIECAM02.

EXPERIMENTAL CONDITIONS

A CRT monitor with a 24-bit graphic card was used to display colour stimuli. Its peak white was set to have chromaticity coordinates of CIE Illuminant D65 with a luminance of 60 cd/m^2. The CRT monitor was carefully characterised using the GOG (gain-offset-gamma) model[10].

Fifty test colour patches were selected to cover a wide colour gamut and brightness range. These colours were displayed to cover the full CRT screen in a darken room. A piece of black cardboard with a hole in the middle was used to mask the rest of screen colour. Neutral density filters were used to cover the stimuli (the hole in the middle) for achieving the desired luminance level. The stimuli had two sizes corresponding to 0.5° and 10° viewing fields. Figure 1 illustrates the viewing field with different stimuli sizes. Each colour was measured using a Minolta CS1000 tele-spectroradiometer (TSR) to obtain tristimulus values. Table 1 summarises the viewing conditions in each phase.

The name of each phase is composed of two parts, e.g. 60-0.5. . The first represents the luminance level, i.e. 60, 5, 1, and 0.1 cd/m^2, respectively. The second part represents the viewing angle of stimuli, 10° or 0.5°, respectively. For example, Phase 60–0.5 had a vewing condition of viewing 0.5° stimulus under an illumination of 60 cd/m^2.

Table 1: Experimental phases

Phase	Name	Viewing angle of stimuli	Luminance of Lw cd/m^2
1	60-0.5	0.5°	60
2	60-10	10°	(photopic)
3	5-0.5	0.5°	5
4	5-10	10°	(photopic)
5	1-0.5	0.5°	1
6	1-10	10°	(mesopic)
7	0.1-0.5	0.5°	0.1
8	0.1-10	10°	(mesopic)

Figure 1: The experimental viewing fields: (Left) 0.5° stimuli and (right) 10° stimuli.

Psychophysical experiments were conducted to obtain visual data by a panel of 9 normal colour vision observers using the magnitude estimation method[11]. Each colour was assessed in terms of brightness, colourfulness and hue. No reference white was displayed for the unrelated colours. The terms lightness and chroma are relative perceptual attributes of colours, and these two attributes do not apply to unrelated colours, because they do not have a similarly illuminated area that appears white. Thus unrelated colours only exhibit the perceptual attributes of brightness, colourfulness, saturation, and hue. A physical sample having a colourfulness of 40 and a brightness of 100 was assigned as an anchor colour for scaling these two attributes. Observers were required to memorise this reference colour viewed in a viewing cabinet before conducting the experiment.

It is important for observers to adapt fully for dark adaptation. In this study, the experiments were conducted in a completely dark room with an adapting time of 20 minutes before commencing the experiment.

RESULT AND DISCUSSION

Observer Variation

The magnitude estimation data were collected and the coefficient of variation (CV) given in Equation (1) was used to indicate the agreement between any two sets of data. For the three colour appearance attributes studied, CV values were calculated between each individual observer's results and the mean results, and between observer's results with two repeats, to represent the performance of observer accuracy and repeatability, respectively. For perfect agreement, the CV value should be zero. A CV of 10 roughly means 10% variation between two datasets.

$$CV = (100/\overline{Y})\sqrt{\sum_{i=1}^{n}(X_i - Y_i)^2 / n} \qquad (1)$$

where n represents the number of samples in X and Y sets, $\overline{Y}$ represents the mean value of dataset Y.

Table 2 summarises the observer variation in each phase. The top 4 phases show the results for 0.5° stimuli and bottom 4 phase for 10° stimuli. Note that in this study, ten colours were randomly selected for examining the observers' repeatability. Therefore 60 colours were presented in each phase.

Table 2 Observer variation

Phase	Name	Accuracy			Repeatability		
		B	M	H	B	M	H
1	60-0.5	28	48	13	15	26	5
3	5-0.5	34	48	15	18	17	5
5	1-0.5	40	44	13	20	29	9
7	0.1-0.5	78	82	19	39	57	11
2	60-10	29	39	17	15	21	6
4	5-10	36	43	15	18	17	7
6	1-10	38	37	15	15	27	7
8	0.1-10	55	68	14	27	37	9
	Mean	41	52	16	20	28	7

The results show that the mean CV values for observer repeatability and accuracy were 20, 28, 7 and 41, 52, 16 for brightness, colourfulness and hue, respectively. This implies that for assessing colour appearance under unrelated viewing conditions, observer accuracy performance is almost twice as bad as that for observer repeatability.

Effects of luminance level of stimuli

Comparisons were made between the phases with different luminance levels of the stimuli by plotting the results between different phases. The figures clearly showed that colours appear brighter and more colourful at higher luminance levels than at lower luminance levels, but that the hues are largely unchanged. These results were found for both the 0.5° and 10° stimuli and were described in previous study[12].

Effects of size of stimuli

For brightness, colourfulness, and hue attributes, Fig. 2 shows the visual results of 0.5° stimuli plotted against those of the 10° stimuli for the 60, 5, 1 and 0.1 cd/m^2 luminance levels, respectively. These are arranged from left to right (60 cd/m^2, P1 vs. P2; 5 cd/m^2, P3 vs. P4; 1 cd/m^2, P5 vs. P6; 0.1 cd/m^2, P7 vs. P8).

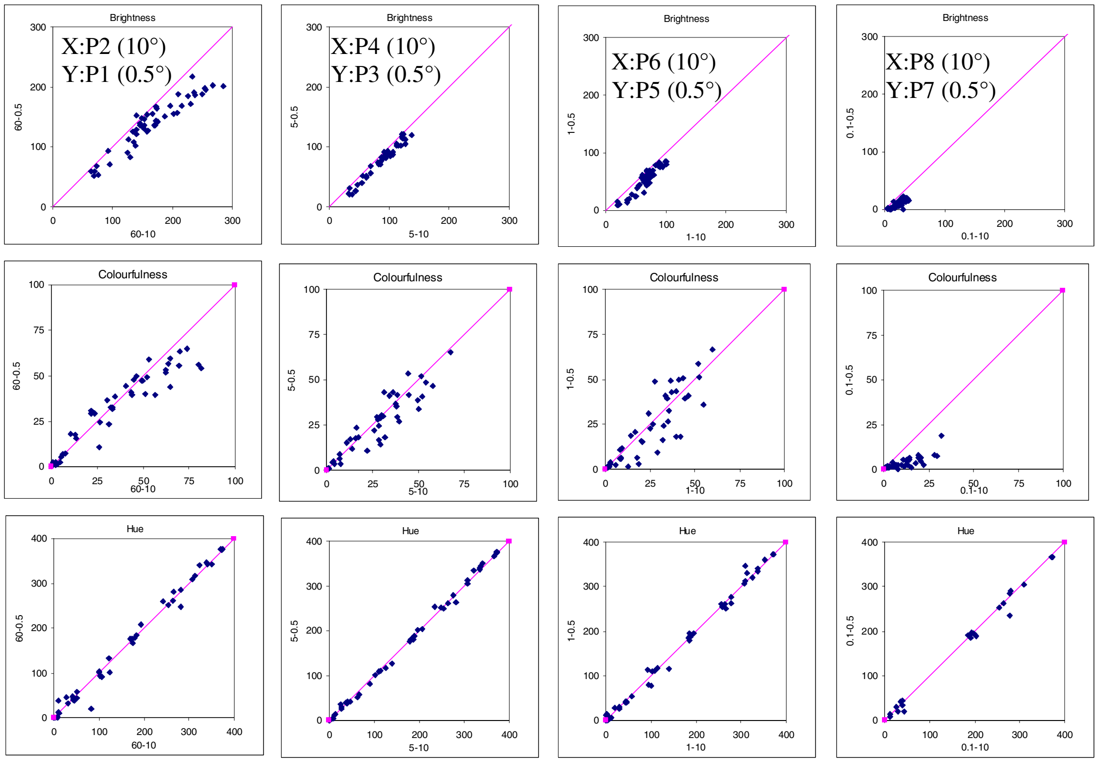

***Figure 2** Comparisons of 10^0 (abscissa) and 0.5^0 (ordinate) mean visual results for brightness (top), colourfulness (middle) and hue (bottom). And stimulus luminance arranged from left to right: 60; 5, 1 and 0.1 cd/m^2 , respectively.*

The above diagrams showed that at 60, 5 and 1 cd/m^2 luminance levels, 10° stimuli appear slightly brighter and more colourful than 0.5° stimuli. The data distributions in these diagrams represent this typical trend found from all luminance levels studied except for the 0.1 cd/m^2, for which all diagrams in right column showed the results for the 0.5° field size are about 50% lower for both brightness and colourfulness, but with no change for hue. Any increase in colourfulness caused by a smaller rod contribution in the 0.5° field at the 0.1 cd/m^2 luminance level was evidently masked by a large reduction in colourfulness caused by the much smaller field size. This implies the importance of field size as a factor affecting the recognition of signal lights.

New studies are being carried out with different field sizes under low luminance levels to clarify the situation further.

Testing CAM97u

In CAM97u[1], Hunt pointed out that, although unrelated colours are usually perceived in surrounds of luminance very much lower than that of the stimuli, in most practical situation the adapting luminance, L_A, can not be taken as zero, because the stimulus being considered provides some adapting light. In CAM97u the luminance of the adapting field is calculated in both photopic and scotopic forms. The photopic luminance, L_A, in cd/m^2, is calculated as:

$$L_A = L^{2/3} / 200$$

where L is the luminance of the sample

The scotopic luminance of the adapting field (divided by 2.26), L_{AS}/2.26 is calculated as:

$$L_{AS}/2.26 = \left(L_S/2.26\right)^{2/3} / 200$$

where Ls/2.26 is the scotopic luminance of the sample

L_S/2.26 is used insread of L_S because L_S/2.26 = L_A for the equi-energy stimulus, S_E.

The CV measure was again used to indicate the agreement between visual results and CAM97u[1] predictions. The results are summarised in Table 2. For testing the model's brightness and colourfulness predictions using the visual results, individual scaling factors were derived for each phase using the gradient of a best-fit straight line that passed through the origin (the ideal black and neutral for brightness and colourfulness respectively). Different mean-scale factors were also calculated for the two different field sizes of the stimuli: Group 1 for the 0.5° field size with Phases 1, 3, 5 and 7; Group 2 for the 10° field sizes with Phases 2, 4, 6 and 8. Finally an overall scaling factor was also calculated. The CAM97u predictions using the mean scaling factor are plotted against the visual data which are shown in Figures 3 and 4 for 0.5° and 10° stimuli, respectively.

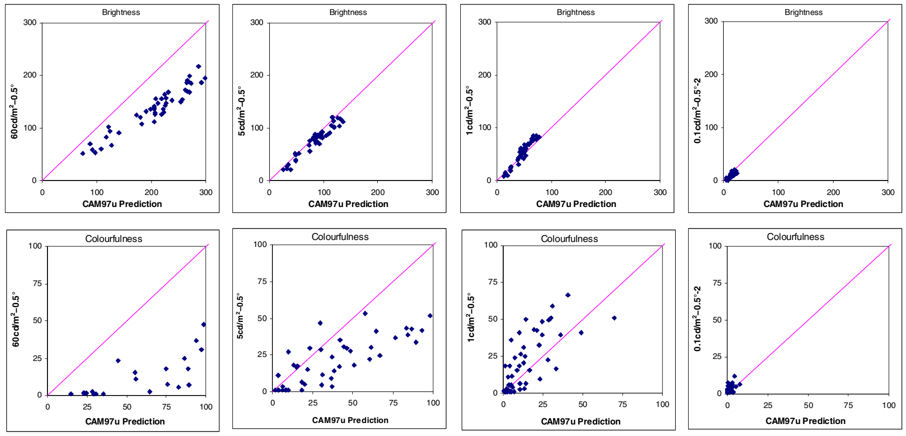

Figure 3 *Comparisons between CAM97u predictions (using mean scaling factor) and visual data in brightness (top) and colourfulness (bottom) for 0.5° stimuli.*

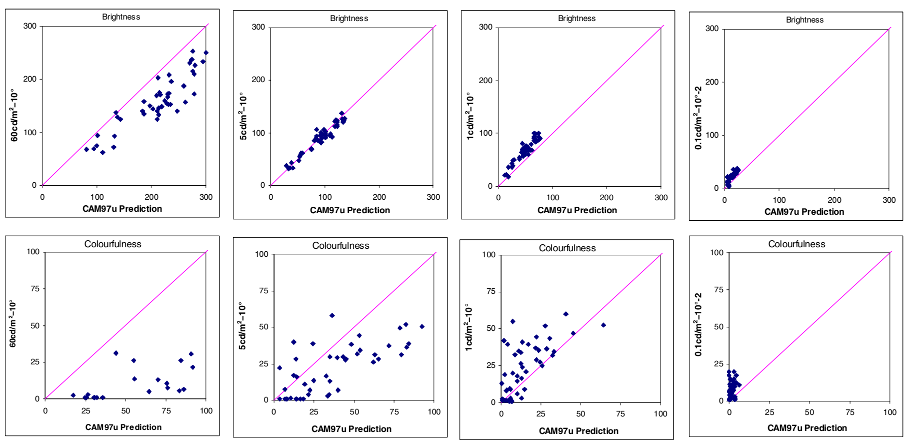

Figure 4 *Comparisons between CAM97u predictions (using mean scaling factor) and visual data in brightness (top) and colourfulness (bottom) for 10° stimuli.*

Table 3 shows the CV values for brightness (CV-B) colourfulness (CV-M) and hue (CV-H). In addition, CV-B′ and CV-M′ were calculated using the group scaling factors (SFg) to scale the predicted results for 0.5° and 10° stimuli; CV-B″ and CV-M″ were computed using the mean scaling factor (SFm) for all eight phases (P1-P8). CV-H was calculated using the raw data, i.e. 0, 100, 200, 300 and 400 corresponding to red, yellow, green and blue unitary hues, respectively.

The results in Table 3 show that CAM97u gave accurate prediction to the brightness and hue visual results, i.e. the predicted errors (30 and 16 units respectively) are smaller than or close to the observer accuracy between all observers (41 and 16 units respectively). However, it performed badly to predict colourfulness visual results (an average of 174 units). This was mainly caused by the large difference in magnitudes of model's predictions between the high (60 cd/m^2) and low (0.1 cd/m^2) luminance levels. It was also found that the group scaling factors produced a slightly improvement in the model predictions.

Table 3: Comparisons between visual results and CAM97u predictions in term of CV values and scaling factors (SF) used for scaling brightness and colourfulness predictions.

Group	Phase	Name	Gradient-B	SFg-B	CV-B′	SFm-B	CV-B″	Gradient-M	SFg-M	CV-M′	SFm-M	CV-M″	CV-H
1	1	60--0.5	5.27	6.74	30	7.94	47	0.78	2.78	303	3.60	426	13
	3	5--0.5	7.15		11		11	1.56		103		158	16
	5	1--0.5	9.09		30		21	4.34		79		69	17
	7	0.1--0.5	5.43		38		53	4.45		86		79	24
2	2	60--10	6.13	9.14	53		29	0.92	4.42	461		354	11
	4	5--10	7.76		20		9	1.76		179		129	14
	6	1--10	10.46		18		30	4.60		63		67	16
	8	0.1--10	12.19		33		44	10.39		101		105	20
	Mean	P1-P8			29		30			172		174	16

Testing CIECAM02

As mentioned before, a version especially for unrelated colours is absent in CIECAM02[6]. In this study, with special parameters selected, CIECAM02 was used to test its performance for unrelated colours.

Since there was no reference white for unrelated colours, a white point (Y=100, x=1/3, y=1/3) was added in calculation when CIECAM02 was used.

The comparisons between visual results and CIECAM02 predictions are summarised in Table 4. Scaling factors similar to those used for CAM97u were calculated. The CIECAM02 predictions using the mean scaling factor are plotted against the visual data which are shown in Figures 5 and 6 for 0.5° and 10° stimuli, respectively.

The results in Table 4 show that CIECAM02 gave reasonable accurate predictions to the visual results, i.e. the brightness and hue prediction errors were 35 and 14 CV units respectively, which were smaller than the observer accuracy performance (41 and 16 units, respectively). It gave a slightly worse performance as CAM97u in predicting brightness and hue visual results, and a better performance as CAM97u in predicting colourfulness visual results.

Table 4: Comparisons between visual results and CIECAM02 predictions in term of CV values and scaling factors (SF) used for scaling brightness and colourfulness predictions.

Group	Phase	Name	Gradient-B	SFg-B	CV-B′	SFm-B	CV-B″	Gradient-M	SFg-M	CV-M′	SFm-M	CV-M″	CV-H
1	1	60--0.5	0.884	0.71	24	0.83	14	0.94	0.74	38	0.83	31	12
	3	5--0.5	0.8313		22		16	0.89		37		31	12
	5	1--0.5	0.7655		24		24	0.95		60		55	10
	7	0.1--0.5	0.3696		107		141	0.19		315		365	25
2	2	60--10	1.036	0.94	21		28	1.09	0.91	37		43	10
	4	5--10	0.9168		13		16	1.00		27		32	11
	6	1--10	0.9094		15		17	1.05		34		40	9
	8	0.1--10	0.8887		20		20	0.51		104		89	20
	Mean	P1-P8			31		35			81		86	14

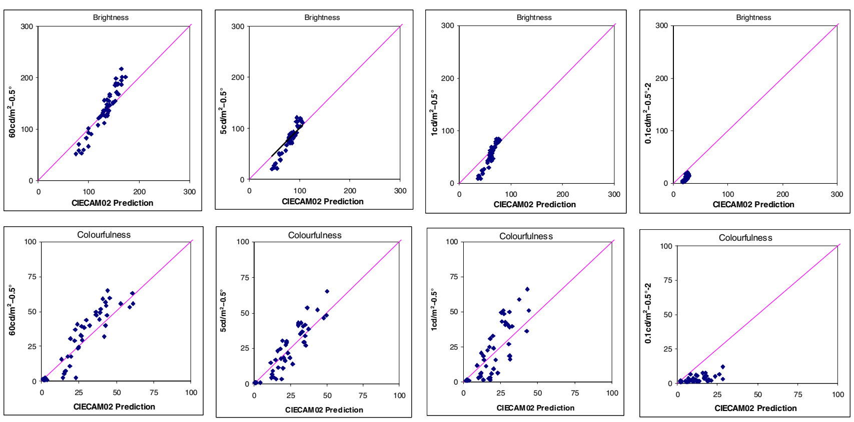

Figure 5 *Comparisons between CIECAM02 predictions (using mean scaling factor) and visual data in brightness (top) and colourfulness (bottom) for 0.5° stimuli.*

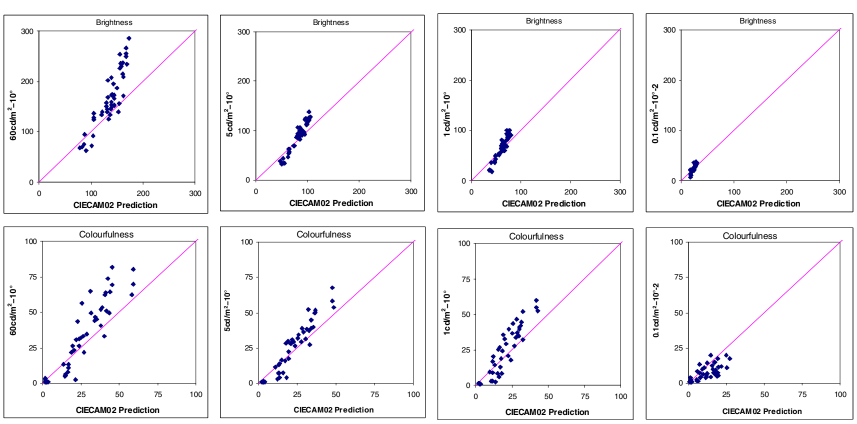

Figure 6 *Comparisons between CIECAM02 predictions (using mean scaling factor) and visual data in brightness (top) and colourfulness (bottom) for 10° stimuli.*

CONCLUSIONS

The aims of this study were to investigate the impact of size of stimuli on colour appearance for unrelated colours under photopic and mesopic vision, to test colour appearance models, CAM97u and CIECAM02 using the unrelated visual data.

In general, for the hue attribute, differences in colour appearance between each of the comparisons were small. This indicates that the perceived hues of colour stimuli do not show significant differences for the different parameters investigated. For both colour appearance models, CAM97u and CIECAM02, the predictions for the hue attribute were satisfactory.

Changing the field size from 0.5^o to 10^o made little difference to the brightness, colourfulness, and hue at the higher luminance levels (60, 5, and 1 cd/m^2), but at 0.1 cd/m^2 the reduction in field size resulted in reductions in perceived brightness of about 50%, and in perceived colourfulness of about 45%.

Comparing the two colour appearance models' performance, the mean-scaled predictions for brightness are better for CAM97u than for CIECAM02. For colourfulness, the mean-scaled predictions are much better for CIECAM02 than for CAM97u. Using different scaling factors for the two different field sizes, i.e. the group scaling factors, produced a slight improvement in the model predictions. For both models, the mean-scale factor for the 0.5° field size is smaller than for the 10° field size for both brightness and colourfulness. This implies that colours are darker and less colourful for a smaller size.

Overall, the results showed that the two models gave reasonably satisfactory performance for brightness and hue visual results, i.e. the errors of predictions are smaller than the typical observer accuracy. CAM97u is better than CIECAM02 for brightness, but worse for colourfulness. New colour appearance model for predicting unrelated colours will be developed based on this study.

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