Evaluation of Colour Differences against Different Coloured Backgrounds

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Abstract

Three experiments were carried out to investigate the change of perceived colour differences against backgrounds varying in lightness, hue and chroma, respectively. The results showed that the perceived colour difference was enhanced when the colours of the background and sample pair were close to each other, and the enhancement will be gradually weakened as the colour difference between them increases. However, this effect is different from the 'crispening effect' found by the previous studies which showed a very sharp increase of perceived colour difference when the background colour has the same colour of the pair considered. The results also showed that lightness background effect is larger than chroma and hue effects. The visual results were modeled for predicting the background effect

Introduction

Over last few decades, the development of colour difference formulae has been intense and many data sets were accumulated for this purpose. The latest CIE recommended formula CIEDE2000 were tested by fitting 4 comprehensive data sets. Comparing with the other formulae, it performs the best amongst all the formulae tested for all 4 data sets. However, all the experimental data collected are based on a set of reference conditions, i.e. a pair of samples with hair line separation against a mid-grey background under a daylight simulator at a high luminance level. Also, the sample size is large and same surface texture for both samples in a pair. The previous studies [1-13] found that perceived colour-difference or colour appearance is influenced by colours of backgrounds.

In this study, three experiments were carried out to investigate the change of perceived colour differences on colour patches against different lightness, hue and chroma backgrounds, respectively.

Lightness Background Study

The first experiment was conducted to investigate lightness background effect. The experiment was divided into 8 phases according to different lightness of backgrounds and two media: paint and CRT samples. For paint phases, painted paper sample pairs were placed in a VeriVide viewing cabinet. For CRT phases, colours of the paint samples were reproduced on a Barco monitor. The details of the 8 phases are summarised in Table 1.

All 21 paint sample pairs were products of Munsell Color Order System supplied by GretagMacbeth. Each sample had a size of 3 by 3 inch with two different gloss levels and their L* values were ranged from 7 to 93. The grey scale method used by Luo *et al* [8-12, 14] was again employed to quantify colour difference. Each sample pair was assessed twice by a panel of 10 normal colour vision observers according to Ishihara test. The arrangement of a 'sample pair' and a 'grey pair' is shown in Figure 1. Observers were asked to scale the colour difference of the 'sample pair' against a 'grey pair' formed by a fixed grey and one sample from the grey scale. The visual results of each individual observer were first converted from grade to visual difference (ΔV), which was calculated based on the relationship of grades and CIELAB ΔL^* values of the grey scale used. The mean ΔV value from all observers in each pair was then calculated as the panel results for the subsequent data analysis.

Table 1 Summary of Phase LP and LC

Media	Number of pairs	Phase (Background colour)	L* of background
Paint	21	LPD (Dark-grey)	20
		LPM (Mid-grey)	51
		LPW (White)	90
CRT	24	LCB (Black)	0.2
		LCD (Dark-grey)	21
		LCM (Mid-grey)	49
		LCL (Light-grey)	72
		LCW (White)	95

Lightness background effect is frequently studied by plotting $\Delta E^*_{ab}/\Delta V$ value of individual sample pair against the averaged L* of the sample pair [14]. For a perfect agreement between the ΔE^*_{ab} and ΔV, all ratios should be located in a horizontal line. Otherwise, the trend of $\Delta E^*_{ab}/\Delta V$ values can be revealed and the relationship can be modeled to take into account the background effect. It was later found that both sample pair and grey scale pair in Figure 1 were compared against the same background. This produces a problem because the background effect can not be discerned. A correction was made as reported in our previous publication [15]. The corrected visual difference results are denoted $\Delta V'$ here.

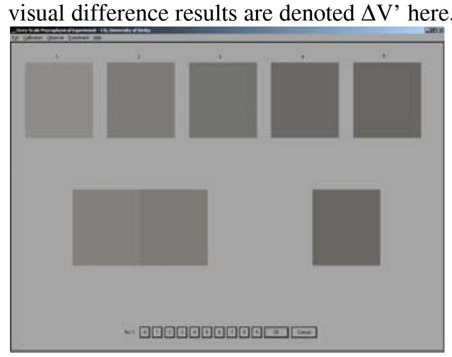
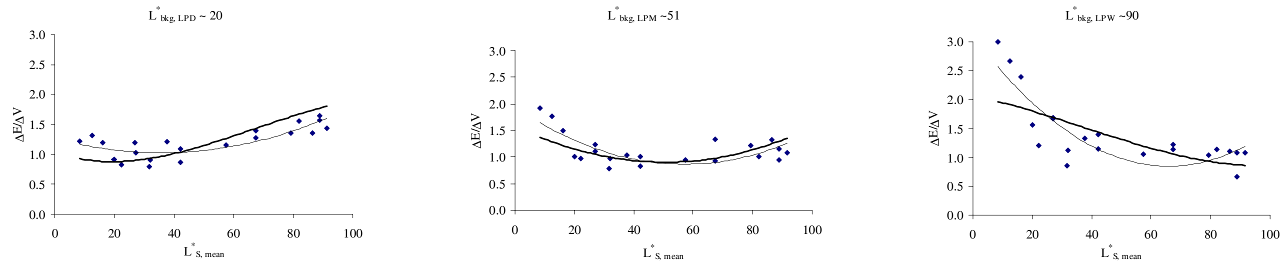
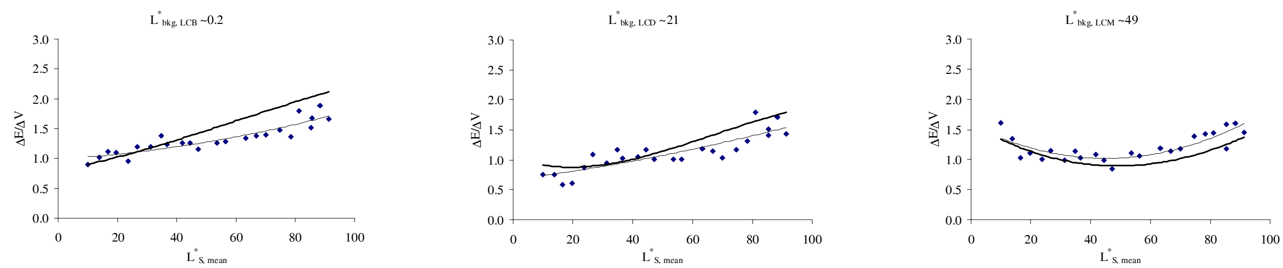


Figure 1 The pattern used in the experiment

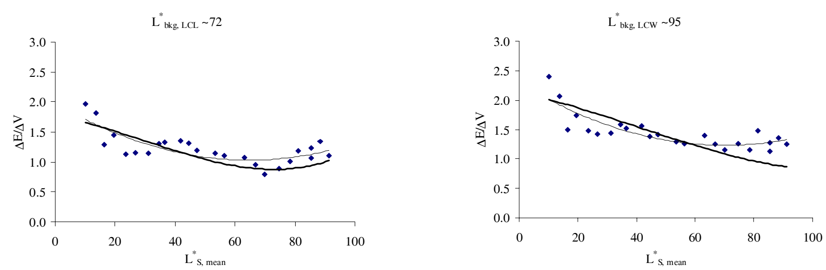


(a) Phase LPD (b) Phase LPM (c) Phase LPW

Figure 2 The $\Delta E^*_{ab}/\Delta V'$ values plotted against the mean lightness values for all paint pairs. The thin curve was the best polynomial fit and the thick curve was obtained using the background effect function (B_L).



(a) Phase LCB (b) Phase LCD (c) Phase LCM



(d) Phase LCL (e) Phase LCW

Figure 3 The $\Delta E^*_{ab}/\Delta V'$ values plotted against the mean lightness values for all CRT pairs. The thin curve was the best polynomial fit and the thick curve was obtained using the background effect function (B_L).

The $\Delta E^*_{ab}/\Delta V'$ values are plotted in Figures 2(a) to (c) and Figures 3 (a) to (e) for paint and CRT phases, respectively.

A secondary order polynomial was used to fit experimental data in each phase as shown in Figures 2 and 3 by the thin curves. A clear trend can be found that the smallest $\Delta E^*_{ab}/\Delta V'$ value in each phase always corresponds to the lightness of background. The best fitted U-shape curve also has a dip in accordance with the lightness of background. The results confirm that there is a lightness background effect up to about 300%, i.e. the ratio of the largest and smallest $\Delta E^*_{ab}/\Delta V'$ values in each diagram of Figures 2 and 3. However, the perceived differences of a sample pair against a background having the same colour of a sample in that pair and against another background having a slight colour difference do not change as much as the so called 'crispening effect' reported by Takasaki [2] and Semmelroth [3]. Note that their studies were carried out based on colour appearance of a single stimulus against a grey background, rather than the judgment of colour differences used in the present experiment. The present results also verified that the S_L weighting function in CIEDE2000 as shown by the thick curves in Figures 2*(b)* and *3(c)*, i.e. the data used to develop the CIEDE2000 formula were samples against backgrounds with L^* values close to 50. All the samples used to derive CIEDE2000 were assessed against a mid-neutral background.

The data collected in the present experiment was also used to test the performance of five existence colour-difference formulae as well as a modified CIEDE2000 formula in Equation (1). The modification was made by replacing the original weighting function S_L by B_L, and kept the rest formula unchanged. The new weighting function takes the lightness of sample as well as the lightness of background into account and allows them to be varying for each individual case. If the background L^* is 50, there is no difference between S_L and B_L. The testing results for all formulae are given in Table 2 in terms of PF/3 values [8]. For a perfect agreement between the predicted and visual results, PF/3 should be zero.

$$\Delta E_{00}' = \sqrt{\left(\frac{\Delta L'}{k_L B_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{k_C S_C}\frac{\Delta H'}{k_H S_H}\right)} \quad (1)$$

where

$$B_L = 1 + \frac{C1\left(\overline{L_S} - L_{bkg}\right)^2}{\sqrt{C2 + \left(\overline{L_S} - L_{bkg}\right)^2}}$$

The results in Table 2 clearly showed that the 'New' formula outperformed the other formulae. The corresponding B_L function plotted in thick curves in Figures 2 and 3 are in general fitted well to the experimental data.

Table 2 Colour difference equations' performance for lightness background data in terms of PF/3

PF/3	CIELAB	CIE94	CMC	BFD	CIEDE2000	New
LPD	21.3	21.3	32.0	15.3	16.8	14.1
LPM	22.9	22.9	53.0	34.5	16.9	17.8
LPW	37.2	37.2	74.2	56.2	35.2	23.6
LCD	29.9	30.0	16.5	19.2	32.0	19.1
LCM	17.6	17.4	34.7	19.5	13.4	13.1
LCB	19.0	19.2	18.1	10.9	19.7	8.6
LCW	17.1	16.9	49.1	34.0	20.4	14.0
LCL	19.5	19.3	49.6	34.4	21.5	13.8
All	25.6	25.6	44.6	31.8	25.2	17.6

Hue Background Study

In the hue background study, the experimental arrangement is shown in Figure 4. The testing background was only partially covered the monitor on the CRT display, i.e. the sample pair was assessed under the testing background but the grey scale pair was always against the mid-grey background. This arrangement can reveal the true background effect unlike the arrangement shown in Figure 1 for which the colour differences from the sample pair and grey scale pair were assessed against the same background. Table 3 gives the CIELAB values for the 8 backgrounds and colour centres used in the experiment.

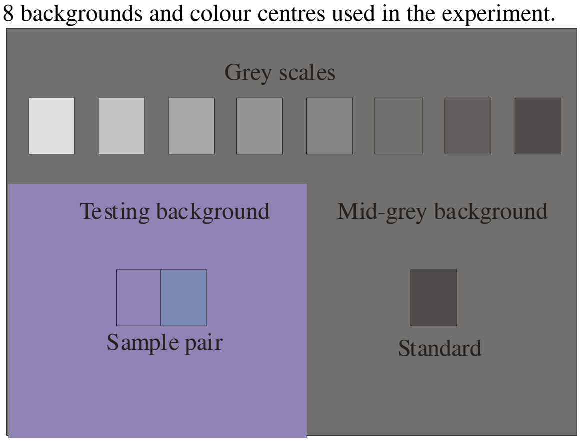


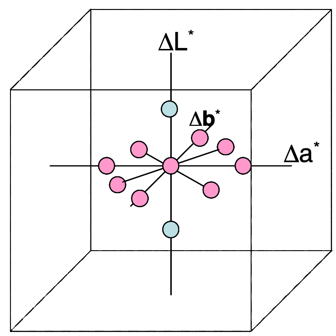
Figure 4 Experimental setup of Phase HC for hue background effect study

Each colour centre includes 10 sample pairs as shown in Figure 5(a), i.e. 8 pairs showing only chromatic differences and 2 pairs showing lightness differences. Each pair was assessed against eight chromatic backgrounds. As show in Figure 5(b), 8 colour centres are uniformly distributed in CIELAB space. The mean colour difference for all pairs were 7.5 ΔE^*_{ab} units.

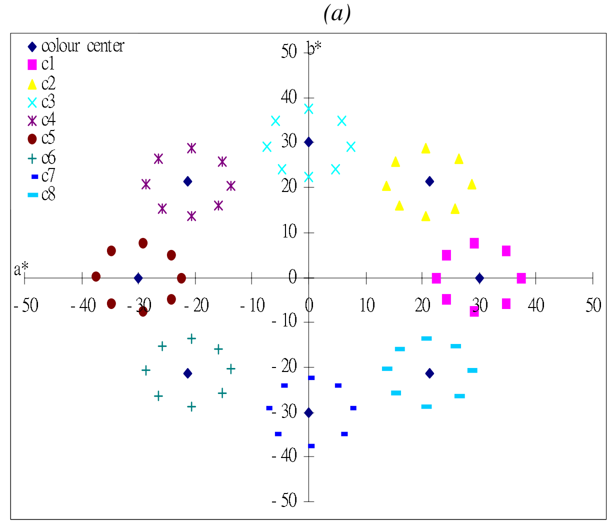
The hue background effect was revealed again by the change of $\Delta E^*_{ab}/\Delta V$ values against different hue angles of the background as summerised in Table 4. A consistent trend was found that the minimum values of $\Delta E^*_{ab}/\Delta V$ were always located where the colour centre and the background have the same colour. This implies that a given background always enhances the colour difference of colour pairs having the same colour more than the other sample pairs. As an example, the $\Delta E^*_{ab}/\Delta V$ values of colour centre with hue angle of 180° are plotted in Figure 6. A curve based on the SHH function (see next section) was also plotted to fit the trend. The hue background effect was found to be about 25% which is much smaller than the lightness background effect (about 250%) found in the last section.

Table 3 Eight phases in the hue background study

Background and colour centre	h_{ab}	L^*	C^*
Red (R)	0	50	30
Yellow-Red (YR)	45	50	30
Yellow (Y)	90	50	30
Green-Yellow (GY)	135	50	30
Green (G)	180	50	30
Blue-Green (BG)	225	50	30
Blue (B)	270	50	30
Red-Blue (RB)	315	50	30



(a)



(b)

Figure 5 Sample distributions in the hue background study

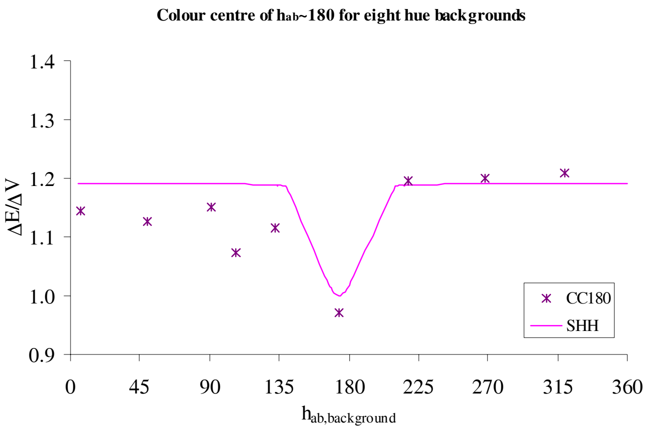


Figure 6 $\Delta E^*_{ab}/\Delta V$ values plotted against the hue ($h_{ab,background}$) for the colour centre of h_{ab} = 180°

Chroma Background Study

In the chroma background study, sample pairs were prepared surrounding 4 colour centres designated as CC00, CC90, CC180 and CC270 corresponding to CIELAB h_{ab} of 0°, 90°, 180° and 270° respectively. The CIELAB values of the colour centres and background colours for each experimental phase are given in Table 5. For example, sample pairs in CC00 were against mid-grey, F00 and H00 backgrounds having the same hue angle as the colour centre but different chroma values. All backgrounds and colour centres had an L^* value of 50. Each sample pair was displayed on a CRT monitor and assessed by a panel of observers using grey scale method with the same arrangement as Figure 4. Ten samples in each colour centre were selected in the same way as the phases in hue background study in Figure 5*(a)* with a mean colour difference 7.4 ΔE^*_{ab} units.

As shown in Table 6, chroma background effect are again analysed by comparing the $\Delta E^*_{ab}/\Delta V$ values of a given colour centre between backgrounds with different chroma but same hue angle. Table 6 shows that the $\Delta E^*_{ab}/\Delta V$ values together with their normalised values by setting the 'H' chroma backgrounds as one. Comparing the mean $\Delta E^*_{ab}/\Delta V$ values for all 12 phases, the lowest $\Delta E^*_{ab}/\Delta V$ values were always found in the 'H' chroma backgrounds where the sample have same chroma as the background. It again implies that the visual colour difference is always enhanced most when the sample pair of a given hue against the same chroma background of the same hue as colour centre. The normalised ratios are ranged from 1.20 to 1.33. This indicates a small chroma background effect (about 25%) in this study. The effect is similar to the hue background effect but still much smaller than the lightness background effect (about 250%).

Colour difference Equations' Performances and Modelling Background Effect

The three data sets accumulated from the present lightness, hue and chroma background experiments were used to test five colour difference formulae: CIELAB, CIE94, CMC, BFD, and CIEDE2000. The results are given in Table 7 in terms of PF/3 units. Each formula was tested by setting k_L=1, and by optimising k_L value to give least PF/3 values (k_C and k_H values are always set to one). They are hereafter named 'original' and 'optimised' formulae, respectively. The numbers of pairs for the lightness, hue, and chroma background data sets are 183, 720, and 120 respectively.

It can be seen in Table 7 that comparing the original formulae, CIEDE2000 performed best, followed by CIE94 and CIELAB, and CMC and BFD the worst. Comparing original formulae with the optimised k_L formulae, it is expected that the former performed worse than the latter formulae, however, they had same rankings. All formulae except CIE94 need to have a k_L less than one. This indicates that lightness differences are more noticeable than the chromatic differences.

A new formula, ΔE01 [Equation (2)], was developed by modifying the CIELAB to take into account of all possible background effects embedded in the current data sets. Its performance is also given in Table 7. The ΔE01 is expected to fit the visual results better because it was developed based on these data sets. However, the formula including 7 correction terms seems to be over-complicated and unnecessary. A simplified formula, ΔE02 [Equation (3)], was later developed by removing the insignificant terms in Equation (2) one after another. Finally, it was found that the terms of SHL and SCL, SCC and SHC, SHH and SCH in ΔE01 formula can be replaced by individual constants, k_L, k_C and k_H, respectively. The performance of ΔE02 is also given in Table 7. As expected, the ΔE02 gives very similar performance to ΔE01 for the lightness background data due to the use of correction term B_L. However, the performances on the hue and chroma data for ΔE02 are worse than ΔE01 as the replacement of functions of chroma and hue differences by constants (k_C and k_H). Equation (1) based on CIEDE2000 was also tested and the results are also reported in Table 3 in the column of ΔE03. Overall, the ΔE02 (20 PF/3 units) and DE03 (21 units) gave similar performance as the complicate formula ΔE01 (19 units).

$$\Delta E_{01} = \sqrt{\left(\frac{\Delta L^*}{B_L \cdot SHL \cdot SCL}\right)^2 + \left(\frac{\Delta C^*}{SCC \cdot SHC}\right)^2 + \left(\frac{\Delta H^*}{SHH \cdot SCH}\right)^2} \qquad (2)$$

where

$$B_L = 1 + \frac{c1\left(L_S - L_{bkg}\right)^2}{\sqrt{c2 + \left(L_S - L_{bkg}\right)^2}}$$

$$SHL = 1 + c3\sqrt{\frac{\left|\Delta H^*_{ab,SB}\right|^{c4}}{\left|\Delta H^*_{ab,SB}\right|^{c4} + 10^{c4}}}$$

$$SCL = 1 + c5\sqrt{\frac{\left|\Delta C^*_{ab,SB}\right|^{c5}}{\left|\Delta C^*_{ab,SB}\right|^{c5} + 10^{c5}}}$$

Where the SHC and SHH functions have the same structure as the SHL but with different coefficients; the SCC and SCH have the same form as SCL with different coefficients.

$$\Delta E_{02} = \sqrt{\left(\frac{\Delta L^*}{B_L \cdot k_L}\right)^2 + \left(\frac{\Delta C^*}{k_C}\right)^2 + \left(\frac{\Delta H^*}{k_H}\right)^2} \qquad (3)$$

Conclusions

A comprehensive study was carried out to investigate the change of perceived colour differences due to the change of background colours. The results confirm that there is a background effect, and lightness effect is larger than that of chroma and hue. Finally, the background effects were modelled. It was found that a simple modification to the lightness weighting function of the existing CIELAB or CIEDE2000 formula can give quite satisfactory prediction to the overall data.

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Author Biography

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Table 4 The $\Delta E^*_{ab}/\Delta V$ values of different colour centre/background conditions

Background	Colour centre							
	HC00	HC45	HC90	HC13	HC18	HC22	HC27	HC315
				5	0	5	0	
R (0^o)	0.97	1.14	1.18	1.30	1.14	1.03	1.11	1.19
YR (45^o)	1.08	0.93	1.18	1.28	1.13	1.03	1.08	1.25
Y (90^o)	1.13	1.12	0.97	1.20	1.15	1.01	1.12	1.22
GY (135^o)	1.09	1.07	1.11	1.07	1.12	1.08	1.09	1.20
G (180^o)	1.15	1.03	1.11	1.24	0.97	1.07	1.20	1.20
BG (225^o)	1.01	1.02	1.14	1.27	1.20	0.91	1.18	1.18
B (270^o)	1.12	1.07	1.15	1.26	1.20	1.00	0.96	1.17
RB (315^o)	1.11	1.07	1.12	1.22	1.21	1.07	1.13	0.96
min	0.97	0.93	0.97	1.07	0.97	0.91	0.96	0.96
max	1.15	1.14	1.18	1.30	1.21	1.08	1.20	1.25
max/min	1.19	1.22	1.22	1.22	1.24	1.19	1.25	1.30

Table 5 Summary of Phase CC for chroma background effect study

		Sample			Background	
Colour centre	Number of pairs	h_{ab}	C^*_{ab}	Phase (Background)	h_{ab}	C^*_{ab}
CC00	10			F00	359	51.5
CC00	10	359	25.2	H00	359	25.2
CC00	10			Mid-grey	229	0.3
CC90	10			F90	90	46.9
CC90	10	90	23.3	H90	90	23.3
CC90	10			Mid-grey	229	0.3
CC180	10			F180	181	23.2
CC180	10	181	11.4	H180	181	11.4
CC180	10			Mid-grey	229	0.3
CC270	10			F270	270	38.4
CC270	10	270	19.4	H270	270	19.4
CC270	10			Mid-grey	229	0.3

Table 6 Results summary of chroma background effect

Colour centre	Background	C^*_{ab} of background	Average $\Delta E^*_{ab}/\Delta V$	Normalized $\Delta E^*_{ab}/\Delta V$
CC00	F00	51.5	1.42	1.28
CC90	F90	46.9	1.25	1.29
CC180	F180	23.2	1.27	1.31
CC270	F270	38.4	1.28	1.33
CC00	H00	25.2	1.10	1.0
CC90	H90	23.3	0.97	1.0
CC180	H180	11.4	0.96	1.0
CC270	H270	19.4	0.96	1.0
CC00	Mid-grey	0.3	1.32	1.20
CC90		0.3	1.23	1.27
CC180		0.3	1.25	1.30
CC270		0.3	1.19	1.24

Table 7 Performance of colour difference formulae

Background Study Data	CIELAB	CIE94	CMC	BFD	CIEDE2000	ΔE01	ΔE02	ΔE03
Lightness data (Original)	25.6	25.6	44.6	31.8	25.2	19.5	19.3	17.4
Hue data (Original)	35.8	20.1	29.3	34.9	21.7	18.8	22.4	21.6
Chroma data (Original)	30.1	19.6	25.4	35.8	24.0	17.3	19.4	24.0
Mean (Original)	30.5	29.8	33.1	34.1	23.6	18.6	20.4	21.0
Mean (Optimised)	23.5	22.7	30.4	27.8	22.5			
k_L	0.72	1.09	0.83	0.73	0.91			