Colour Appearance Modelling for Mobile Displays

YungKyung Park, ChangJun Li, M. R. Luo*
Wonhee Choe, Seongdeok Lee and Changyeong Kim**
University of Leeds, Colour Imaging Lab, UK*
Samsung Advanced Institute of Technology, Yongin, South Korea**

Abstract

High image quality on the small display of mobile phones is becoming highly desirable as the availability of functions for playing computer games, watching still and moving images. An experiment was carried out to accumulate colour appearance data on a 2" mobile display using the magnitude estimation method. It was divided into nine phases according to three surrounds (dark, dim and average) and three backgrounds (light-grey, black, and white). The visual data are expressed in terms of lightness, colourfulness and hue. The visual results from different phases were compared to reveal different colour appearance effects. The results were also used to test and refine the CIE colour appearance model, CIECAM02 [1]. Two revised versions were made as a new mobile colour appearance model. There were large improvements from the new versions, especially for the colourfulness results.

Introduction

Recent growth of the mobile displays has led to new functions being included to the mobile phones. Additional to the conventional usage of receiving and calling, a digital camera with high resolution has made it possible to use as a digital camera and as a digital photo album. The acoustic functions such as MP3 player and radio player are becoming part of the standard package. The visual functions such as computer games, navigation systems, TV media services and internet have recently started its services, which all demand high image quality.

Unlike the other types of displays, many viewing parameters will affect the colour appearance of the mobile display. First of all, the display size is small in order to be easily carried around. It is important to achieve acceptable image quality (both spatial and colour) for viewing images with small size. Secondly, the portability allows the display to be viewed under various surround conditions varying from dark room, dark night to bright sunlight. This raises the challenge for mobile phone display manufacturers.

In this study, the aim is to be able to model the change of colour appearance under the wide range of viewing conditions.

A characterisation model was derived to transform from the CIE tristimulus values to the monitror's RGB values for each of the 40 test colours. Psychophysical experiments were conducted under different ambient lighting conditions. Each test colour was estimated by ten observers in terms lightness, colourfulness and hue appearance attributes. Nine experimental phases were carried out to study the change of colour appearance under three different surrounds and three backgrounds. The visual data obtained by the psychophysical experiment were used to evaluate the CIE colour appearance model, CIECAM02 [1]. The model was then modified for mobile displays viewing conditions. Two new models were developed and are called MobileCAMv-1 and MobileCAMv-2.

Colour Appearance data

Experiment setup

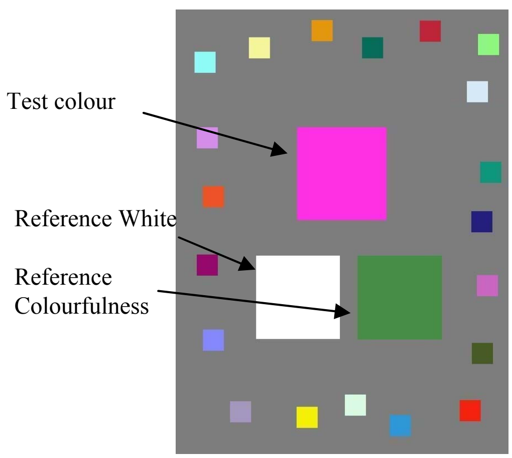


***Figure 1**. Layout of the display*

Figure 1 show the pattern used in the experiment. The physical size of the test colour, the reference white and the reference colourfulness was 0.5cm×0.5cm with a 1° viewing field at a viewing distance of 30cm. Three backgrounds, light-grey, black and white, were used in the experiment under three surround conditions.

Table 1: Conditions of the nine experimental phases

Phase	Surround (cd/m^2)	Background (Y)
1	Dark (0)	Grey (43)
2		Black (4)
3		White (99)
4	Dim (5.5)	Grey (43)
5		Black (4)
6		White (99)
7	Average (1024)	Grey (43)
8		Black (4)
9		White (99)

Table 1 summarises the experimental conditions used in the nine phases of the psychophysical experiments. Figure 2 shows the test colours plotted in CIELAB a*b* diagram. A Minolta CS1000 spectroradiometer (TSR) was used to measure all the colours in the experiment.

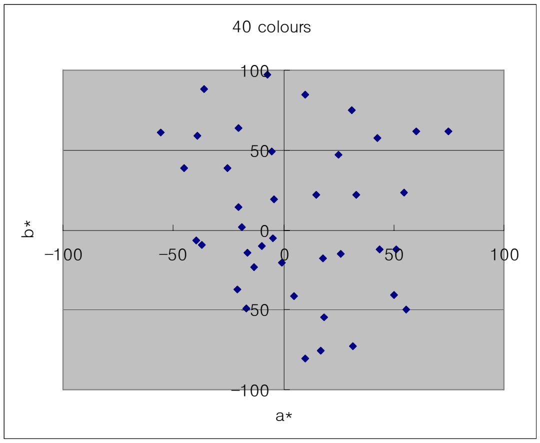


***Figure 2**. Test colours plotted on CIELAB a*b* diagram*

Twenty decoration colours located in the border of the test pattern (see Figure 1) were also chosen to make the whole scene as a complex image. The display was placed inside a viewing booth equipped with a D65 stimulator. The viewing and illumination of geometry was 0/45. Ten normal colour vision observers attended the experiment. Each observer was asked to estimate each test colour in terms of lightness, colourfulness, and hue closely following the method used by Luo et al [2]. Lightness was scaled against the reference white having a lightness of 100 and an imaginary black, 0. An anchor patch (NCS 3040-R20B) that was assigned a colourfulness of 40 was shown in a viewing booth. Each observer had to judge the colourfulness of the reference patch in the beginning of each session regarding to the anchor patch. The hue was judged by reporting the percentage of the two colours from the four psychological hues.

The colorimetric values of these colours were converted into RGB values using the reverse PLCC (piecewise linear interpolation assuming constant chromaticity) model [3]. The converted RGB values were displayed on the mobile display and measured by the TSR. The measured CIELAB values were compared with the targeted CIELAB values. The colour difference (ΔE^*_{ab}) was calculated and the results of the average, maximum, and median ΔE^*_{ab} are given in Table 2.

Table 2: The performance of the PLCC characterisation model in terms of ΔE^*_{ab}

Average	4.5
Max	9.4
Median	4.3

Ten colour patches were randomly selected among the 40 colour colours for investigating the observer repeatability performance. Therefore, 50 colour patches were estimated for each session.

Observer variations

Ten students, 3 females and 7 males, having normal colour vision took part in the experiment. They had abundance experience for scaling colour appearance using the magnitude estimation method. In total, 13500, estimations were made including 10 observers × 50 colours × 9 sessions × 3 estimations.

Observer variations in terms of repeatability and accuracy were examined. The former was compared between each observer's repeated judgements. The accuracy was compared between each individual observer and mean visual results. The measure of Coefficient of Variation (CV) given in equation (1) was used to indicate the disagreement between two sets of data. It is a measure of the distance of the points from the 45° line. The more the points are scattered about the line, the poorer the agreement. Therefore a perfect agreement, CV should be zero and larger the value, the poorer the agreement.

$$CV = 100\frac{\sqrt{\sum(x_i - k \times y_i)^2 / n}}{\bar{y}} \qquad (1)$$

where x_i ; x data set
y_i ; y data set
n ; Number of samples
K; a scaling factor
$\bar{y}$; Average of second estimated values

In the present analysis, the scaling factor (k) was set to one. The repeatability performance in the experiment is 16, 22 and 7 CV units for the lightness, colourfulness and hue, respectively. These were 19, 29 and 9 CV units, respectively for the accuracy performance. These are larger than the 11, 16 and 7 in Luo et al's study [2] due to the property of the viewing conditions involved, i.e. small screen and large variation of surround conditions.

Comparison of different backgrounds and surround

The visual results for nine phases were compared to each other. The results are summarised below:-

- Hue appearance hardly changes when comparing phases with different backgrounds, or with different surrounds.
- A colour always appears lighter against a black background than a grey or a white background.
- Hardly any colourfulness difference between different backgrounds.
- A colour appears slightly lighter under the average surround than under the dim and dark surround.
- The colourfulness of a colour increases when it is displayed under average surround than under a dim or a dark surround.

Note that the surround luminance is very high in the current study (over 1000 cd/m^2).

Development of Mobile CAMs

The CIECAM02 model is the colour appearance model recommended by CIE. It includes four parts: a cone response transform, a chromatic adaptation transform, a dynamic response function and colour spaces formed by different combinations of colour appearance attributes. The initial step is to convert the colorimetric values (x, y, Y) to cone responses (R G B) via a matrix transform. This is then followed by transforming them to the corresponding responses ($R_C\ G_C\ B_C$) via the CAT02 chromatic adaptation transform, which transforms the corresponding colour from a test to the reference equal energy illuminant. The $R_C\ G_C\ B_C$ signals are then transformed to the brightness adapted cone responses ($R_a'\ G_a'\ B_a'$) via the dynamic response function in the form of a hyperbolic equation to take into account the extent of changes of responses due to a particular luminance level. The signals are further used to calculate colour difference signals: a (redness-greenness) and b (yellowness-blueness), and A and A_W , achromatic signals for sample and reference white respectively. Finally, several correlates that describe the colour appearance are calculated: lightness (J), brightness (Q), saturation (s), chroma (C), colourfulness (M), hue angle (h) and hue composition (H).

Table 3 shows the input parameters for CIECAM02 according to the surround conditions used.

Table 3: Parameters of CIECAM02 regarding different surrounds

Viewing Condition	*c*	*F*	N_c
Average Surround	0,69	1,0	1,0
Dim Surround	0,59	0,9	0,9
Dark Surround	0,525	0,8	0,8

The visual results were used to test CIECAM02. It was found that its performance is somewhat dissatisfactory, i.e. the results in terms of CV (equation (1)) in predicting current results are worse than those in predicting LUTCHI data [2]. Hence, various trials were made to improve the model's performance for predicting visual data from the mobile display viewing conditions. Finally, two versions were obtained, which are named: MobileCAMv-1 and MobileCAMv-2. The general principle of the modification is to change CIECAM02 model as little as possible. These are described below.

MobileCAM-v1

For MobileCAMv-1, the modification was made only for the surround input parameters under various viewing conditions c , F and N_c (see Table 4).

Table 4: Parameters of MobileCAM-v1 regarding different surrounds

	c	*F*	N_c
Average	0.9325	1.0000	1.0000
Dim	0.8930	0.9999	0.9999
Dark	0.8825	0.9242	0.9998

Comparing between the coefficients between Tables 3 and 4, it can be seen that the differences between three surround conditions are much smaller under mobile display viewing conditions.

Another modification was made for calculating the chromatic adaptation factor (N_{cb}), i.e. $0.725(1/n)^{0.1425}$ where n = Y_b/Y_W (Y_b and Y_W are the luminance factors for the background and for the reference white, respectively). This change is necessary in order to improve its performance for predicting black background conditions. The current CIECAM02 model can not accurately predict the colourfulness for darker background.

MobileCAM-v2

The main structure of the CIECAM02 model was kept for MobileCAM-v2 as in the previous version, i.e. the equations are the same except those coefficients in the model. The coefficients for the viewing conditions c , F , and N_c which is described in Table 3 were changed once again.

Table 5: Parameters of MobileCAM-v2 regarding different surrounds

	C	F	Nc
Average	0.4332	1.0000	0.6159
Dim	0.4331	0.9999	0.6158
Dark	0.4330	0.9998	0.6157

The following modifications were made:

$$N_{cb} = 0.7249(1/n)^{0.001}$$
$$z = 3.0101 + n^{0.1883}$$
$$C = t^{0.8149}(J/100)^{0.6646}(1.64 - 0.29^n)^{0.0001}$$
$$M = C(F_L)^{0.0517}$$

Comparison of Model Performance

Lightness comparison

The lightness visual results were used to test CIECAM02, MobileCAM-v1 and MobileCAM-v2. The results are given in Table 6 in terms of the CV values, where CV was calculated using equation (1) with *k*=1. Because both Models' predictions and visual results run from 0 (black) to 100 (white), the scaling factor is not needed. The performance for each model is summarised in Table 6.

Table 6: Performance between different colour appearance models in terms of CV measure

	Dark-grey	Dark-black	Dark-white
CIECAM02	41	36	35
MobileCAM-v1	28	20	28
MobileCAM-v2	30	19	28

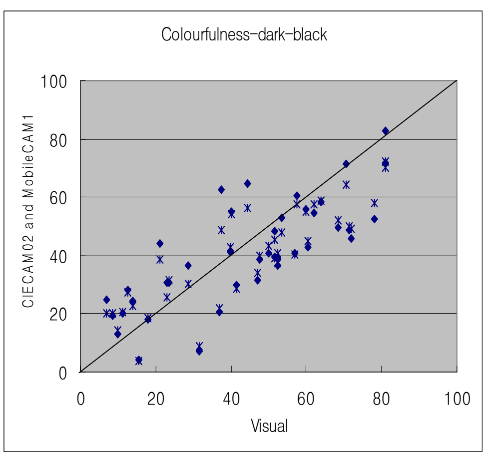
	Dim-grey	Dim-black	Dim-white
CIECAM02	34	35	36
MobileCAM-v1	26	21	27
MobileCAM-v2	27	19	30

	Average-grey	Average-black	Average-white
CIECAM02	21	14	25
MobileCAM-v1	29	18	37
MobileCAM-v2	24	18	26

The results in Table 6 showed that for dark and dim surround phases, MobileCAM-v2 performed the best, followed by MobileCAM-v1, and CIECAM02 the worst. On the other hand, CIECAM02 performed the best for the average surround phases with a similar performance between the two mobile models. The current prediction errors for each model are worse than the typical observer accuracy (each individual observer's against the mean results), i.e. 19 CV units.

Colourfulness comparison

The colourfulness results predicted by the CIECAM02, MobileCAM-v1, and MobileCAM-v2 were plotted against the visual results. Figures 3 to 5 show the visual colourfulness results plotted against the models' predictions for the phases having black background under a dark, a dim, and an average surround, respectively. It can be seen that there is a significant improvement by the MobileCAM model for the black background results for all surrounds. Each figure includes two diagrams; two models' predictions were plotted. CIECAM02 and MobileCAMv-1 plotted on the top diagram, and CIECAM02 and MobileCAMv-2 plotted on the bottom diagram.



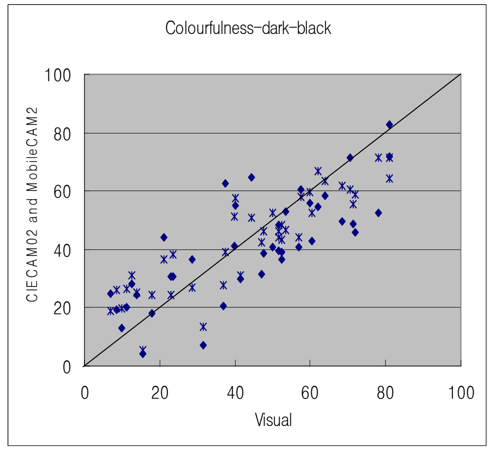


***Figure 3**. Colourfulness visual results against predicted values of CIECAM02 (filled diamond) and MobileCAM-v1 (top), CIECAM02 (filled diamond) and MobileCAM-v2 (bellow) under dark surround against a black background.*

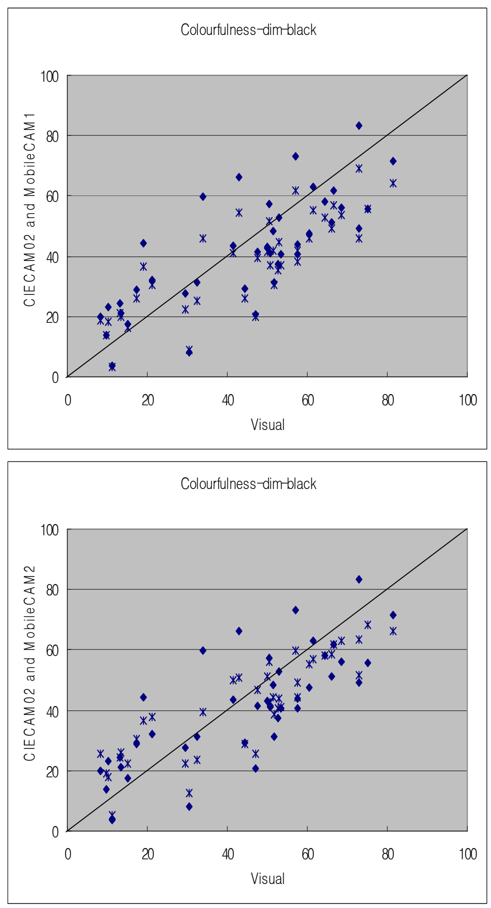


***Figure 4**. Colourfulness visual results against (Top) predicted values of CIECAM02 (diamond) and MobileCAM-v1 (cross), (Bottom) CIECAM02 (diamond) and MobileCAM-v2 (cross) under dim surround against a black background.*

Figures 4 and 5 show the improvement using the MobileCAM, i.e. the crosses are closer to the 45° line than those diamonds. The models' performances are also summarised in Table 9 in terms of CV values, which were calculated using equation (1) where the scaling factor k was obtained by the least square fitting between the visual data and the predicted data. Subsequently, the scaling factors for each phase were averaged. Only one single scaling factor was applied to all experimental phases.

Table 7 shows that all of the CV values for the two MobileCAMs are smaller compared with those for the CIECAM02 model, especially the CV values for the black background have improved dramatically.

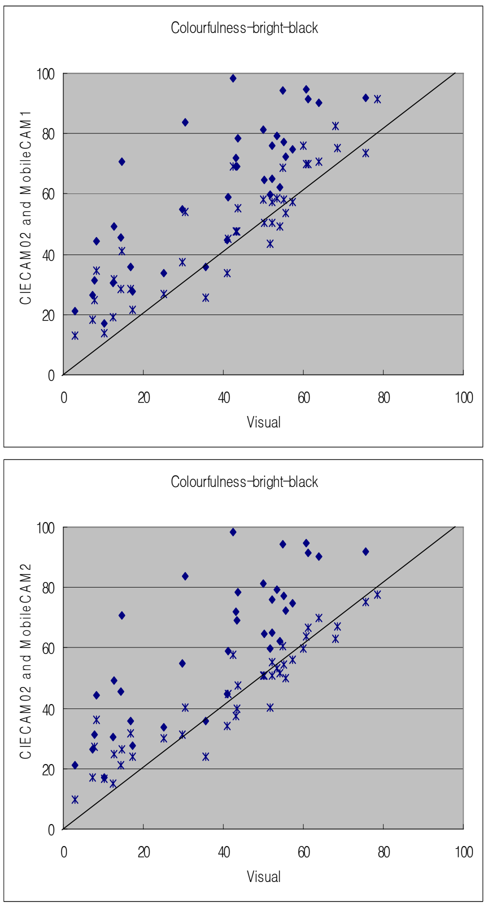


***Figure 5**. Colourfulness visual results against (Top) predicted values of CIECAM02 (diamond) and MobileCAM-v1 (cross), (Bottom) CIECAM02 (diamond) and MobileCAM-v2 (cross) under average surround against a black background.*

Table 7: CV values of colourfulness between visual and CIECAM02 and MobileCAM's predicted results

	Dark-grey	Dark-black	Dark-white
CIECAM02	33	32	28
MobileCAM-v1	22	27	18
MobileCAM-v2	19	23	18

	Dim-grey	Dim-black	Dim-white
CIECAM02	33	31	27
MobileCAM-v1	26	30	20
MobileCAM-v2	24	25	20

	Average-grey	Average - black	Average - white
CIECAM02	38	74	26
MobileCAM-v1	33	29	26
MobileCAM-v2	34	21	23

Hue Comparison

The hue CV values have not improved as the colourfulness has improved. The reason for this is that modification on CIECAM02 for MobileCAM's been mainly on the background and surrounds effect. Hue is not affected much by the background and surrounds parameters. All three of the mentioned colour appearance models predicted the hue well except in the green to blue region. This is also found by Kwak [4].

Conclusion

Nine psychophysical experimental phases were accomplished to collect visual data for the mobile display under none phases of viewing conditions including three background (grey, black, and white), and three surrounds (dark (0 cd/m^2), dim (5.5 cd/m^2) and average (1024 cd/m^2)). The results were used to investigate the observer variations in terms of repeatability and accuracy. The visual results from different phases were also compared to reveal the colour appearance effects. It was found that the observer variations are larger than those from the earlier study using other media viewing conditions. This means that there are more experimental errors under the mobile display viewing conditions.

Two new colour appearance models for mobile displays have been established by modifying CIECAM02. Two models are proposed: MobileCAM-v1 and MobileCAM-v2. The average CV values for the lightness and colourfulness are smaller using the two new mobile models than CIECAM02.

Comparing the two newly developed Mobile models, MobileCAM-v2 fitted the visual results slightly better than that of MobileCAM-v1. However, MobileCAM-v1 keeps the same equations as CIECAM02 except the input viewing parameters, i.e. it is a simple modification of CIECAM02. Therefore MobileCAM-v1 is recommended as the new mobile colour appearance model for mobile phones. The input viewing parameters (N_c , F , and c) in Table 4 visual results are not much different (smaller contents) between different surround conditions compared with the earlier data used to developed CIECAM02 model. The new N_c factor also shows a smaller different between the average and dark surround for mobile phone conditions. A new modified version of CIECAM02 for mobile displays named MobileCAMv-1 is obtained in this study.

References

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Author Biography

Yungkyung Park received her BS in physics from the Ewha Womans University, Korea (2001) and her Masters in colour science from Derby University, UK (2003). After then she has worked in the Ewha color design institute as a researcher. Present, she is a PhD student at Leeds University (UK) studying colour imaging science.