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Skin tone on mobile displays under different ambient lighting

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Abstract

This experiment was aimed to study the preference of mobile phone facial images captured under different simulated ambient lightings. The experiment was carried out by assessing the preference of images for two facial images under 11 lightings (5 correlated colour temperature levels at 2 illuminances plus a dark condition). Forty-five images were processed via CAT02 chromatic adaptation transform to simulate the pictures captured under different light environments. The results revealed that the preferred capture region was between 6500 and 8000K around -0.05 Duv. Furthermore, it was found that the preferred skin tones of all the 45 rendered had good agreement under all the ambient lightings of viewing, i.e. to have mean values of L^*, C_{ab}^*, h_{ab} *of [76.3 25.1, 46.4°] units under D65/10° conditions.*

Introduction

Facial profiles play an important role in colour images for mobile phone applications. Producing pleasing colour reproduction for facial skin tone is crucial for mobile phone products. Extensive studies have been carried out to find preferred skin centre for human visual perception. Bartleson studied the reproduction of preferred skin tone and found that there was a significant difference in chromaticity between the actual colour and the memory colour, and the preferred skin tone was more yellowish and chromatic than the real skin tone [1-3]. Sanders investigated the colour preferences of natural objects and found that the preferred human facial colour was more saturated than the actual facial colour [4]. Hunt et al.'s study on preferred colour reproduction in colour photography concluded that for reflective printing, the preferred Caucasian skin tone is slightly yellowish than true skin tone [5]. Sanger et al. studied the portraits photos of three ethnicities and found that the preferred skin tone increased steadily in the order of Caucasian, Mongolian, and Negroid. The hue angles are almost the same for the three ethnicity groups [6]. Yano and Hashimoto studied Japanese's preference on women complexion and found that Japanese preferred slightly higher chroma and more reddish complexion. The direction of hue shift was different from that of Caucasian women who preferred colourful skin tone [7]. Park et al. investigated the preference for skin tone reproduction on the display. The skin tone was moved to the preferred skin tone centre around a small colour area to enhance the preference [8]. Kuang et al. studied the effects of different factors on skin tone preference in photographic colour reproduction. They found that background brightness had little effect on skin tone preference; the difference in skin tone preference between Orientals and Caucasians was smaller than that of Indians and African Americans; the cultural differences between different ethnic observers were not significant [9]. Fernandez and Fairchild studied the cultural differences to find the preferred colour reproduction of images. Their experiments showed that the images that contain people typically change less than the images of no people. The preference was influenced by the image contents and different ethnic groups of observers, instead of cultural background [10]. Bodrogi found that the observer long-term memory skin tone tends to be more yellowish than the original colour [11]. The above studies were all conducted on display devices under a single light environment, and there were few studies using mobile displays under ambient environment on preferred skin tone. The goal of this study is to study the preferred capturing lighting conditions under different lightings ranged from 3000K to 6500K at two illuminance levels. All the experiments were carried out using mobile phones.

Experimental

Camera and display characterization model

Two human skin images were captured by a Nikon Z6 digital camera. The capturing was conducted under a CIE D65 simulator lighting condition at 1000 lux. A male and a female volunteer participated in the photo shoot against a white wall. The Macbeth Colour Checker Chart (MCCC) including 24 colours were also captured using the same camera setting at the same position under the same lighting condition. The 24 colours were then measured by a JETI-Specbos 1211 spectroradiometer (called TSR) under the same lighting condition. The TSR was used to measure all the lightings and colours in this study. The polynomial model proposed by Hong et al. [12] was used to build a mathematical model based on the measured tristimulus values and the camera's RGB values. The final model was used to predict MCCC colours, where the mean *CIELAB* colour difference was 2.13 ranged from 1.06 to 2.35. The performance is considered to be satisfactory.

The experimental images were displayed on five 6.1-inch Huawei P20 Pro OLED mobile displays. The screen had a native resolution of 2240 × 1080 and DCI-P3 gamut. The monitors had a mean luminance of 394 cd/m^2, and a white point of 7513K measured by the TSR. The auto-brightness-function of the smart phones was turned off throughout the experiment. There were 96 colours used to build the display model, including 24 MCCC colours and the other 72 colours (18 × 4, along the r, g, b channels and their corresponding neutral colours of 18 colours from 0 to 255 at an interval of 15). The 96 colour patches were placed against a grey background in a dark room with a measuring distance of 40 cm. The Gain-Offset-Gamma(GOG) models [13] were built for each phone, in accordance with the 96 colour patches of rgb data and the corresponding measured tristimulus values. The display models were also verified by the measured 24 MCCC colour targets. The mean *CIELAB* colour difference of the phone between the predicted and measured results was 1.78. Further investigation was conducted to compare the inter-display agreement, the mean colour differences between each smart phone and the others four smart phones was about 1.9. This meant that the predictive accuracy from the GOG model was almost the same as the inter-display discrepancy between different displays, indicating the good agreement between the 5 mobile phones used. Figure 1 illustrates the experimental images shown on two displays.

Figure 1 Experimental software

Image rendering

The captured original images were processed and adjusted from the original colours into a set of 45 testing stimuli to simulate the shooting environment of 45 different light sources. Firstly, in order to reduce the effect of uneven white wall on skin tone perception in the pictures, image processing software was used to cut out the white wall of the two pictures and replaced them with a uniform grey. The uniform grey background had a CIELAB L^*, a^*, b^* values of [50, 0, 0] under D65/10^o condition. The luminance of the grey background was 35 cd/m^2. Secondly, in order to simulate the captured environment, the original image including face and grey background was transformed pixel by pixel via *CAT02* chromatic adaptation transform [14] into 45 different white points, including 9 CCTs levels (3000K, 3500K, 4000K, 4500K, 5000K, 6000K, 7000K, 8000K, 10000K) and 5 Duv levels (-0.01, -0.005, 0, 0.005, 0.01). Although *CAT02* transform can be quite accurately for colour transform for the surface colours, it also has somewhat large predictive errors as found by Zhai and Luo [15] for the display colours, i.e. it performs inaccurately for viewing display colours under the ambient lighting having low CCTs. They proposed a new incomplete adaptation function (D) in *CAT02* as given in Equation (1).

$$D = 0.723 \bullet \left(1 - \frac{1116}{CCT} + 8.64 \bullet Duv - \frac{49266 \bullet Duv}{CCT}\right)$$

$$CCT > 2000\text{K},\ Duv \in [-0.03, 0.03] \qquad (1)$$

For improving the accuracy of *CAT02*, the D factors are also calculated according to Zhai and Luo's Model. Figure 2 shows the average skin stimuli (open circles) varying at 9 CCTs and 5 Duv levels. The coloured filled circles in the blackbody locus were the chromaticity of the lightings at 5 CCT levels. In total, there were 90 testing stimuli, i.e. 2 original images × 45 transformations.

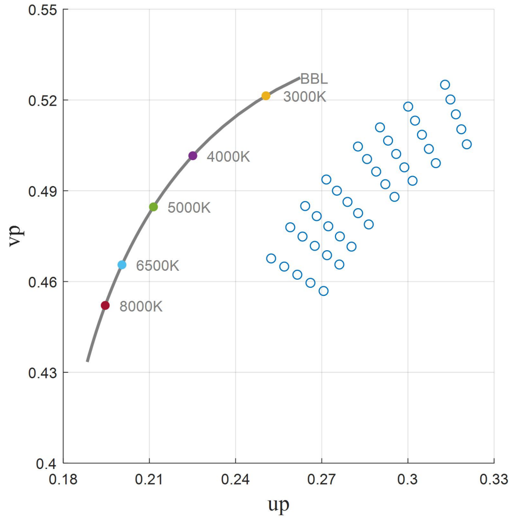


Figure 2 The transformed skin tone plotted in CIE 1976 u' v' diagram together with the lightings used in blackbody locus.

Lighting Conditions

The lighting system used was a spectrum tunable LED illumination system, LEDCube supplied by the Thouslite®. It includes twelve identical light units which are evenly arranged on the ceiling, and semi-transparent frosted diffuser plates are installed to ensure uniform light emission. Eleven ambient illuminations were used in the experiment, including one dark condition and two illuminance levels (500 lx and 1,000 lx) at the blackbody locus but varied at CCT of 3000, 4000, 5000, 6500, 8000K, respectively. Table 1 lists the measured illuminance, chromaticity coordinates, *CCT*, *Duv* and *CRI* (colour rendering index) R_a of the ambient lighting conditions. The luminance of the display under different ambient lighting conditions against a reference white was measured using the TSR at the position where the smart phone was placed during the experiment. As it can be seen, the colour quality of lightings are high, i.e. accurate *CCT*, illuminance, and high R_a values. The observers seated in the centre of the room and read instruction to observe the smart phone at a viewing distance of about 30 cm.

Table 1: Measured parameters of 11 ambient lightings

No.	[cd/m²]	[lx]	u'	v'	CCT[K]	Duv	R_a
1	308	1055	0.2482	0.5199	3070	-0.00010	91.6
2	302	1035	0.2254	0.5018	3985	-0.00004	97.7
3	315	1079	0.2108	0.4836	5069	-0.00006	96.5
4	316	1083	0.2012	0.4661	6410	-0.00042	97.5
5	312	1069	0.1944	0.4513	8109	-0.00006	97.4
6	157	538	0.2497	0.5216	3022	0.00043	96.1
7	158	541	0.2237	0.5019	4046	0.00093	95.8
8	157	538	0.2119	0.4861	4932	0.00033	92.5
9	157	538	0.2031	0.4694	6505	-0.00062	93.4
10	154	528	0.1940	0.4521	8061	0.00054	97.0
11	0	0	-----	-----	-----	-----	-----

Observers and procedure

Twenty-four observers participated in the experiment. They were all university students. There were 15 Female and 9 Male observers with a mean age of 19.3 ranged from 18 to 23 years old. All observers passed the Ishihara colour vision test and had normal colour vision. Twenty-four observers were divided into 7 groups of varying numbers, with each group consisting of 3 to 5 observers. They were asked to sit around a table covered with a grey table cloth and each hold a smart phone to do the experiment at one time. Observers evaluated 90 facial image stimuli under 11 ambient lighting conditions. They were asked to keep a fixed observation distance of 40 cm throughout the experiment. Prior to the experiment, observers adapted in the room for 5 minutes under the lighting No.9 (see Table 1). They then used the forced choice method to judge whether they liked or disliked the displayed facial skin tone or not. In total, 27,000 judgments were obtained in the experiment, i.e. 2 images×45 rendered stimuli ×(11 ambient illuminates + 1 repeat) × 25 observers. Each observer had evaluated 90 stimuli under light No. 9 (showed in Table 1) twice as a repeat group.

The order of stimuli and ambient lightings for each group of observers were randomized. When the ambient illuminant changed to a new one, the observers were asked to scan the room for 1 minutes for adaptation purpose. Note that due to the bright illumination, 1 minute should be sufficient to achieve the full chromatic adaptation. The same procedure was repeated for all the 90 stimuli under each ambient lighting condition. The whole experiment lasted for around 50 minutes for each observer.

Results and discussion

The data were presented by the number of the preferred decisions, which is calculated by the number of the liked decisions from all of observers, and the preferred rate *P%*, which was calculated by the number of the liked decisions divided by the total number of observers multiplying by 100.

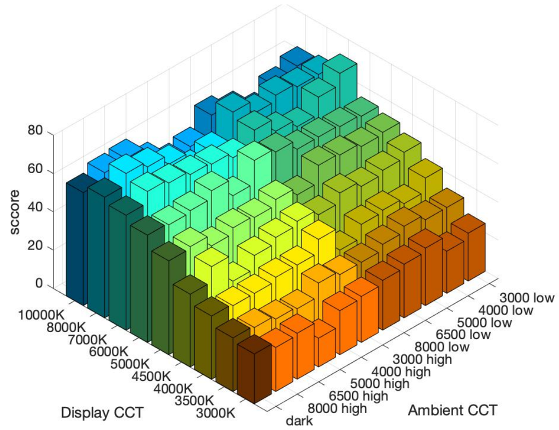
Inter- and Intra-observer variations

Based on the preference rate from all observers, inter-observer variation was first analyzed. For a *P%* of an image is greater than 50, it is counted as 'liked', otherwise it was counted as 'disliked'. For investigating inter-observer variation, if the answer from an individual observer agreed with the panel decision, it was counted as a 'right decision'. By adding these number together, it represented the 'right decision' for each individual observer. The average of them from all stimuli represented the inter-observer variation. In this study, the inter-observer variation was 66% ranged from 51% to 80%. The observer consistency is about 66%.

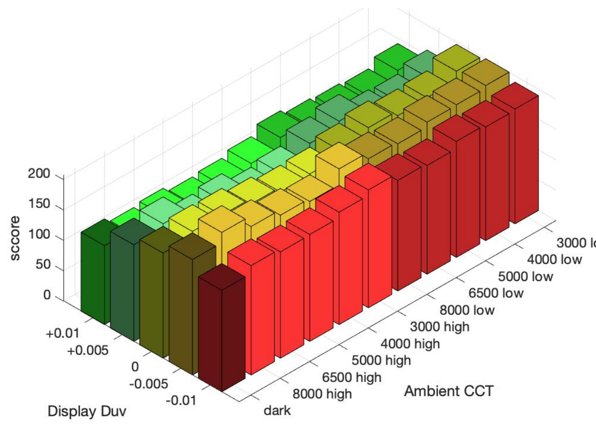
Ninety stimuli were repeatedly judged (No. 9 lighting). For evaluating intra-observer agreement, the 'right decision' measure was again used. If each individual's two repeated decisions agreed with each other, it counted a right decision. The average across all stimuli/illumination conditions was defined as intra-observer variation. It had a value of 60% ranged from 53% to 77%. The results indicated that very similar performance between the inter- and intra- observer variations.

Preferred skin tones

The preferred skin tone under each ambient lighting was carried out. As shown in Figure 3, 3D histograms were produced to reveal the most preferred colour region. Figure 3 plots the preferred score (the number of the preferred decision) against the CCT of ambient lightings, and CCT and Duv values of ambient lighting and of display white, respectively. Three clear trends can be found. Firstly, the preferred display CCTs were ranged between 6500 and 8000K. This implied that the observers preferred skin tones to be always illuminated by a higher CCTs. Secondly, the preferred display images were located under a lighting to have slight negative Duv (about -0.005 (purplish)). Finally, the display images observed under higher level illumination was less preferred than those viewed under lower illumination.



(a)



(b)

Figure 3 Preferred decision plotted against the Ambient CCT and a) the Display CCT and b) the Display Duv.

Preferred facial skin tone and tolerance ellipses

Each observer's 'liked' images under an ambient lighting were recorded. *P%* for each image were used to fit the tolerance ellipses for the male and female images under each ambient lighting. Equation (2) shows a logistic function to transform between the model predicted probability (Pp) and DE' calculated from an ellipse equation in *CIELAB* a^*b^* diagram. The ellipse equation defined the boundary corresponding to Pp equals to 50%, i.e. half of the observers like the stimulus and the other half disliked it. An optimisation process was established to obtain the 6 coefficients in equation (2), i.e. k_1, k_2, k_3, a_0, b_0 and α by maximizing the correlation coefficient between the *Pp* and *Pv*, which is the preference percentage from the visual results. Note that α is the colour difference calculated from the ellipse equation corresponding to 50% ellipse boundary.

$$\mathrm{Pp} = \frac{1}{1+e^{(\Delta E' - \alpha)}} \qquad (2)$$

where
$\Delta E' = k_1\sqrt{(a^* - a_0)^2 + k_2(b^* - b_0)^2 + k_3(a^* - a_0)(b^* - b_0)}$.

The results were presented on *CIELAB* colour space. *CIELAB* is a common space that various research results on skin tones are specified. However, CIELAB has a shortcoming on its poor performance in chromatic adaptation [18]. So, it was decided to adopt a more robust chromatic adaptation transform, *CAT02*, to convert the data under different illuminations condition (3000, 4000, 5000 and 8000K) to 6500K, and to define the colour centre and the limit defined by colour discrimination ellipses. This will allow the results from different ambient lightings to be directly compared. The 6500K ambient lighting condition was selected as neutral white for investigating the degree of chromatic adaptation under other lighting conditions as the Smet *et al.*'s neutrality for object illumination [17]. Also, it was in the ranged of the current preferred display CCT range. For *CAT02*, equation (1) was used to estimate the degree of incomplete chromatic adaptation (*D*) under each ambient lighting condition.

Figure 4 shows the preferred colour centres and their tolerance ellipses under different lightings. It can be seen that all the preferred skin tone centres and ellipses had very good agreement. The difference between the male and female images was only 1° in hue angle. The average L^*, C_{ab}^*, h_{ab} under all 10 illuminations were [76.3 25.1, 46.4°] for the mean of two images. The average ellipse parameters including semi-major, semi-minor axes and were [19.3, 7.6, 71.2°] for two images, respectively. The chroma of the preferred skin tones will slightly increase as the ambient lighting CCT decrease.

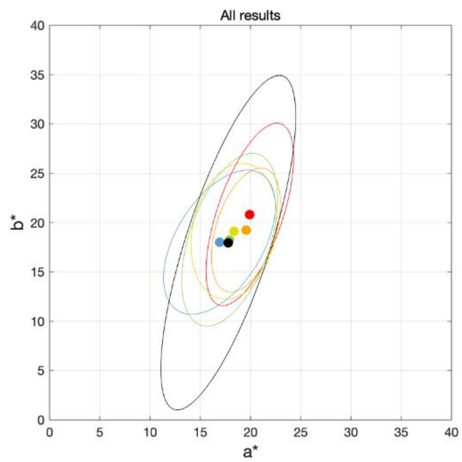


*Figure 4. Plot of tolerance ellipses transformed from their original lighting condition in a*b* diagram under the D65/10° condition, where red, orange, yellow, green, blue and black ellipses represent 3000K, 4000K, 5000K, 6500K, 8000K and dark lighting condition respectively. The ellipse sizes are reduced to half of their original sizes.*

Conclusion

This experiment was aimed to study the preference of mobile phone facial images captured under different simulated ambient lightings. The experiment was carried out by assessing the preference of images for two facial images under 11 ambient lightings by 24 observers. Forty-five images were simulated via CAT02 transform to simulate the pictures captured under 45 light environments. The results revealed that the preferred capture region was between 6500 and 8000K around -0.05 Duv. Furthermore, it was found that the preferred skin tones for all the 45 lightings rendered had good agreement under all the ambient lightings of viewing, i.e. having mean L^*, C_{ab}^*, h_{ab} *values of [76.3 25.1, 46.4°] under D65/10° conditions, and the chroma of the preferred skin tones will slightly increase as the ambient lighting CCT decrease.*

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