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Preferred skin tones reproduction of three ethnic groups under different ambient lighting conditions

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Abstract

A large-scale experiment was conducted to investigate facial image quality on mobile phones. There were 8 original facial images from 4 skin tone types, each included a male and a female image. Each image was captured at 6500K and they were rendered to have 5 CCT (correlated colour temperature) and 5 Duv (the shifts away from the Blackbody locus) levels via CAT02 chromatic adaptation transform to simulate the effect of the images captured under 25 different lighting conditions. Each image was assessed under 9 ambient lighting conditions (including one dark condition) by 90 observers from 3 ethnic groups (Caucasian, Chinese and South Asian), each 30 observers. Preferred facial skin tone ellipse was established by maximizing the correlation coefficient between the model predicted probability and the preference percentage from the visual results. Four types of preferred skin tones had small differences in hue angle and chroma, but concentrated into a small colour region, about [24.7, 46.1°] for C_{ab}^* and h_{ab} values respectively. All ethnic group preferred images taken under illuminants having high CCT (6500-8000 K). It was also found that the chroma of the preferred skin tones will slightly increase as the ambient lighting CCT decrease.

Introduction

Many scholars support the view that there is a preferred skin tone centre for human visual perception. In preferred colour reproduction, moving skin tones toward the preferred centre can improve the colour preference. Finding the preferred skin tone centre is very important to preferred skin tone reproduction. In nowadays, the main objects in colour images are usually people, especially facial patterns. Reproducing them with high image quality is crucial in photographic colour reproduction. Since people usually rely on their preference for skin tone to judge the colour reproduction quality of facial objects, it is important to know the preferred skin tone for preference colour reproduction.

Bartleson [1] found that the chroma of the actual colour and the memory colour was significantly different, and the preferred skin tone was more yellowish and saturated than the real skin tone. Bartleson and Bray [2] further studied the preferred colour reproduction of memory colours including skin tone, and found that the preferred skin tone of Caucasian skin had the same chroma as the mean memory colour of the flesh tone. Sanders [3] studied the colour preferences of natural objects and found that the preferred Caucasian face colour was more saturated. Sanger *et al.* [4] further used photos of Mongolian, Caucasian and African people to study their preferred skin tones, and found that the chroma of their preferred skin tones increased steadily in the order of Caucasians, Mongolians and Africans. The preferred hues among the three groups were about the same, and the dominant wavelength is about 590 nm. Hunt *et al.* [5] studied the preferred colour reproduction in colour photography, and concluded that for reflection prints the preferred Caucasian skin tone had about the same purity as the real skin tone but was a little yellower. Yano and Hashimoto [6] studied the skin tone preference of Japanese people and found that Japanese women preferred reddish skin tone and slightly higher chroma. The direction of hue shift was different from that of the Caucasian women; and the preferred skin tone of Caucasian women was more colourful than that of Japanese women. Park *et al.* [7] used a binary Gaussian function to fit the skin tone. The centre of the skin tone boundary was used as the preferred skin tone centre. To enhance preference, the skin tone was moved into a smaller colour area around the centre of the preferred skin tone. Kuang *et al.* [8] studied the influence of different factors on skin tone preference for photographic colour reproduction. They found that background lightness had little influence on skin tone preference; the preference variances on East Asian and Caucasian skin tones were smaller than those on Indian and African American; and no significant culture difference among different ethnic observers. Their found that capturing illuminants had significant influence on skin tone preference. Bodrogi and Tarczali [9] used photo-realistic images and independent colour patches obtained from corresponding skin tones. Memory colour shift in photo-realistic images was found larger than that in colour patches, memory skin tones tended to be yellower than original colours. Fernandes and Fairchild [10] studied observers and cultural variability. Their experiments proved that although the preference variability due to the observer's cultural background was statistically significant, it was not visually significant. Preference variability caused by image content and variability among observers was more significant than cultural background variability. Zeng and Luo [11] found that East Asians consistently prefer slight less chromatic skin tones than Caucasians and Africans, and Africans prefer more chromatic Caucasian and East Asian skin tones than Caucasians and East Asians.

It can be concluded from different studies that the preferred skin tone was different from the actual skin tone. However, the preferred skin tone centres from various studies were different because they used different experimental methods, such as: stimulus type, display equipment, experimental lighting, image ethnic and observer ethnic. However, most of them conducted their experiments on outdated display devices in the dark or under a single light condition. In order to have a deep investigation of skin tone preference for reliable skin tone enhancement on mobile display images, psychophysical experiments were conducted to verify preferred skin tones, to determine preferred skin tone regions, and to study the influence of surrounding light environment and subjects' cultural background.

The goals of this study are to study the preference of images taken from different ambient lighting conditions and to find the culture difference among different ethnic groups.

Experiment

Image capturing

Eight skin images representing 4 different skin tone types, each with 2 genders, were prepared, as the images in Figure 1. Each image was captured by a Nikon Z6 digital camera. The capturing was conducted under a CIE D65 simulator lighting condition at 1000 lx. Four males and four females were invited to take the photo shoots. They represented different skin tone types: Caucasian, East Asian, South Asian and African. All models stood in front of a gray fabric background and wore a black jacket to avoid the influence on the judgment of skin tone. An XRite Macbeth ColourChecker Chart (MCCC) including 24 colours was also captured under the same camera setting at the same position under the same lighting condition. Each colour was measured by a JETI-Specbos 1211 spectroradiometer (called TSR) under the same lighting condition. The instrument was used to do colour measurement in the whole experiment.

***Figure 1**. Captured images of 4 skin tone types.*

Display model

Images were displayed respectively on five 6.1-inch Huawei P20 Pro organic lighting-emitting diode screens. The screen had a native resolution of 2240 × 1080 and large colour gamut. All monitors were adjusted to achieve a peak luminance of 400 cd/m^2 and a white point at 7500K in CCT using the TSR. The auto brightness function of the smart phones was turned off. The 3D LUT method was used to characterize each display, including 729 colours (9 × 9 × 9) to build the 3D-Look-Up-Table (3D-LUT) display model [12]. The five mobile phones were measured 0 degrees perpendicular to the display plane at the distance of 30 cm in the dark condition. The mean colour differences of each smart phone between the predicted and measured results were 1.51, 1.76, 1.37, 1.24 and 1.79, respectively. The mean colour difference between before and after working continuously for an hour of the 5 mobile phones was 0.28. The measurement of the same 24 colour patches was repeated at 24 hour intervals, the average colour difference was 0.36. This means these five displays have good device self-stability. Further investigation was conducted to compare the inter-display agreement, the mean colour difference between each smart phone and the others four smart phones was about 1.9. This means that the predictive accuracy from the 3D-LUT model was almost the same as the inter-display discrepancy between different displays, indicating the good agreement between the 5 mobile phones used.

Image rendering

The captured original images were processed and adjusted from the original colours into a set of 25 testing stimuli. In order to make the entire image have a uniform colour shift, the image was transformed pixel by pixel via *CAT02* chromatic adaptation transform [13] in XYZ value. The whole image white was transformed from D65 into 25 different white points, specified by 5 CCTs levels (4000K, 5000K, 6500K, 8000K, 10000K) and 5 Duv levels (-0.01, -0.005, 0, 0.005, 0.01). *CAT02* had large predictive errors as found by Zhai and Luo [14], it performed inaccurately for viewing display colours under the ambient lighting, especially having low CCTs. This equation can greatly improve by modifying its incomplete adaptation factor (*D*) as given in Equation (1). Figure 2 shows the 25 rendered average skin tones (open circles) of eight original images. It was designed to simulate the images captured under the typical ambient lighting conditions. The coloured filled circles in the blackbody locus were the chromaticity of the lightings at 4 CCT levels. In total, there were 200 testing stimuli, i.e. 8 original images × 25 transformations.

$$D = 0.723 \bullet \left(1 - \frac{1116}{CCT} + 8.64 \bullet Duv - \frac{49266 \bullet Duv}{CCT}\right)$$
$$CCT > 2000K, Duv \in [-0.03, 0.03] \qquad (1)$$

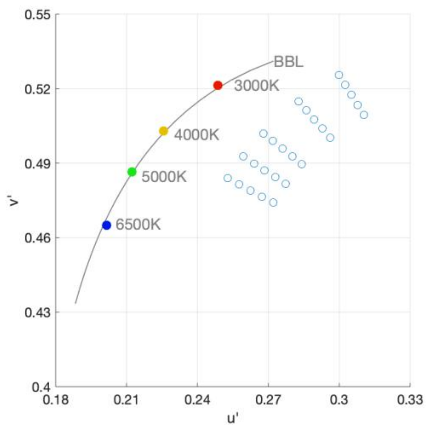

***Figure 2**. The 25 skin tones and 4 lightings plotted in CIE 1976 u' v' diagram. Four coloured dots show the chromaticity coordinates of the lightings used in this experiment.*

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. Nine 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 3000K, 4000K, 5000K, 6500K, respectively. Table 1 lists the measured illuminance, chromaticity coordinates, CCT, Duv and CRI (colour rendering index) Ra [15] 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 was high, i.e. accurate CCT, illuminance, and high Ra values. Figure 3 shows the spectral power distribution of the 8 lightings. The observers seated around a table and received instruction and did the experiment as shown in Figure 4. The viewing distance between the eyes and mobile phone display was about 40 cm, and the field of view was 17°.

Table 1. Chromaticity characteristics of 9 lighting conditions

No.	Luminance [cd/m²]	u'	v'	CCT [K]	Duv	R_a
1	308	0.2482	0.5199	3070	-0.0001	92
2	302	0.2254	0.5018	3985	0.0000	98
3	315	0.2108	0.4836	5069	-0.0001	97
4	316	0.2012	0.4661	6410	-0.0004	98
5	157	0.2497	0.5216	3022	0.0004	96
6	158	0.2237	0.5019	4046	0.0009	96
7	157	0.2119	0.4861	4932	0.0003	93
8	157	0.2031	0.4694	6505	-0.0006	93

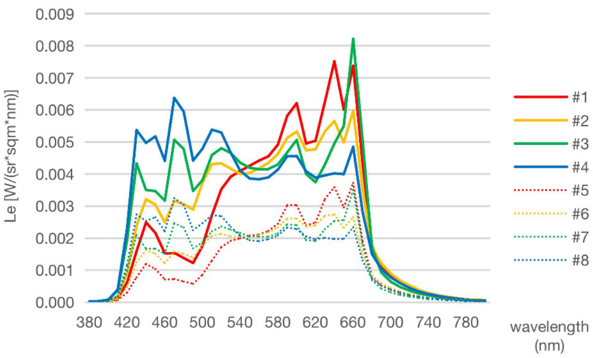

Figure 3. *Spectral power distribution for 8 light conditions.*

Observers and procedure

The psychophysical experiment was designed to study the preference of 4 skin tone types (Caucasian, East Asian, South Asian and African) judged by a pool of observers having 3 ethnic groups (Caucasian, East Asian, and South Asian). Ninety observers participated in the experiment. Each ethnic group had 30 observers, coming from Europe including 14 countries, Chinese and Pakistanis respectively. They were all students of Zhejiang University. There were 43 female and 47 male observers with a mean age of 26 ranged from 18 to 40 years old. All observers passed the Ishihara colour vision test and had normal colour vision.

Figure 4. *Experimental situation.*

Figure 4 shows the experimental environment. They were asked to sit around a table covered by a grey cloth and sit in front of a smart phone to do the experiment simultaneously. Observers were required to evaluate 200 random colour stimuli under each of the nine ambient lighting conditions in terms of preferred skin tone. The evaluation had a forced choice method to judge whether they preferred the human facial skin tone or not (either 'like' or 'dislike'). In total, 180,000 judgments were obtained in the experiment: 8 (images) × 25 (display stimuli) × 10 (9 ambient illuminants + 1 repeat) ×90 (observers). The order of stimuli and ambient illuminants for each groups of observers was randomized to eliminate any sequential effect. When the ambient illuminant changed, the observers were asked to adapt in the room for 1 minutes. The whole experiment lasted for approximately 90 minutes for each observer.

Results and discussion

The results were in the form of 'like' and 'dislike'. They were arranged in the form of preferred rate *P%*, which was calculated by the number of the liked decisions divided by the total number of observers multiplying by 100.

Observer variations

The standardized residual sum of squares (STRESS) given in Equation (2) has been introduced [16] as a measurement between two sets of data such as the investigations of the intra-observer and inter-observer variations and testing the performance of the colour-difference formula.

$$STRESS = 100\sqrt{\frac{\sum(\Delta P_1 - f\Delta P_2)^2}{\sum \Delta P_1^2}} \quad (2)$$

where $f = \sum \Delta P_2 \Delta P_1 / \sum \Delta P_2^2$

When the intra-observer variations were calculated, the P_1 and P_2 were all observers averaged and individual observer P% of each image, respectively. When the inter-observer variations were calculated, the P_1 and P_2 were the *P%* obtained from two sets of repeated judgments under the same lighting condition. For a perfect agreement between two data sets, STRESS will be zero. A higher STRESS value indicates a larger dispersion, i.e., a lower correlation between the two variables. A higher STRESS value indicates a poorer agreement between the two variables.

Each observer had evaluated 200 stimuli under light No. 4 (showed in Table 1) twice as a repeat group. The intra-observer variations STRESS of each observer ranged from 10 to 20 at the mean of 15. This indicated that the experimental results of most of the subjects were quite consistent. The STRESS values of African skin tone type were little higher than those of other skin types for East Asian and South Asian observers. This indicated a slightly lower observer accuracy when they judged African skin tone. But for Caucasian observers, they had a lower judgment accuracy on East Asian skin tones. Each ethnic group of observers judged their own ethnic image more accurately as they had less intra-variation STRESS values.

Table 2. Observer variations in *STRESS*

Intra	*Caucasian*	*East Asian*	*South Asian*	*African*	*mean*
Caucasian obs.	16	18	17	17	17
East Asian obs.	12	12	12	17	13
South Asian obs.	14	15	14	15	15
mean	14	15	14	16	15
Inter	***Caucasian***	***East Asian***	***South Asian***	***African***	***mean***
Caucasian obs.	32	33	31	25	30
East Asian obs.	28	29	27	41	31
South Asian obs.	28	29	26	27	27
mean	29	30	28	31	30

The inter-observer variations were calculated from the evaluation scores of each observer and the mean results of all observers. The inter-observer variations of each observer ranged from 16.43 to 47.24 at the mean of 29.62. This indicated the observers had a larger variation and the results were influenced by their own personal preference and characteristics. Caucasians showed a high degree of consistency in judging the skin tone of Africans, while the consistency of East Asians observers was significantly decrease when they judged the skin tone of Africans. Observers did not show a higher degree of consistency on judgments of their own skin tone types. Table 2 lists intra- and inter-observer variations in STRESS.

Preferred rendered images

The data were presented by the number of the preferred decisions, which were calculated by the number of the liked decisions from all observers. Figure 5 plots the 'like decision' scores of all images obtained from all judgments together with their error bars (2 standard deviations). The top score for each image is 1,350, i.e. 30 (observers) × 9 (ambient lightings) × 5 (display CCTs or display Duvs). A higher score indicates a more 'prefer' lighting.

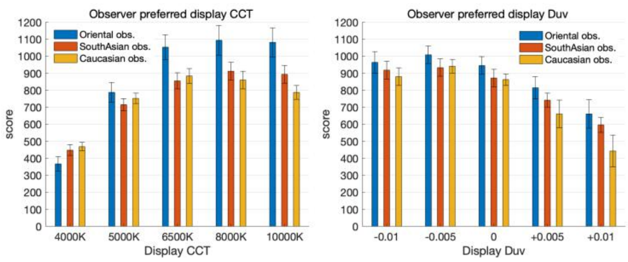

***Figure 5.** Preferred decision histogram for all image.*

It can be clearly seen from Figure 4 that the images captured between 6500K and 10,000K lightings were more preferred by observers from all ethnic groups. Chinese observers had a higher score than those from the other 2 ethnic groups. As for Duv, the trend was also obvious, i.e. all ethnic groups preferred skin tones to appear slightly purplish (-Duv direction) than greenish (+ Duv).

Preferred facial skin tone ellipse

From the earlier studies, the preferred skin tones were described as ellipses in *CIELAB* colour space. The ellipse model was derived in a matrix form and a polynomial form. Each observer's 'liked' images under an ambient lighting were recorded. *P%* for each image were used to fit the tolerance ellipses under each ambient lighting. Equation (3) 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 (3), 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.

$$Pp = \frac{1}{1+e^{(\Delta E' - \alpha)}} \quad (3)$$

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 6 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 average C_{ab}^*, h_{ab} under all illuminations were averaged for four types of skin images. The mean results were [24.7, 46.1°]. The average ellipse parameters including semi-major, semi-minor axes and θ were [16.5, 9.7, 68.7°]. The chroma of the preferred skin tones will slightly increase as the ambient lighting CCT decrease.

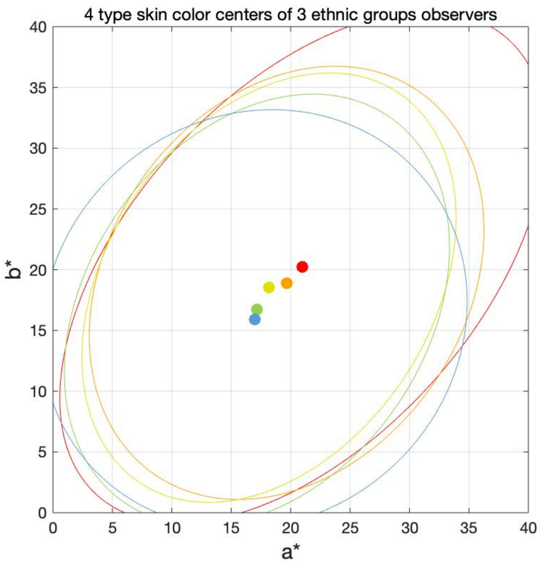

Figure 6. *Plot of tolerance ellipses transformed from their original lighting condition in a*b* diagram under the D65/10o condition, where red, orange, yellow, green and blue ellipses represent 3000K, 4000K, 5000K, 6500K and dark lighting condition respectively.*

Figure 7 plots the preferred skin tone ellipses from the four skin types in *CIELAB a*-b** plane together with its each centre. The size of African preferred skin tone ellipse was smaller than other three skin types for all three ethnic group observers, this means people have stricter criteria for African skin tones. Only a small range of African skin tones was preferred.

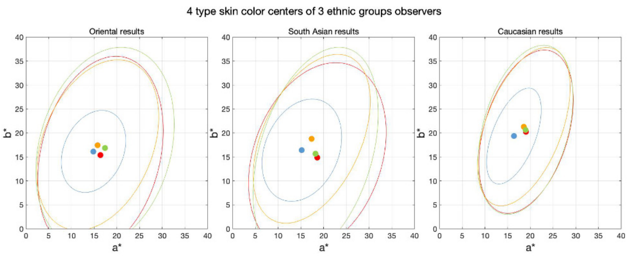

Figure 7. *Plot of tolerance ellipses transformed from their original lighting condition in a*b* diagram under the D65/10o condition for three ethnic group of observers, where red, orange, green and blue ellipses represent the mean preferred skin ellipse of each two East Asian, South Asian, Caucasian and African images, respectively.*

Four types of preferred skin tone assessed by all observers

The mean preferred skin tone centres from images of four skin type groups were judged by all observers from three ethnic groups. Preferred skin tone centre of Caucasian, East Asian, South Asian, African judged by all observers had a metric chroma (C_{ab}^*) and hue angles (h_{ab}) of [25.4, 44.5°], [24.5, 43.7°], [25.7, 48.3°], [23.0, 48.0°], respectively. It can be seen that there was hardly any difference among the images of four skin tone types. Although the skin tone centres were spread in a large area, their hue angles were located in a narrow range with a mean of 46.1°. Overall, the preferred four types of skin tones had a slight difference in hue and chroma, the average metric chroma value and hue angle were [24.7, 46.1°].

Preferred skin tone assessed by observers from three ethnic groups

Preferred skin tone centre of all the images judged by Caucasian, East Asian, South Asian observers had a metric chroma (C_{ab}^*) and hue angles (h_{ab}) of [25.6, 45.9°], [23.9, 45.7°], [24.8, 46.0°], respectively. East Asians consistently prefer slight less chromatic skin tones than Caucasians and South Asians, and Caucasians prefer more chromatic skin tones than Caucasians and South Asians. Overall, it can be concluded the observer variation due to different ethnic groups was small.

Skin tone appearance under different ambient lightings

Table 3 lists the average preferred skin tone centres of all images judge by observers from three ethnic groups under 5 ambient lightings. It can be clearly seen that the preferred skin tone changed with the change of the ambient light CCT. The chroma and hue angle of the preferred skin tone decreased slightly as the ambient CCT increased. In addition, people in dark environment preferred skin tones with slightly lower chroma (weaker) and hue angles (redder). The shifts of preferred chroma and hue angle caused by the ambient lightings were small, and the variation was much smaller than the preference variation caused by image content and variation among the observers. This proved that when the observers observed the skin tone images on the mobile display, the observers were almost fully adapted from the light on the display and the ambient lightings do not affect the appearance much at all.

Table 3. Preferred skin tone centres under different ambient lightings

Lightings	*Caucasian Observers*				*South Asian Observers*				*East Asian Observers*			
	a^*	b^*	C^*_{ab}	h_{ab}	a^*	b^*	C^*_{ab}	h_{ab}	a^*	b^*	C^*_{ab}	h_{ab}
3000K	20.0	21.2	29.2	46.8	19.4	19.0	27.2	44.4	17.5	18.5	25.4	46.6
4000K	19.8	19.6	27.9	44.7	14.3	15.9	21.4	48.1	18.7	18.0	25.9	44.0
5000K	17.3	19.0	25.8	47.7	16.8	18.0	24.6	47.0	17.3	18.0	25.0	46.1
6500K	17.0	17.6	24.4	46.1	16.2	18.2	24.3	48.4	14.8	11.4	18.7	37.7
dark	15.6	15.9	22.3	45.5	16.2	16.9	23.4	46.1	13.8	18.0	22.7	52.5
mean	17.9	18.7	25.9	46.2	16.4	17.6	24.0	46.8	16.4	16.7	23.4	45.5

Conclusion

Psychophysical experiment was conducted to evaluate the preferred skin tones and to study the influence of cultural background and ambient lightings. Summaries of experimental results are: 1) all observers preferred skin tone images captured under the lightings with high colour temperature and negative Duv; 2) the four types of preferred skin tones agreed well with each other, about [24.7, 46.1°] for C_{ab}^* and h_{ab} values respectively; 3) the 3 ethnic groups also gave similar results; 4) The CCT of lightings did slightly affect colour appearance, i.e. skin appears to be less colourful and redder under a higher CCT illumination. These findings could help to guide to achieve preferred colour reproduction.

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Author Biograph

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