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Spectrophotometric Measurement of Human Skin Colour

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Abstract:

This paper focuses on human skin colour. Three different colour measuring instruments were used: a tele-spectroradiometer, a de:8° and a 45°:0° spectrophotometers. They were used to measure 47 subjects who were divided into four skin groups: Chinese, Caucasian, South-Asian and Dark. Eight locations for each subject were measured. The spectral reflectance results were first compared. They all showed the 'W' shape between the 550 nm-580 nm as found by the other studies. Those from the tele-spectroradiometer had an increase from 600 nm while the others were flatter. The colorimetric data calculated from the spectral measurements revealed similar patterns to describe the colour distribution of each skin group. It was found that two scales: whiteness-depth, and blackness-vividness could well describe these distributions. The results also showed systematic differences between the four ethnic groups, between eight body locations, between two genders, and between the measurements from the three instruments.

1. INTRODUCTION

Skin colour has been extensively studied over many years. It is important to applications in many industries including photography, printing, medical, lighting, retail, cosmetics, etc. For most of these applications, the accurate reproduction of skin colour is essential. This has led to many attempts to accurately measure the colour of skin. However, skin is a biological material. It includes three-layered tissue composed of epidermis, dermis and subcutaneous tissues with several kinds of chromophores like melanin and hemoglobin. Thus, the reflected light of skin is a combination of surface reflected light and diffuse light which reach into the deeper skin layer and then be reflected to the device. Therefore, the density of some chromophores can be estimated by analyzing the spectral reflectance of skin[1].

Two techniques have been frequently used: contact measurement and non-contact measurement. And both have their advantages and disadvantages. The contact measurement method typically uses a spectrophotometer. The non-contact measurement method usually uses a

tele-spectroradiometer (TSR), a digital camera, or visual assessment. The TSR measures the spectral power distribution (SPD) of a colour illuminated by a source, whereas the spectrophotometer measures the spectral reflectance of a surface colour. Many studies have been carried out using the non-contact method. Angelopoulou[2] used an Oriel Multispec 77400 spectrograph to measure the Bidirectional Reflectance Distribution Function (BRDF) of the palm and the back of the hand. The experiment involved 23 subjects: 16 Caucasians, 3 Asians, 2 of African descent and 2 Indians, and 18 were male, 5 were female. The results showed that, despite variations, the spectral distribution of the skin measurements exhibited a systematic pattern based on the composition of human skin. There was a 'W' shape in the spectral reflectance from 550 nm to 580 nm that is mainly caused by the absorption bands of haemoglobin and melanin (shown in Fig. 1). Sun and Fairchild[3] used a PhotoResearch SpectraScan 704 spectroradiometer to measure the skin colour of 34 subjects. Among their subjects there were 23 females, and 11 males from five different races: Pacific-Asian, Caucasian, Black, Subcontinental-Asian and Hispanic and for each subject the face, eye, lips and hair were measured. The characteristics of the spectral reflectance data were analysed using a Principle Component Analysis (PCA) method, and the results indicated that the first three basic functions could provide a sufficiently accurate reconstruction of the spectra of all races and individual facial locations. Visual assessment has also been used by means of reference colours presented by a fan deck or a colour chart. A typical example is that of De Rigal et al.[4] who measured skin colours to design a skin colour chart as a visual aid. This method provides an easy and inexpensive method to evaluate the effect of clinical treatment or to find a product to match skin in retail stores. However, it suffers from less accurate results due to variation by human observers and lighting conditions.

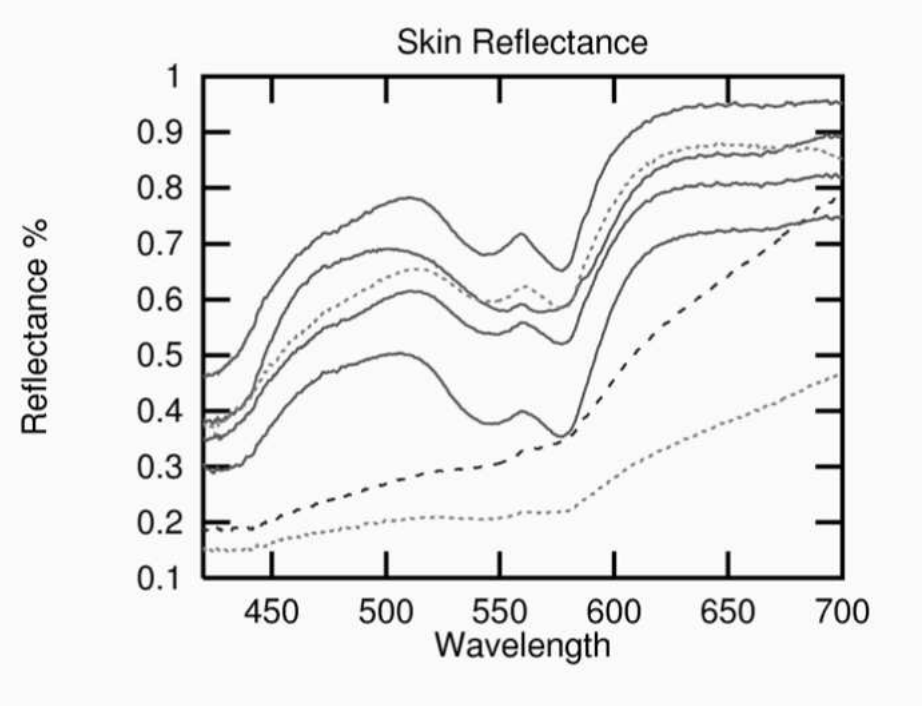


FIG. 1. Angelopoulou's result showing the "W" shape in the reflectance of human skin from 550 nm to 580 nm.

For the contact method, usually with a spectrophotometer, an illumination/viewing geometry of either d:8° or 45°:0°, is used. Care should be taken to apply constant pressure for measuring colour. It is well known that skin colour changes colour under different pressure. The data are typically used in the medical industries and the surface colour industries, for which colour management and colour specification are vitally important. Spectrophotometers are normally used to measure colours at a fixed skin location to obtain the spectral reflectance which can be used to calculate colorimetric coordinates, or sometimes haemoglobin concentration.[5] Many investigations have been carried out using a spectrophotometer. Marszalec et al,[6] used a Minolta CM 2002 spectrophotometer to measure 100 persons with pale skin (European descent), 5 persons with yellowish skin (Asiatic descent) and 6 persons with dark skin (African descent) with the condition of specular component excluded. More recently, Xiao et al[7] used a Minolta CM-2600d spectrophotometer with d:8^{o} geometry to measure the skin colour of 202 Chinese subjects at nine locations on the human body (forehead, tip of nose, cheek, ear lobe, chin, back of hand, palm, dorsal forearm, and ventral forearm). The colour distributions between different locations and genders were reported.

Because of the importance of skin colour, ISO ISO/TR 16066-2003 Graphic Technology – Standard object colour spectra database for colour reproduction evaluation (SOCS)[8] provides a database including 51,182 sets of spectral reflectance data, of which 8,213 are skin colours. There are 6 skin groups, provided by 5 organizations. Each subject was measured at the forehead, cheek, neck, zygomatic (cheek) region and arm. However, the SOCS database did not report the instrument or measurement conditions used such as, geometry, aperture size, wavelength range, wavelength interval, etc. In fact, there are not many studies on the skin colour measurement and mostly focus on specific applications. Due to the unique structure of skin, the uncertainty of skin colour measurement is not the same as other surface colour measurement. On one hand, before any applications, especially those require high accuracy, e.g. estimation of the density of melanin and hemoglobin based on the spectral reflectance, the measurement methods should be carefully considered. Or at least there should be a clear idea about what is the difference between different measurement and how big the difference is. On the other hand, the difference between different races, genders and body locations should be considered as well, when the topic is related to colour perception.

Furthermore, the International Commission on Illumination (CIE) established a Technical Committee in 2013: TC 1-92 Skin Colour Database[9] to investigate the uncertainty in skin colour measurement, to recommend protocols for good measurement practice, and to evaluate skin colour measurements covering different skin types, genders, ages and body locations.

As mentioned earlier, most of the previous studies did accumulate skin colours using one instrument to measure limited number of subjects. The present experiment was designed to use more than one instruments measuring exactly the same locations of a subject. It was intended to reveal the measuring uncertainty, inter-comparison and colour distribution between different instruments. It is a preliminary experiment of a large scale project of skin colour measurement. The main experiment has been carried out at the University of Leeds and Liverpool in UK[10]. The aim of the present study is to accumulate a skin colour database from different body locations using different measurements. There were three different measuring instruments: a 45^o:0^o spectrophotometer, a de:8^o spectrophotometer and a tele-spectroradiometer. The data were analysed, and the measuring variation between different groups of measurements were described.

Certain trends of colour shift of human skin colour were discovered and discussed. The results indicate that these differences are too large to be ignored.

2. EXPERIMENT

In the present study, three measurement methods were used to measure human skin colour: a 45^o:0^o spectrophotometer, a de:8^o spectrophotometer (SP) and a tele-spectroradiometer (TSR). In total, 47 subjects from 17 countries were recruited for the experiment. There were 20 Chinese subjects (10 males and 10 females), 10 Caucasian subjects (7 females and 3 males), 10 Pakistanis (10 males), 5 Africans (5 males) and 2 Sri Lankans (2 males). Table 1 summarizes the information of all the subjects. Since the Africans and Sri Lankans had similar dark skin colour, they were combined together to form one group. In this way, all the subjects can be divided into four groups: Chinese, Caucasian, South Asian and Dark. The Chinese group contained 20 Chinese, the Caucasian group contained 10 Caucasians, the South Asian group contained 10 Pakistanis and the Dark group contained 7 other subjects.

TABLE 1. The general information of the 47 subjects

Culture	No. of subjects	No. of females	No. of males	Average age
Chinese	20	10	10	24.3
Caucasian	10	7	3	22.9
Pakistani	10	0	10	28.5
African	5	0	5	26.5
Sri Lankan	2	0	2	30.5
Totals	47	17	30	25.4

All the subjects had good health, i.e. they were not under any therapy or medical treatment which could lead to an unstable skin condition. They were instructed not to use any skin care or makeup products and to clean the target locations before the experiment. During the experiment, glasses and accessories were removed.

The experimental procedure consisted of two parts. Part one included the measurements of eight body locations of each subject using a JETI Specbos 1211UV tele-spectroradiometer under a ceiling light which contained a florescent lamp to simulate CIE illuminant D65. Figure 2 shows

a typical measurement situation. Fig. 3 plots the spectral power distribution (SPD) of the simulator. In the second part, a Datacolor 600 with de:8^{o} geometry and a X-Rite SpectroEye spectrophotometer with 45^{o}:0^{o} geometry were used to measure the eight body locations. The eight locations were the forehead, right cheek, left cheek, back of hand, back of fist, palm, ventral (inner) forearm and dorsal (outer) forearm.

FIG. 2. Subject in measurement position under a florescent illuminant D65 simulator ceiling light.

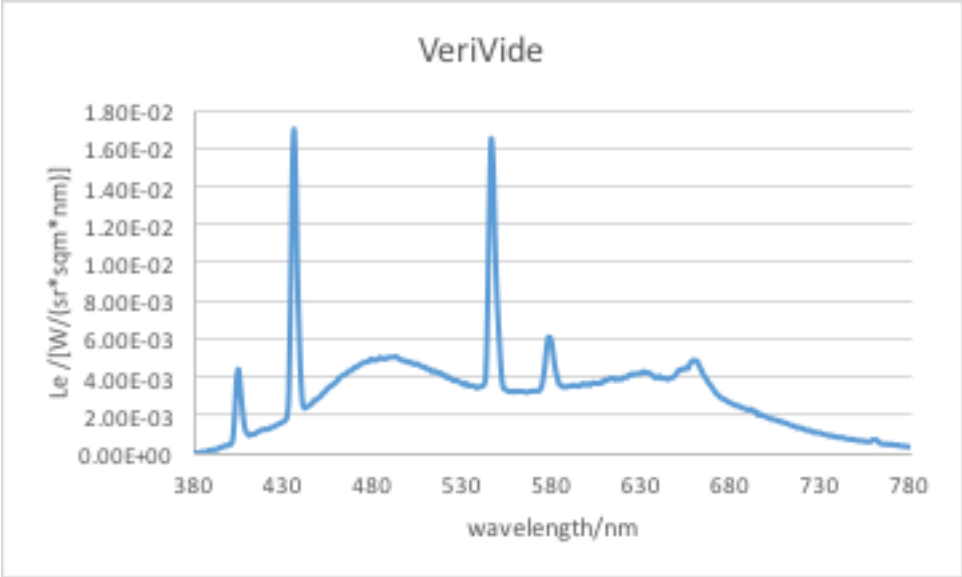


FIG. 3. Spectral power distribution of the VeriVide ceiling light D65 simulator (5918K, 320 cd/m^2)

The eight locations could be divided into two groups as shown in Fig. 4. One group included the locations on the face (forehead, right cheek, left cheek), and the second group included the locations on the limb (back of hand, back of fist, palm, ventral forearm, dorsal forearm). The two groups can be used to represent different degrees of suntan, i.e. facial skin is exposed more to the sun than limbs, especially the forehead. Exposure to the sun influences the melanin density of the skin, which may lead to pigmentation.

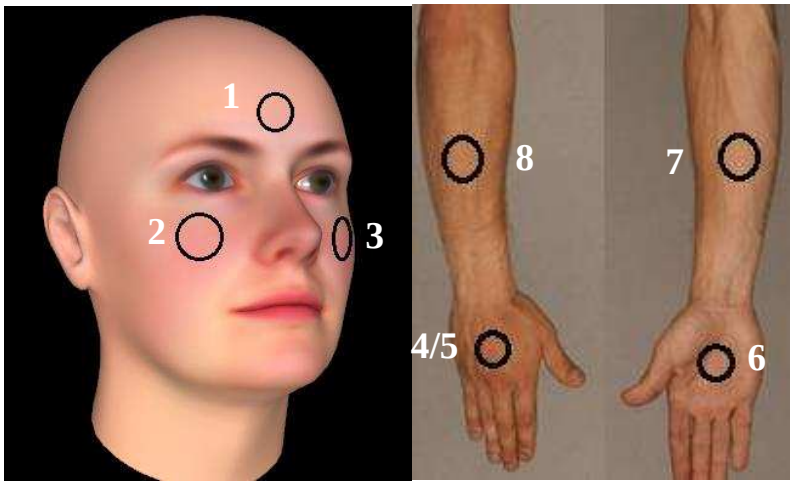


FIG. 4. The eight measurement locations (1-forehead, 2-right cheek, 3-left cheek, 4-back of hand, 5-back of fist, 6-palm, 7-ventral forearm, 8-dorsal forearm)

When making measurements using the TSR, the device was located approximately one metre away from the subject. The aperture size of the TSR was approximately 20 mm. Each measurement position was marked during the measurement, and later an X-Rite white balance chart were measured at the same position. Given the reflectance of the white balance chart, the reflectance of measurement target could be calculated using Eq. 1 below:

$$R_t = R_c * \frac{SPD_t}{SPD_c} \quad (1)$$

where R_t and R_c are the reflectance of target skin sample and white balance chart respectively. SPD_t and SPD_c are the measured spectral power distribution of the target skin sample and white balance chart.

For measurements using the SPs, the instruments were applied in such a way that they did not give too much pressure to the skin. The aperture size of the de:8^o and 45^o:0^o geometries were 8 mm and 4.5 mm respectively. All the measurement results were finally arranged from 400 nm to 700 nm with a measurement interval of 10 nm.

3. RESULT AND DISCUSSION

3.1 Device accuracy

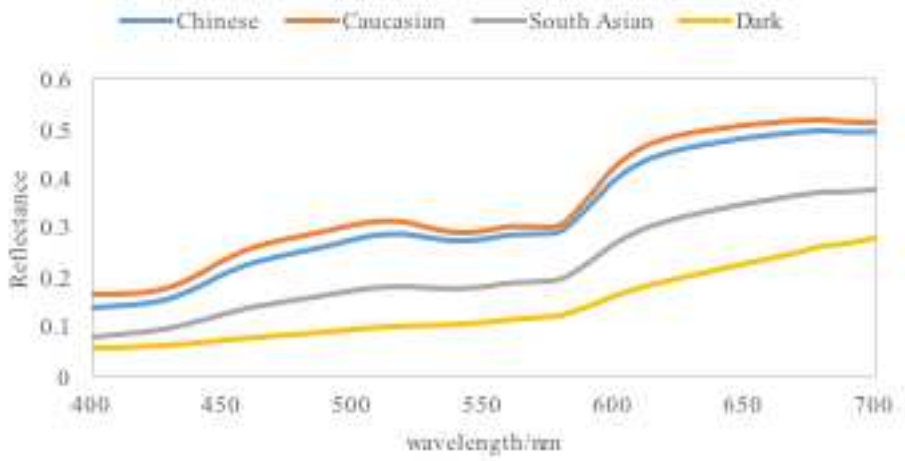
Before the skin colour measurement, the short-term repeatability and inter-instrument agreement were tested. The Mean Colour Difference from the Mean (MCDM)[11] is introduced to evaluate the repeatability of the measurements. The short-term repeatability used a matte sample from Pantone Skintone chart. It was repeatedly measured by the same operator, at same position, continuously 5 times. The MCDM values were 0.12, 0.02 and 0.06 for TSR, de:8^o and 45^o:0^o SPs respectively. Contact measuring methods have higher short-term repeatability than non-contact measuring methods. The inter-instrument agreement was compared using the 24 colours at the XRite ColorCheck® Chart. The average colour difference of pairwise comparison was 2.08, 2.47 and 1.34, between TSR and de:8^o, between TSR and 45^o:0^o, and between de:8^o and 45^o:0^o respectively.

3.2 Comparison of the spectral reflectance measurements

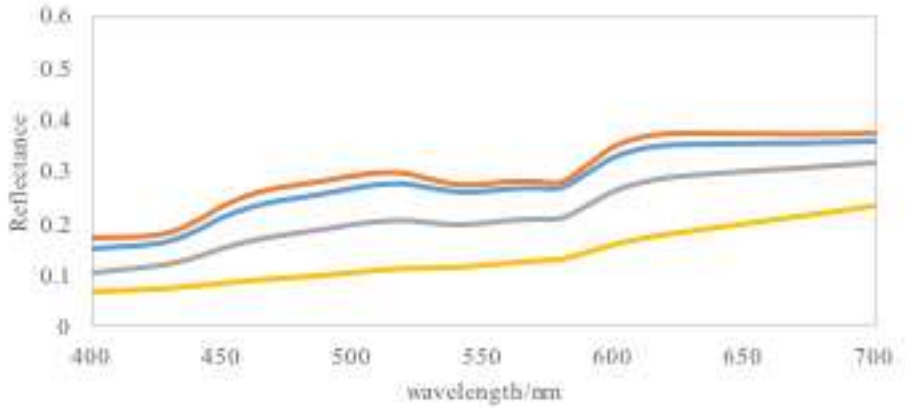
3.2.1 Comparison between different skin groups

The ethnic diversity can be seen from the skin reflectance of different skin groups. Fig. 5 plots the mean spectral reflectance of each skin group. It can be seen that, the four spectral reflectance functions had a similar shape. All the curves had a “W” shape in the middle from 550 nm to 600 nm, which is consistent with the result of Angelopoulou[2]. The “W” shape is mainly caused by the absorption bands of haemoglobin near to 550 nm and 580 nm. However,

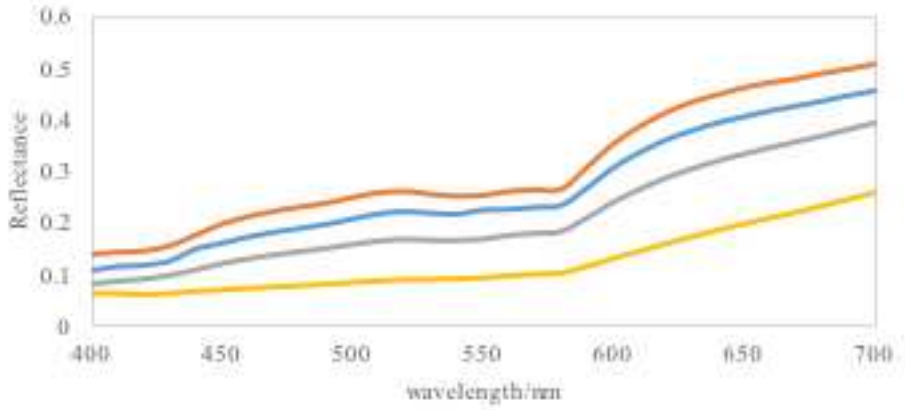
this shape was not obvious for the dark skin colour due to the relatively low reflectance. Darker skin has a high density of melanin, which absorbs most of the incident light. With less light to interact with the haemoglobin, the effect of hemoglobin is weakened. Hence the “W” shape is hardly evident.



(a)



(b)



(c)

FIG. 5. Average spectral reflectance of the four skin colour groups (Chinese, Caucasian, South-Asian, and Dark) for the three instruments: (a) de:8°, (b) 45°:0°, (c) TSR, respectively.

3.2.2 Comparison between different measurement instruments

Fig. 6 compares the reflectance of every skin group measured by three instruments. The measurement results for 45°:0° and de:8° SPs were similar to the results for the TSR. All the measurements revealed a similar pattern as discussed in the earlier sections. However, the difference between different measurements cannot be neglected. 45°:0° and de:8° SPs are both contact methods, but in the long wavelength range (greater than 580 nm) the amplitude of the de:8° data is much higher than that of the 45°:0° data. The spectral reflectance calculated from the TSR measurements had a similar shape to that of the de:8° measurement but the amplitude is slightly lower. In the range from 600 nm to 700 nm, the spectral reflectance of the TSR measurements increased instead of being level as for the de:8° and 45°:0° measurements. The CIELAB colour-differences between the average spectral reflectance for the de:8° and the TSR, for the de:8° and the 45°:0°, and for the TSR and the 45°:0° were 4.5, 6.4 and 6.9 respectively, which can be clearly discernible by human observers.

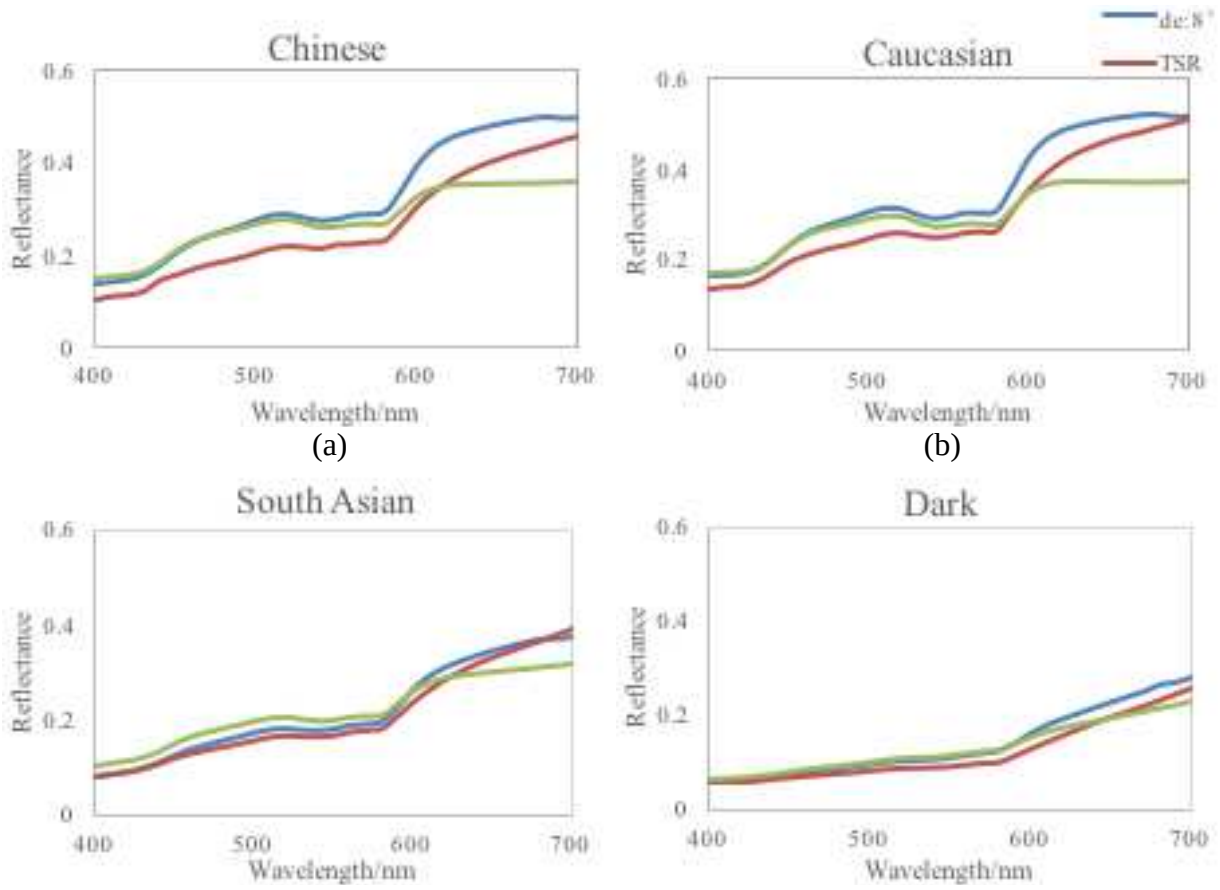


FIG. 6. Average spectral reflectance of data from the three measurement instruments: (a) Chinese, (b) Caucasian, (c) Sub-Asian, (d) Dark skin groups respectively.

3.3 Comparison of colorimetric coordinates

For further analysis, the CIELAB colorimetric coordinates were calculated for each set of spectral reflectance data under CIE D65 illuminant and the CIE 1964 standard colorimetric observer.

3.3.1 Measurement uncertainty

Human skin colour is spatially non-uniform and changeable over time and these factors can have a great impact on the accuracy of the measurements. The colour-difference between each of the four repeated measurements of the same location, and their mean, were first calculated. These colour-differences were then averaged as the MCDM value. For a perfect repeatability performance, MCDM should be zero.

Before the experiment, four subjects were recruited for a pre-experiment. The four subjects were Chinese, Caucasian, Pakistani and African, respectively, to represent each skin group. For each subject the eight body locations described above were measured four times. Table 2 summarises the repeatability results for each measurement method. The mean MCDM for each location and each race were also reported together with its standard deviation (SD).

TABLE 2. MCDM for the three instruments: top, 45°:0° spectrophotometer; middle, de:8° spectrophotometer; bottom, tele-spectroradiometer

45°:0°	**hand back**	**fist back**	**palm**	**dorsal**	**ventral**	**forehead**	**left cheek**	**right cheek**	**mean**	**SD**
Chinese	0.45	0.45	0.31	0.10	0.59	0.45	0.62	0.57	0.44	0.17
Caucasian	0.14	0.29	0.57	0.46	0.22	0.37	0.45	0.65	0.39	0.17
Pakistani	0.13	0.56	1.31	0.37	0.39	0.44	0.55	0.46	0.53	0.34
African	0.20	0.57	0.51	0.36	0.12	0.48	0.46	0.13	0.35	0.18
Mean	0.23	0.47	0.67	0.32	0.33	0.44	0.52	0.45	0.43	0.14

d:8°	**hand back**	**fist back**	**palm**	**dorsal**	**ventral**	**forehead**	**left cheek**	**right cheek**	**mean**	**SD**
Chinese	0.32	0.09	0.19	0.11	0.64	0.14	0.12	0.18	0.22	0.18
Caucasian	0.52	0.50	0.31	0.22	0.52	0.29	0.39	0.65	0.43	0.15
Pakistani	0.27	0.58	0.68	0.41	0.09	0.15	0.27	0.33	0.35	0.20
African	0.34	0.08	0.28	0.26	0.28	0.12	0.18	0.15	0.21	0.09
Mean	0.36	0.31	0.36	0.25	0.38	0.18	0.24	0.33	0.30	0.07

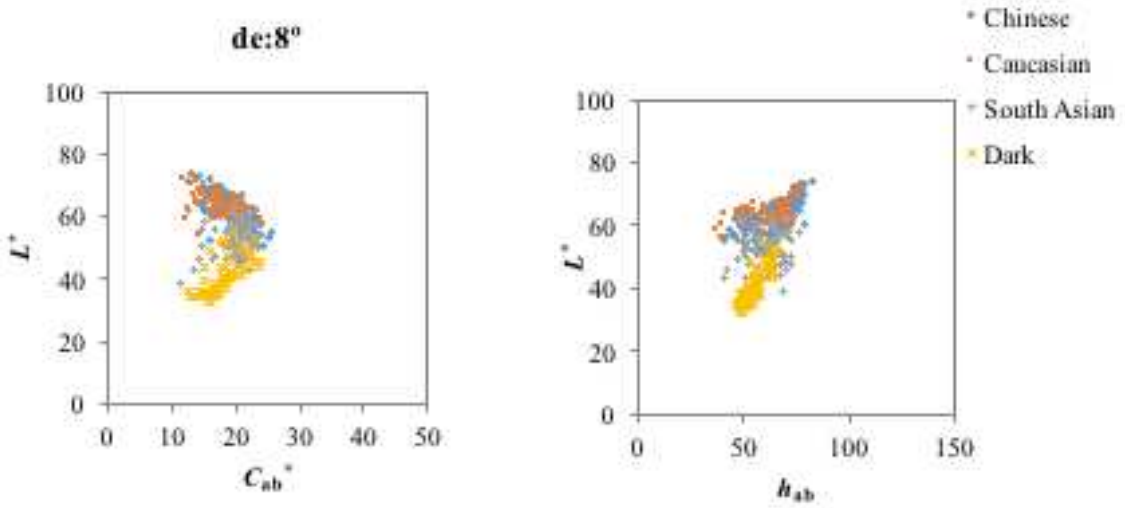
TSR	**hand back**	**fist back**	**palm**	**dorsal**	**ventral**	**forehead**	**left cheek**	**right cheek**	**mean**	**SD**
Chinese	0.23	0.27	0.39	0.57	0.72	0.25	1.50	0.54	0.56	0.42
Caucasian	0.29	0.57	1.02	0.12	0.46	0.33	0.27	0.82	0.49	0.30
Pakistani	0.27	0.41	0.83	0.22	0.40	0.24	0.66	0.41	0.43	0.21
African	0.33	0.31	0.36	0.12	0.34	0.37	0.96	0.22	0.37	0.25
Mean	0.28	0.39	0.65	0.26	0.48	0.30	0.85	0.49	0.46	0.20

The results showed that generally the values of the MCDM for the three instruments were below 0.50 (0.43 for the 45°:0° spectrophotometer, 0.30 for the de:8° spectrophotometer and 0.46 for the tele-spectroradiometer). Note that the MCDM values are less than 1 ΔE_{ab}^{*} which is typically considered to be a just perceptible difference. Thus, the de:8° SP had the lowest value of MCDM, implying that it is more repeatable than the other two instruments.

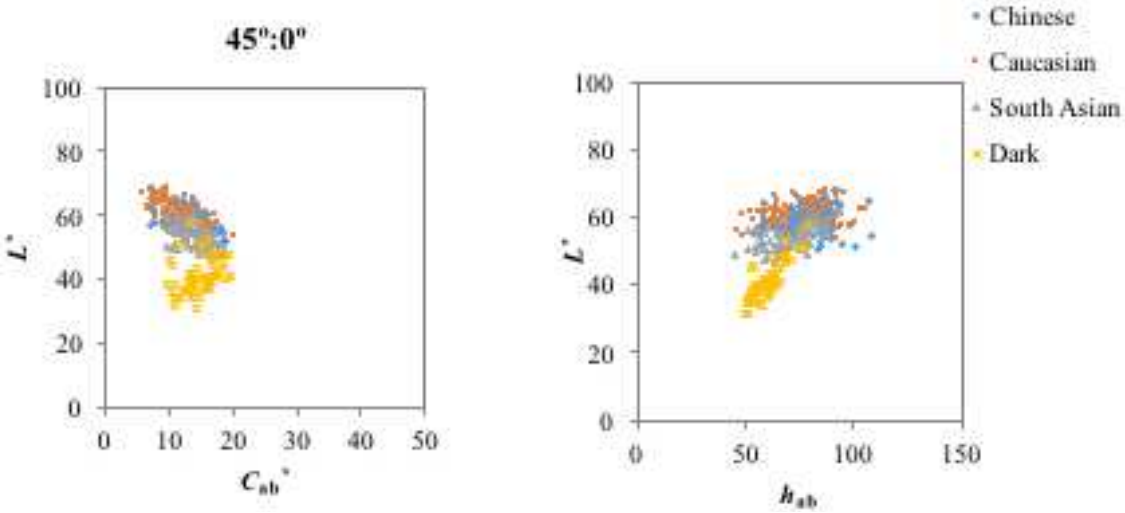
Comparing the previous repeatability study by measuring a uniform Pantone colour patch for each instrument, it has five times less variation than by measuring the skin colour.

3.3.2 Measurement results between different groups

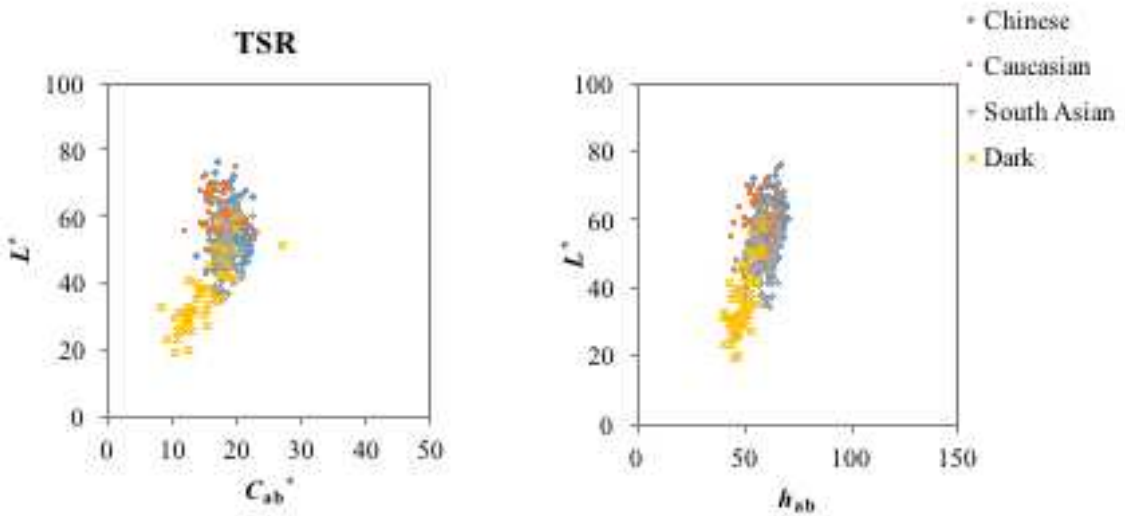
Four different skin colour groups were defined to represent different skin tones. The Caucasian group had the lightest tone, followed by the Chinese group, the South Asian group, and the Dark skin group had the darkest tone. Fig. 7 plots all the measurement data in an C_{ab}^{*}-L^{*} plane and the h_{ab}-L^{*} plane for all three measurement methods. Human skin colour has a specific distribution in the C_{ab}^{*}-L^{*} plane and this pattern appeared in the measurements from all three instruments.



(a) de:8°



(b) 45°:0°



(c) TSR

FIG. 7. Experiment data for the three instruments. Left CIELAB C_{ab}^* vs L^*, Right CIELAB h_{ab} vs L^* for the three instruments.

From the skin colour distributions in Fig. 7, a banana shape can be seen on the C_{ab}^*-L^* plane. High lightness values are associated with low chroma values, i.e. when lightness values decrease, chroma values will increase. However, as the lightness values continue to decrease below a certain level, the chroma values will decrease as well. The data can be described by some of the recently proposed colour appearance scales, for example those proposed by Berns[12] based on the CIELAB system: vividness and depth. Fig. 8 shows these two colour appearance scales. The two scales are defined as vividness: a vector from $L^* = 0$ and $C_{ab}^* = 0$ to a point on the C_{ab}^*-L^* plane, and depth: a vector from $L^* = 100$ and $C_{ab}^* = 0$. It can be seen in the C_{ab}^*-L^* plane in Fig. 7 that the Chinese and Caucasian skin colours are close to the depth scale, while the Dark skin colour samples are close to the vividness scale. The South-Asian samples are distributed about the cross point of the two scales, where the skin colours had the highest chroma values. These two scales are also close to the definition of the 'whiteness' and 'blackness' scales in the Swedish Natural Color System (NCS) system[13] which are also shown in Fig. 8. The whiteness and blackness scales have a strong negative correlation to the depth and vividness scales, respectively[14]. The vividness (V_{ab}^*) and depth (D_{ab}^*) scales can be defined by Eqs. 1 and 2, respectively. Eqs. 3 and 4 define the whiteness (W) and blackness (B) scales respectively.

$$V_{ab}^* = \sqrt{(L^*)^2 + (a^*)^2 + (b^*)^2} = \sqrt{(L^*)^2 + (C_{ab}^*)^2} \quad (1)$$

$$D_{ab}^{*} = \sqrt{(100 - L^{*})^2 + (a^{*})^2 + (b^{*})^2} = \sqrt{(100 - L^{*})^2 + (C_{ab}^{*})^2} \quad (2)$$

where L^{*}, a^{*}, b^{*} and C_{ab}^{*} are the coordinates in the CIELAB system.

$$W = L^{*} - \left(C^{*}/C_{p}^{*}\right)L_{p}^{*} \quad (3)$$

$$B = (100 - L^{*}) - \left(C^{*}/C_{p}^{*}\right)\left(100 - L_{p}^{*}\right) \quad (4)$$

where the L^{*}, C^{*} are coordinates in the CIELAB system, and the L_{p}^{*}, C_{p}^{*} are the lightness and chroma of the 'full colour', a colour has maximum chromaticness in each hue of the NCS system.

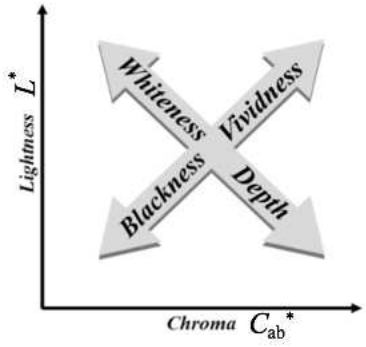


FIG. 8.The concepts of Depth, Vividness[10], Whiteness and Blackness[11] defined in the C_{ab}^{*}-L^{*} plane.

In practice, objects change their colour appearance when seen in different viewing conditions and, in general, the lightness (L^{*}) and chroma (C_{ab}^{*}) attributes change simultaneously. So, colour-naïve people might not understand the meaning of lightness and chroma. However, they might be more familiar with the terms vividness, depth, whiteness and blackness, each of which represents a combination of lightness and chroma. Thus, the paramteres defined by Eqs. (1)-(4) above might better describe human skin colour. For example, Chinese and Caucasian subjects had a whiter skin tone, in this case, their whiteness values were higher than those of the other groups. The Dark skin group had the darkest skin tone, their data can be fitted by the blackness scale, and this group had the highest blackness values. The South Asian group had medium skin tone and their data were distributed close to the point where the whiteness-depth and the blackness-vividness scales cross, and they also had the highest chroma values.

From a different perspective, the colour distribution within each skin group, as shown in Fig. 7, shows that the whiteness and depth scales follow the trend of the lighter skin colour groups (i.e. the Caucasian and the Chinese data), i.e. whiter (or less deep) colours are in the lighter and less colourful colour regions. For the Dark skin group, their distribution can be well fitted by the blackness and vividness scales, i.e. blacker (or less vivid) colours are in the darker and less colourful regions.

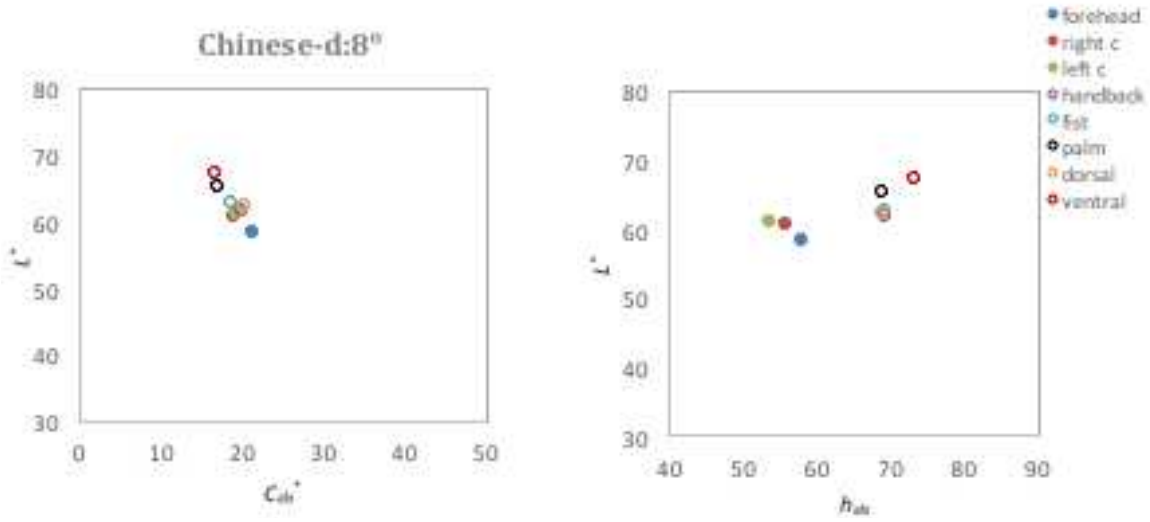
Whiteness of facial skin is an important perception as described by the study of the effect of chromatic components on facial skin whiteness by Yoshikawa[15]. Their results showed that a lower chroma facial skin colour appears whiter than a high chroma colour, and a reddish colour appears to be whiter than a yellowish colour.

Fig. 7 also shows the data plotted in the h_{ab}-L^* plane. The Dark group has the smallest hue range, followed by South Asian group. The Caucasian and the Chinese groups have the largest hue range. For human skin colour, the hue also changes together with the lightness: when the lightness decreases, the variation in hue also decreases, which suggests that there is less diversity in colour of dark human skin.

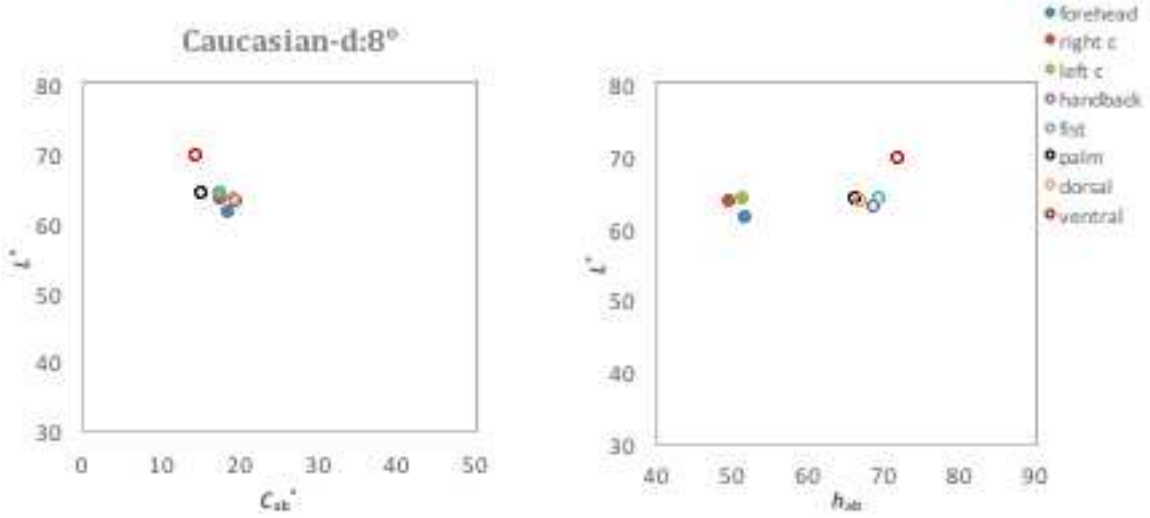
3.3.3 Measurement results between different locations

Since the measurements of the three instruments all gave results that followed a similar pattern, the data measured using the de:8^o spectrophotometer are presented hereafter for brevity.

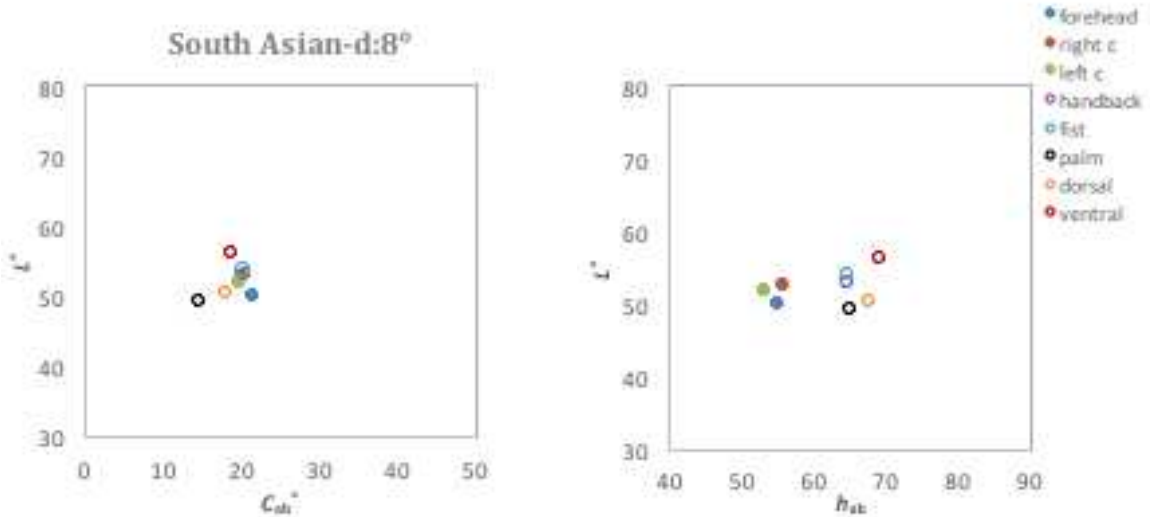
Fig. 9 shows the mean colour coordinates of the eight locations for Chinese, Caucasian, South Asian and Dark skin groups respectively. For each skin group, the results are plotted in C_{ab}^*-L^*, and h_{ab}-L^* planes respectively.



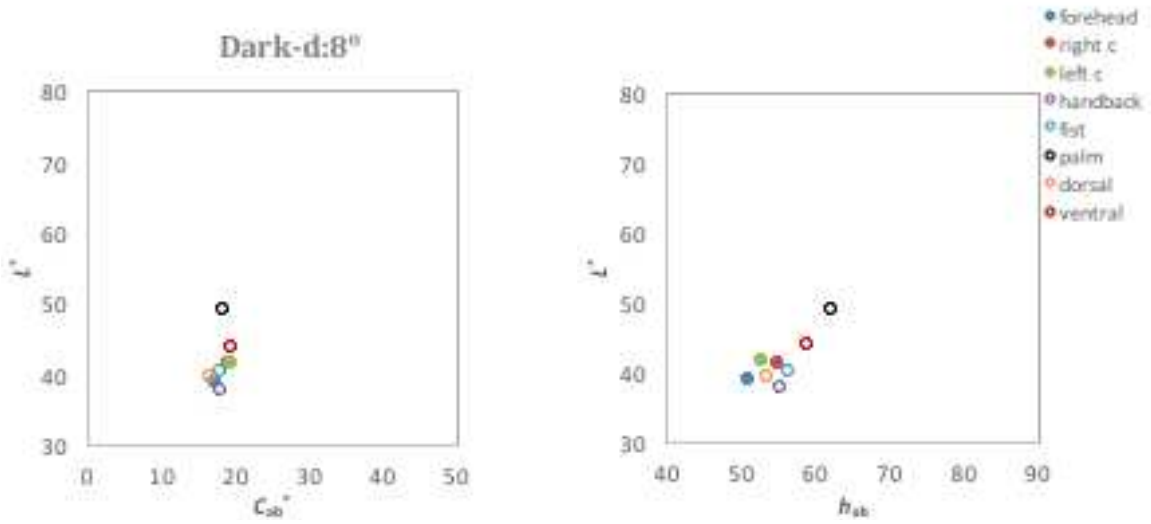
(a)Chinese group



(b) Caucasian group



(c) South Asian group



(d) Dark group

FIG. 9. Mean data of eight body locations measured by a de:8° geometry spectrophotometer. Left CIELAB C_{ab}^* vs L^*, Right CIELAB h_{ab} vs L^* for each skin group.

The h_{ab}-L^* plane in Fig. 9 shows a hue shift between the eight locations, i.e. the eight locations could be divided into two sub-groups. The left group exactly contained all the three locations on the face (forehead, right cheek, left cheek), while the right group exactly contained all the five locations on the limb (back of hand, back of fist, palm, ventral forearm, dorsal forearm). The results showed that human facial skin colours had smaller values of hue angle (average 56°) compared to those of the limb (average 70°). This indicates that facial skin colours appear to be reddish compared to those on the limb. However, as the skin colour became darker, the difference of the hue between face and limb became smaller. The eight locations could not be distinguished for the dark skin group.

Fig. 10 compares all the data between face and limb for the de:8° spectrophotometer. Skin colour of the limb followed a clear trend, i.e. most whiter colours appeared yellower. This pattern may suggest another to-be-developed scale suitable for human skin colour. However, this trend cannot be found in the facial skin colour.

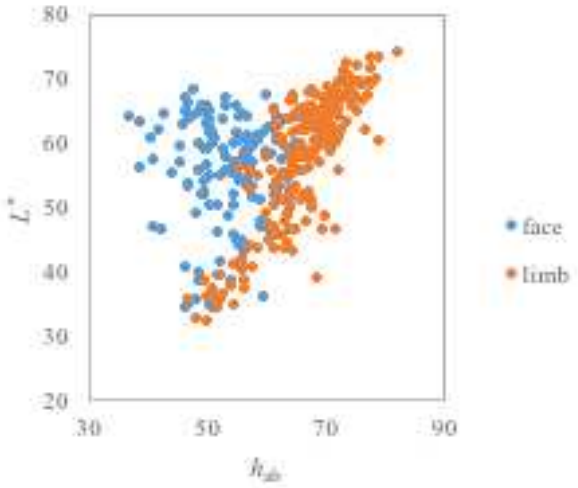


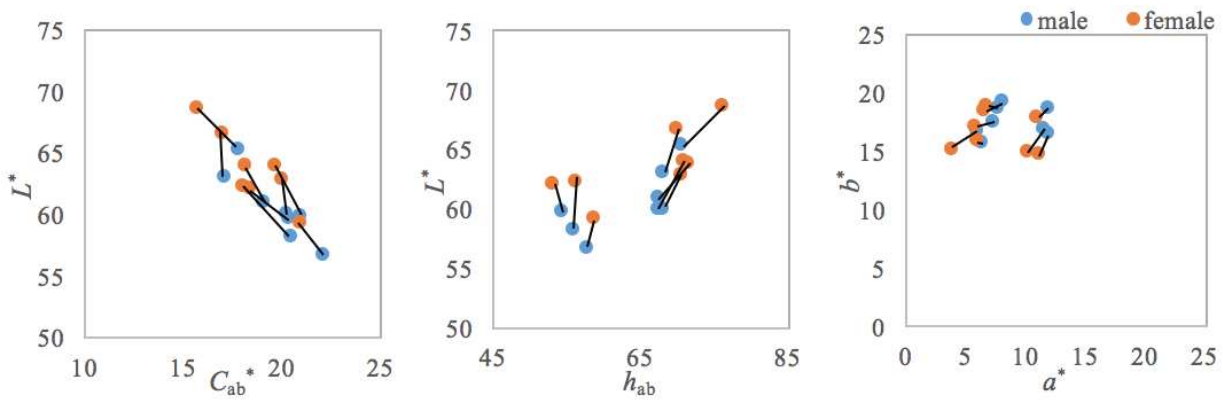
FIG. 10. Skin colour of face and limb in h_{ab}-L^* plane measured using de:8^o spectrophotometer.

3.3.4 Measurement results between different genders

Females generally tend to have a skin tone that is fairer than that of males. In this study 47 subjects were recruited from all over the world and among all the skin groups, the gender ratio for the Chinese subjects was 1:1. The data of the Chinese group were analysed as an example to compare the gender difference in skin colour.

The Chinese data were divided into two groups: female and male. From each group it was possible to calculate the average skin colour at eight locations. All these data are plotted on h_{ab}-L^* and C_{ab}^*-L^* planes and shown in Fig. 11.

In Fig. 11, the pattern of different locations discussed in the previous section is shown again. The distribution of the two genders was consistent, with a small colour shift. Fig. 11 and Table 3 show that, the skin colour of males tended to have a smaller hue angle compared to that of females, which suggests the skin colour of males tended to be redder (or the skin colour of females tended to be yellower). Also, skin colours of females always had higher lightness values and lower chroma values than those that of males, i.e. the skin colours of females had higher whiteness values. This result is consistent with our experience.



(a) (b) (c)

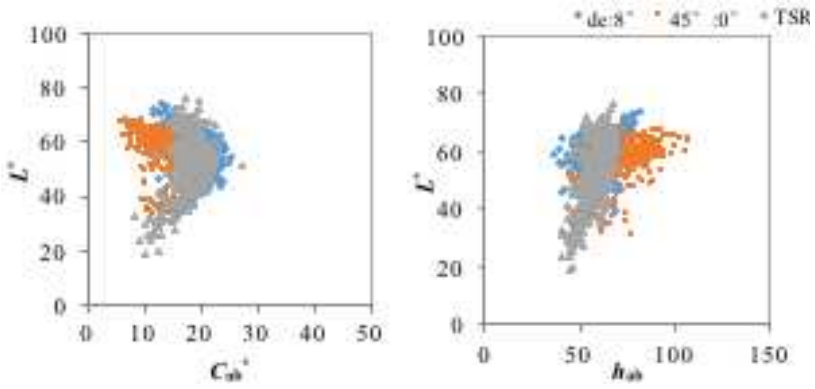
FIG. 11. Gender difference of skin colour presented in (a) C_{ab}^{*}-L^{*} plane, (b) h_{ab}-L^{*} plane, and (c) a^{*}-b^{*} plane (de:8°)

TABLE 3. The colorimetric difference between Chinese female and male subjects: the difference data on the right were calculated using the data of the male minus the data of the female.

Female	L^{*}	C_{ab}^{*}	h_{ab}	Male	ΔL^{*}	ΔC_{ab}^{*}	Δh_{ab}^{*}	ΔH_{ab}	ΔE_{ab}
forehead	59.27	20.92	58.52	forehead	-2.52	1.20	-0.92	-0.34	2.81
right cheek	62.40	18.01	56.09	right cheek	-4.15	2.46	-0.19	-0.06	4.82
left cheek	62.05	18.38	53.05	left cheek	-2.30	1.97	1.15	0.39	3.06
handback	62.96	19.96	70.46	handback	-2.91	0.27	-2.41	-0.84	3.04
fist	63.92	18.14	71.34	fist	-2.93	0.90	-3.93	-1.28	3.32
palm	66.69	16.92	69.78	palm	-3.60	0.13	-1.71	-0.51	3.64
dorsal forearm	63.99	19.66	70.85	dorsal forearm	-4.07	1.29	-3.53	-1.25	4.45
ventral forearm	68.62	15.62	76.18	ventral forearm	-3.24	2.13	-5.54	-1.61	4.19

3.3.5 Measurement results between different measurement methods

Fig. 12 compares data between the three measurement geometries: de:8° SP, 45°:0° SP and TSR again on two different planes. The three data sets had a similar lightness range. The data for de:8° SP overlapped with the data for the TSR, while the results for 45°:0° SP had lower chroma values and a larger hue range than those for the de:8° SP and the TSR. The main reason for this difference may be the different sizes of the measurement aperture: the aperture size of the TSR and the de:8° SP were larger (20 mm and 8 mm respectively) compared to the 45°:0° SP (4.5 mm). The measurements were the average result of the target area, and large aperture would average the inhomogeneity of skin colour, hence the hue range will be smaller.



(a) (b)

FIG. 12. All the data of three measurements (de:8°, 45°:0° SPs and TSR) presented in (a) C_{ab}^{*}-L^{*} plane, and (b) h_{ab}-L^{*} plane.

Table 4 and Fig. 13 summarise the results of the three sets of instrument measurements. All three sets revealed the banana shape on the C_{ab}^{*}-L^{*} plane. For a certain skin group, the 45°:0° SP and the de:8° SP had similar lightness values, while the TSR and de:8° SP had similar hue values.

TABLE 4. Mean data of the four skin groups for the three measuring instruments measurements

Device	Group	L^{*}	C_{ab}^{*}	h_{ab}
TSR	Caucasian	59.75	17.63	59.95
	Chinese	56.15	18.60	61.58
	South Asian	50.07	18.29	59.24
	Dark	37.96	15.13	50.95
de:8°	Caucasian	64.03	17.24	62.03
	Chinese	62.25	18.78	64.69
	South Asian	52.12	19.12	61.76
	Dark	41.46	18.27	56.09
45°:0°	Caucasian	61.23	10.87	76.77
	Chinese	59.62	12.27	77.98
	South Asian	53.47	13.95	71.02
	Dark	41.67	14.53	61.76

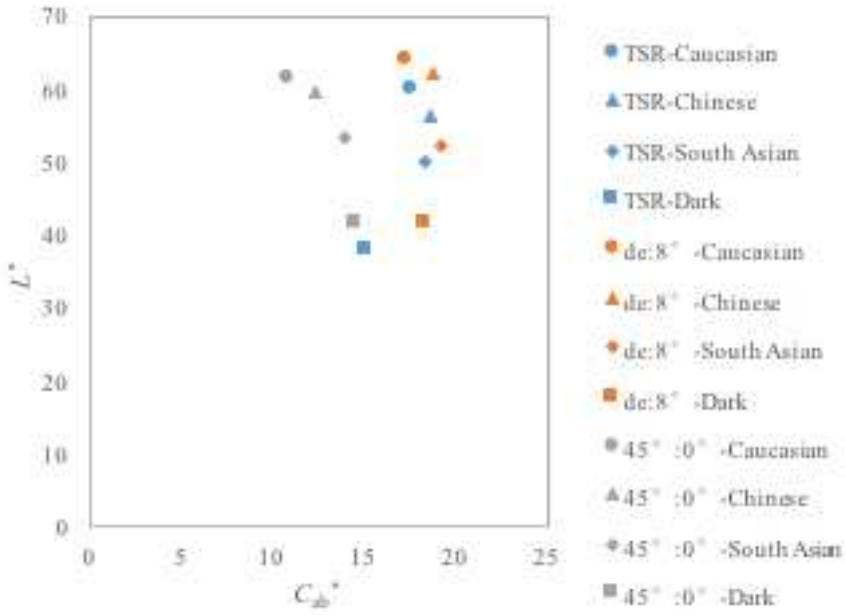


FIG. 13. Mean data of the four skin groups for the three instruments (The data are plotted using same colour representing the same measurement and same shape representing same skin group).

It can be seen from the above results that regardless which instrument used, the results do have systematic colour shift, according to gendar, locations, skin groups. Typical applications include to perform inter-instrument modelling between the measurement results from different instruments across different remote locations. The skin database obtained can also be used to characterize digital cameras to capture images in terms of colorimetric data for a particular instrument.

4. CONCLUSIONS

This paper has considered the measurement of the colour of human skin. Measurements from three different instruments were included in the experiment to reveal the characteristics of human skin colour: a de:8^o spectrophotometer, a 45^o:0^o spectrophotometer and a tele-spectroradiometer. Forty-seven subjects in total (17 females and 30 males) were recruited in this experiment, and they were divided into four skin groups: Chinese, Caucasian, South-Asian and Dark respectively. For each subject eight body locations, forehead, right cheek, left cheek, back of hand, back of fist, palm, ventral (inner) forearm and dorsal (outer) forearm, were measured. The results showed that different body locations had different skin colour. The skin colours of the face and limb had different hue angles with the hue angle of the face lower than that of the limb. There was also some difference between the two genders. Female skin colour had a lower chroma value, a higher lightness value and a higher hue angle: it could also be described as ‘whiter’ and ‘more

reddish'. Different ethnicities had different skin tones. The data revealed that the distribution of skin colour in an C_{ab}^*-L^* plane followed certain rules. The lightness and chroma values changed together rather than independently. Hence the concepts 'whiteness', 'blackness', 'depth' and 'vividness' were recommended as suitable scales to describe the appearance of skin colour, instead of the L^*, a^*, b^*values of the CIELAB 1976 system. Human skin colour related image processing may follow these scales to make it natural, which were proved to be closer to the human visual experience.

In this paper, measurements of skin colour using three different instruments were compared. The difference between the different instruments was marked. Thus, there is good reason to not allow inter-comparison of measurements made using different instruments, especially when they have different geometries and/or aperture sizes. The main reason for the deviation lay in the spectral reflectance as measured by the different instruments. Though at lower wavelengths, the spectral data for the de:8^o SP and the 45^o:0^o SP instruments agreed with each other, the reflectance varied for longer wavelengths. For purpose of accuracy, certain application should choose certain data from the database, since the variation of different measurements can be too large to be ignored.

This work is a preliminary study for the creation of a skin colour database. It contains the spectral skin colour data of different body locations and different measurements. This type of database can be further used for estimating the principle component analysis to compare different types of instruments, to work out correction models to correlate between different instruments, to estimate the melanin and haemoglobin pigments, to verify or create the skin tone charts.

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