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Characterising the variations in ethnic skin colours: a new calibrated data base for human skin

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Background: Accurate skin colour measurements are important for numerous medical applications including the diagnosis and treatment of cutaneous disorders and the provision of maxillofacial soft tissue prostheses.

Methods: In this study, we obtained accurate skin colour measurements from four different ethnic groups (Caucasian, Chinese, Kurdish, Thai) and at four different body locations (Forehead, cheek, inner arm, back of hand) with a view of establishing a new skin colour database for medical and cosmetic applications. Skin colours are measured using a spectrophotometer and converted to a device-independent standard colour appearance space (CIELAB) where skin colour is expressed as values along the three dimensions: Lightness L^*, Redness a^* and Yellowness b^*. Skin colour differences and variation are then evaluated as a function of ethnicity and body location.

Results: We report three main results: (1) When plotted in a standard colour appearance space (CIELAB), skin colour distributions for the four ethnic groups overlap significantly, although there are systematic mean differences. Between ethnicities, the most significant skin colour differences occur along the yellowness dimension, with Thai skin exhibiting the highest yellowness (b*) value and Caucasian skin the lowest value. Facial redness (a*) is invariant across the four ethnic groups. (2) Between different body locations, there are significant variations in redness (a*), with the forehead showing the highest redness value and the inner arm the lowest. (3) The colour gamut is smallest in the Chinese sample and largest in the Caucasian sample, with the Chinese gamut lying entirely the Caucasian gamut. Similarly, the largest variability in skin tones is found in the Caucasian group, and the smallest in the Chinese group.

Conclusion: Broadly speaking, skin colour variation can be explained by two main factors: individual differences in lightness and yellowness are mostly due to ethnicity, whereas differences in redness are primarily due to different body locations. Variations in lightness are more idiosyncratic probably reflecting the large influence of environmental factors such as exposure to sun.

Key words: skin appearance – skin colour – calibrated skin data base – ethnicity – body location – skin colour variation – colour space – skin variation – skin colour differences

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INTEREST IN the colour of human skin has been greatly stimulated by the increased need to understand its properties for a wide range of multidisciplinary applications, including skin colour measurement for the diagnosis of cutaneous disease (1), skin colour segmentation for face detection and recognition (2), skin colour reproduction for graphic arts (3) and skin colour matching for body and maxillofacial soft tissue prostheses (4). For these applications, a comprehensive knowledge of the range of skin shades of a representative sample of individuals, an understanding of how skin colour varies across different body locations and how people perceive these differences in a wide range of viewing conditions, is of vital importance.

CIE Colorimetry (5) provides a tool to objectively measure skin colour. However, skin colour is a non-flat and non-uniform surface, and skin measurements are significantly affected by various parameters, including the measurement distance, field size, pressure applied to the skin and body area. It is therefore difficult to compare skin measurements obtained under different conditions with different instrument parameters (6–9).

In this paper, we report commensurable skin measurements for different ethnicities at different geographical locations by (i) adhering to a strict measurement protocol and (ii) obtaining these measurements at different body areas. In addition to establishing the average differences in skin colour between different ethnic groups, we also calculate skin colour variability between and within the three different ethnic groups and body areas, and precise skin colour boundaries.

Materials and Methods

Samples and protocol

Skin colour measurements are obtained from a Caucasian, Chinese, Kurdish and Thai sample of individuals, in the UK, China, Iraq and Thailand respectively. Caucasian skin measurements were acquired at the University of Sheffield, Manchester Metropolitan University and University of Liverpool in the United Kingdom. Chinese measurements were obtained at the Beijing Institute of Technology, Minzu University of China and Beijing Institute of Graphic Communication in China; all measurements for the Kurdish group were taken at the University of Sulaimani in Iraq. The Thai samples are undertaken at Chulalongkorn University in Thailand. Crucially, all measurements adhered to the same protocol. Ethical approval was obtained from the University of Sheffield Research and the University of Liverpool and ratified by the other host institutions.

A Minolta CM-2600d spectrophotometer is used for skin colour measurements of Caucasian, Chinese and Kurdish groups, and an X-Rite SP62 spectrophotometer for the Thai group. Both instruments have the same technical specifications, with a viewing geometry of d/8 (diffuse illumination/8-degree viewing). The measurements are taken with the specular component included and presented in CIE XYZ tristimulus values assuming a 2° standard observer (5). The illuminant is set to the CIE standard D65 to simulate skin colour in daylight conditions. The aperture size of the Minolta CM-2600d was set to 3 mm, and the X-Rite SP62 to 4 mm. The reliability of the Monolta CM-2600d and the X-Rite SP62 is within 0.04 ΔE*ab and 0.05 ΔE*ab respectively. Furthermore, the inter-instrument agreement is within 0.20 DE*ab.

Measurements are obtained at four different body areas: forehead, cheek, back of hand and inner forearm. For each participant, age, gender and ethnicity are recorded.

Skin colour appearance

CIELAB uniform colour space is a device-independent standard colour space used to objectively specify the visual appearance properties of surfaces. In CIELAB colour space, a stimulus is described by three attributes: L^* represents lightness, a^* represents the value along the red-green dimension, and b^* indicates the value along the yellow-blue dimension. In addition, chroma (C^*) is defined by Eq. 1; chroma is loosely related to saturation, i.e. variations from pale colours to saturated colours.

$$C^* = \sqrt{a^{*2} + b^{*2}} \tag{1}$$

All measurements will be represented in terms of these three attributes – L^*, a^* and b^*. Average skin colours as a function of ethnicity were obtained by calculating the means for all participants along these three dimensions.

Measures of skin colour variation

Skin colour variation

Skin colour variation indicates the extent to which the skin colour of an individual subject aligns with the average skin colour from a particular sample. To evaluate skin colour variation for each of the ethnic groups, the grand mean for each ethnic group is established by averaging each of the three attributes (L^*_M, a^*_M, b^*_M) across the entire sample; then for each of the n individuals the deviation from the group mean is calculated for all three attributes. The square root of the sum of the squared differences in lightness (ΔL^*_i), redness (Δa^*_i) and yellowness (Δb^*_i) is then averaged across all subjects to obtain an overall perceptual distance ΔE^*_{ab}. This is expressed in Eq. 2.

$$\Delta E^*_{ab} = \sum_{i=1}^{n} \sqrt{(L^*_i - L^*_M)^2 + (a^*_i - a^*_M)^2 + (b^*_i - b^*_M)^2} \quad (2)$$

Colour variations within a particular body area are quantified similarly. In this case, the grand mean for each of the three attributes (L^*, a^*, b^*) is calculated for a particular body area and then Eq. 2 was used to derive the overall perceptual skin variation.

Skin colour boundaries
The gamut spanned by human skin is shown by plotting all skin colours in the a^*-b^* chromaticity diagram. To represent the relationship between lightness and chroma, skin colours are also plotted in the C^*-L^* diagram. Each point in the scatter plots represents one skin colour for a specific subject and body area. From the chromaticity coordinates, the skin colour gamut (boundary) and the area within the gamut are derived using *convexhull* (Matlab®), which is based on the convex hull algorithm (10); the skin colour boundary is the smallest polygon that encompasses all skin colours. To obtain information about the gamut in three-dimensional colour space, the volume in $L^*a^*b^*$ space is also derived; the latter measure includes variations in lightness, whereas the area only reflects variation in chromaticity.

Results

Skin colour measurements were obtained from 960 individuals from four different ethnic groups (Table 1). Their age ranged from 18 to 75, however, the majority of the individuals were college students aged between 20–40 years.

We report measurements for four body areas (forehead, cheek, back of hand, inner arm) for each of the 960 individuals, resulting in a total of 3860 data points. Measurements were obtained in CIE XYZ coordinates and then converted to CIELAB space to extract the three perceptual attributes L^*, a^* and b^*: L^* corresponds to LIGHTNESS, a^* indicates the dimension from green to red ('REDNESS') and b^* indicates the dimension from blue to yellow ('YELOWNESS').

TABLE 1. Number and gender of individuals in each ethnic group

	Caucasian	Chinese	Kurdish	Thai
No. of subjects	187	202	145	426
No. of female	102	65	74	283
No. of male	85	137	72	143

Skin colours shifts
Scatter plots of all skin measurements irrespective of body area are shown in Fig. 1; (a) in the chromatic a^*b^* plane and (b) in the chroma-lightness plane, in order from left to right: Caucasian, Chinese, Kurdish and Thai. Mean chromaticities are denoted by the large diamond; numerical values are provided in the last column of Table 2. There is a large overlap in skin chromaticties, chroma and lightness values between the four ethnicities. Large lightness values are associated with small chroma values and vice versa; this negative association is most prominent in the Chinese and Thai sample.

While there is a large overlap in lightness and chromaticity between the four ethnic groups, there are systematic mean differences (cf Table 2). The mean lightness value is highest in the Caucasian group (L^* = 60.5) and smallest in the Kurdish sample (L^* = 58). There is little variation in redness amongst the four ethnic groups, values range from 9.1 (Caucasian), 9.5 (Kurdish), 9.7 (Thai) to 9.9 (Chinese). Larger ethnic differences occur with Yellowness, with the smallest value in the Caucasian group (14.6) and the highest value in the Thai group (17.9). The mean differences are summarised in Fig. 2. In Fig. 2a, chromaticities are plotted in the chromatic a^*b^* plane for all four ethnic groups, averaged over all body areas. Axes were scaled to equal length to visualise the large ethnic differences along the yellowness dimension and the relatively small ethnic differences in redness. Similarly, in Fig. 2b, skin colours are averaged across ethnicities to demonstrate the large differences in redness between different body areas and the relatively small differences in yellowness.

To evaluate how ethnicity and body location affects skin colour, a two-factorial analysis of variance is performed (factor 1: ethnicity; factor 2: body location). There was a significant main effect for ethnicity ($P < 0.01$) and for body location ($P < 0.01$) in all three appearance attributes (lightness, redness and yellowness).

Figure 3 shows the skin measurements as a function of body area, for each of the four

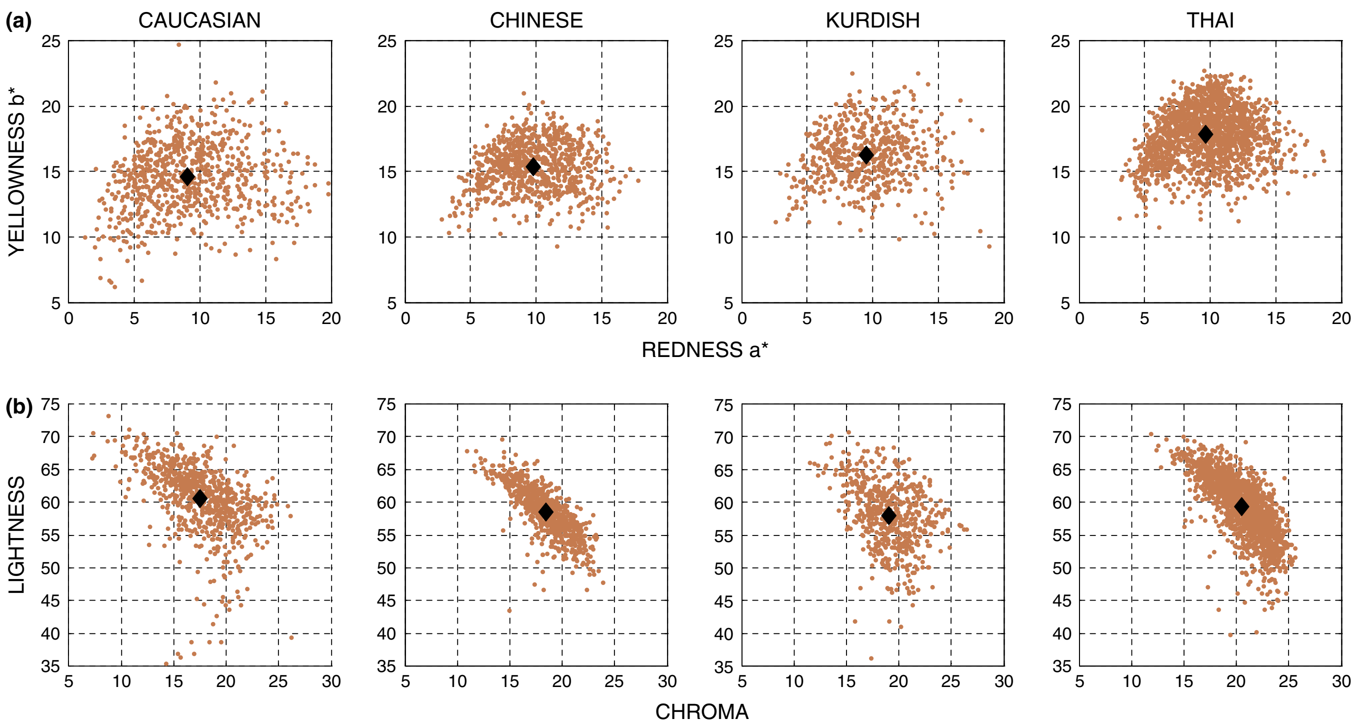

*Fig. 1. Scatter plots in (a) the chromatic a*b* plane and in the (b) chroma-lightness plane for all four ethnic groups, in order from left to right: Caucasian, Chinese, Kurdish, Thai. Mean chromaticities are denoted by the diamond symbol (♦).*

TABLE 2. Skin colour means (standard deviation) for all body areas and ethnicities

	Forehead	Cheek	Back of hand	Inner arm	All
Caucasians					
*L**	59.2 (5.1)	59.6 (5.5)	60.1 (5.5)	63.0 (5.5)	60.5 (5.6)
*a**	11.6 (2.8)	11.8 (3.1)	7.4 (1.9)	5.6 (1.9)	9.0 (3.6)
*b**	15.1 (2.3)	14.6 (2.6)	14.7 (2.4)	14.0 (2.9)	14.6 (2.6)
Chinese					
*L**	56.4 (3.2)	58.9 (3.1)	57.9 (3.5)	60.9 (3.4)	58.5 (3.7)
*a**	11.7 (2.1)	11.4 (2.1)	9.3 (1.9)	7.0 (1.7)	9.8 (2.7)
*b**	16.3 (1.4)	14.2 (1.5)	16.1 (1.6)	15.0 (1.8)	15.4 (1.8)
Kurdish					
*L**	56.1 (4.5)	58.0 (4.4)	57.3 (5.5)	60.6 (4.8)	58.0 (5.1)
*a**	11.3 (2.1)	11.7 (2.3)	8.6 (1.9)	6.5 (1.6)	9.5 (2.9)
*b**	16.4 (2.2)	15.8 (2.1)	16.5 (1.9)	16.4 (2.3)	16.2 (2.2)
Thai					
*L**	56.8 (4.1)	60.7 (4.0)	57.6 (4.5)	61.9 (3.7)	59.3 (4.6)
*a**	11.6 (2.2)	10.5 (2.3)	9.4 (1.7)	7.1 (1.7)	9.7 (2.6)
*b**	17.7 (1.8)	17.2 (2.1)	19.0 (1.8)	17.4 (2.0)	17.9 (2.1)

ethnic groups. (a) Lightness values are highest at the inner arm, and lowest at the forehead. Five of the 6 pairwise comparisons are significant ($P < 0.01$) with the lightness differences the most robust across ethnicities. Figure 3b shows the mean Redness values: high values for Redness are located in the facial region ($a^* > 10$), and low values are located in the arm and hand regions ($a^* < 10$). The mean differences in redness between the different locations are much larger than the differences between the four ethnicities. The distribution pattern across body locations is very similar for all four ethnicities, with small inter-ethnic differences present. In contrast, a different pattern emerges for Yellowness (b^*; Fig. 3c): major differences exist between the ethnic groups, rather than between the different body locations. The patterns are idiosyncratic for each ethnicity; on average, yellowness values (b^*) is largest in the Thai group ($b^* = 17.9$) and smallest in the Caucasian group ($b^* = 14.6$). The main finding is that redness values are fairly constant across ethnicity, whereas large mean differences arise in lightness and yellowness as a function of ethinicity.

Figure 3 only shows the main effects either due to body location without visualising the interactions (body location × ethnicity). The significance of all pairwise comparisons between ethnicities for each of the four body locations is shown in Table A1 (Appendix). For redness, only four of the 24 differences are significant, and is consistent with the previously mentioned small effect of ethnicity for redness (cf. Fig. 3). For yellowness, a different pattern emerges and 15 of the 24 comparisons yield significant results. For lightness, 12 of 24 comparisons are significant.

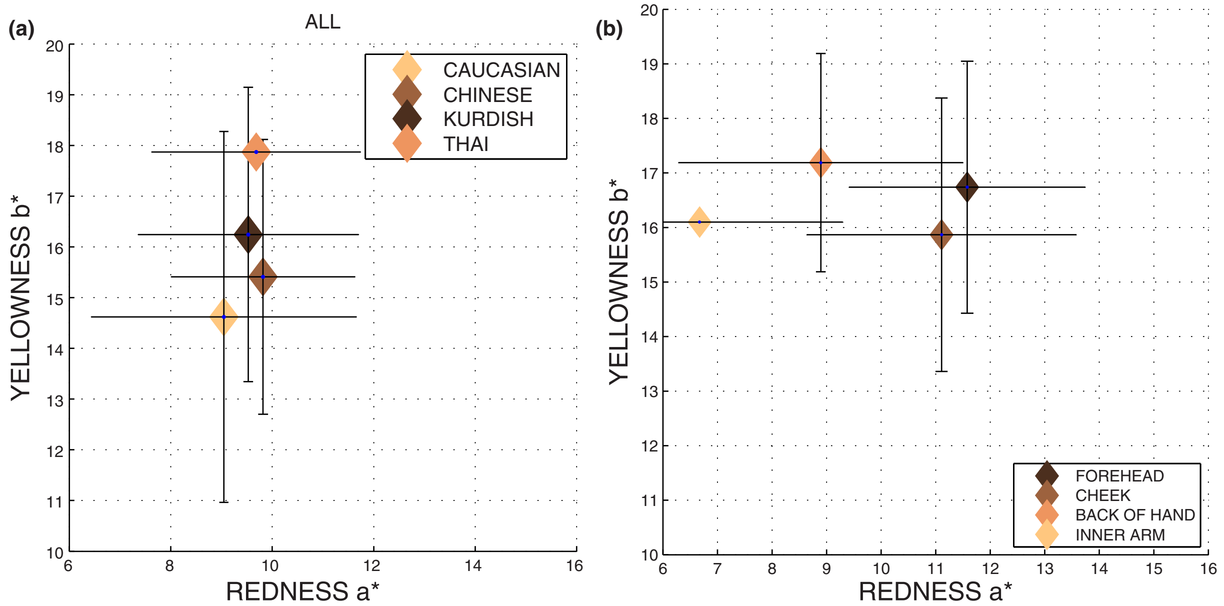

*Fig. 2. (a) Mean chromaticities are plotted in the chromatic a*b* plane for all four ethnic groups (averaged over all body areas). Error bars denote 2 standard deviations. (b) Mean chromaticities are plotted for each of the four body areas (averaged over all ethnicities). Axes are scaled to equal length for comparison.*

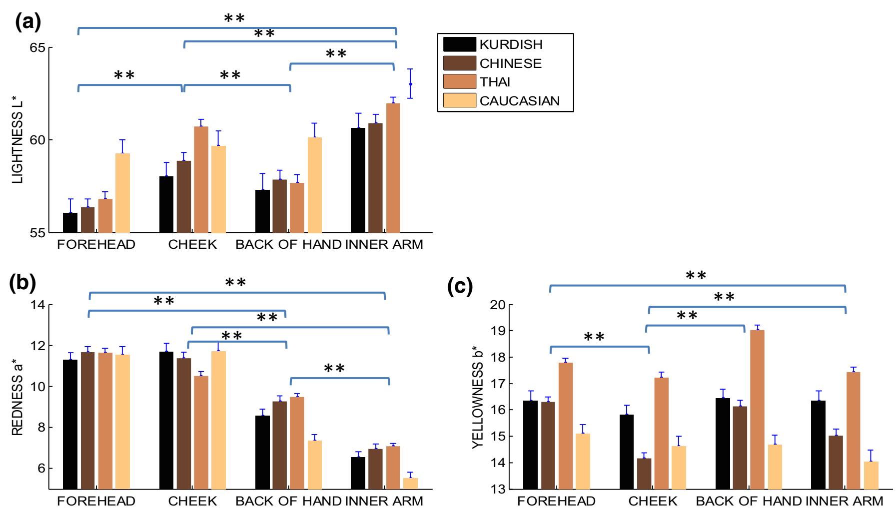

*Fig. 3. Effect of ethnicity and body location on skin colour. Values for Lightness (a), Redness (b) and Yellowness (c) are plotted as a function of location (forehead, cheek, back of hand and inner arm) for each of the four ethnicities. (a) Lightness (b) Redness (c) Yellowness. Note that the differences between different body locations are usually much larger than the differences due to ethnicity. **Indicates significant differences.*

Skin colour boundaries

The skin colour boundary, i.e. the smallest polygon that encompasses all skin colours is calculated for both the a^*b^* chromaticity plane (Fig. 4a) and the lightness-chroma plane (Fig. 4b); the gamut size is expressed as the area within each colour boundary. In the a^*b^* chromaticity plane, the area is smallest for the Chinese group (dashed line in Fig. 4a; area = 116.7) and largest for the Caucasian group (solid line; area = 227), by almost a factor of 2. The range of Redness in caucasian skin is large, ranging from 2 to approximately 20, Yellowness ranges from 6 to approximately 25; in comparison, Redness in the Chinese sample ranges from about 3 to 18, and yellowness from approximately 9 to 21. Gamuts for the Kurdish and the Thai sample demonstrate high levels of overlap with intermediate areas of 164 and 130 respectively.

Since the gamut in the chromatic a^*b^* plane does not take into account variations in

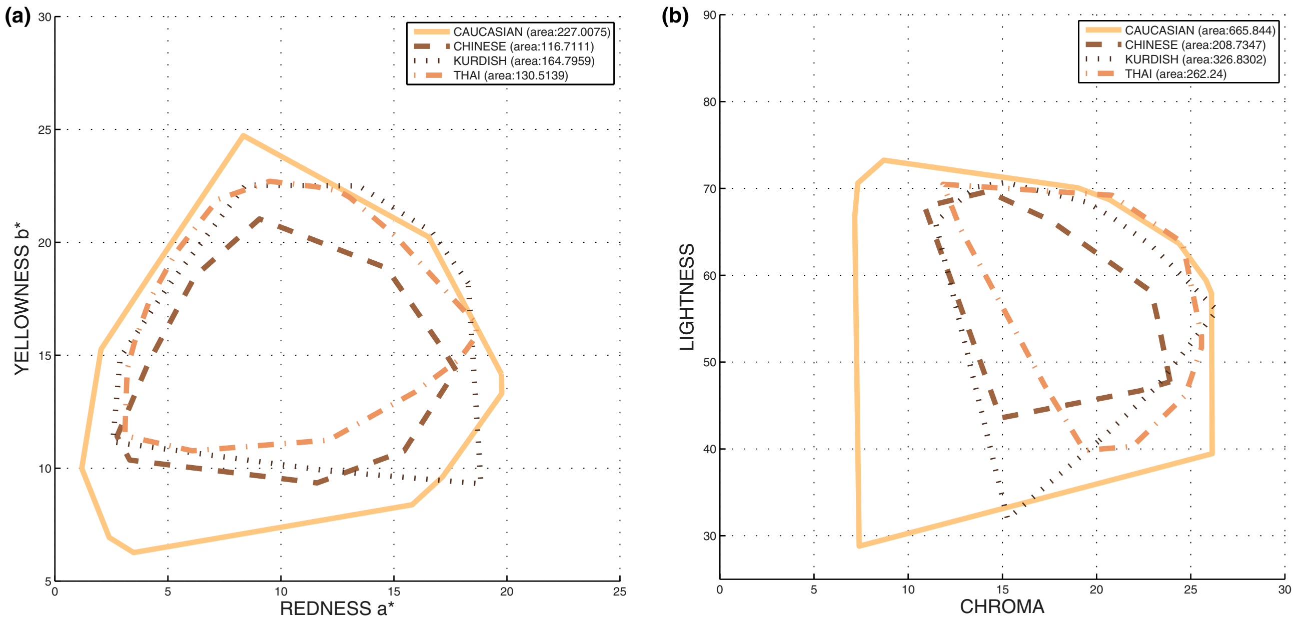

*Fig. 4. Skin colour gamuts in (a) the chromatic a*b* plane and in the (b) chroma-lightness plane. Caucasian skin (solid lines) occupies the largest gamut, and chinese skin the smallest gamut (dashed lines) in both representations.*

lightness, the gamut is also determined in the *L*-C** plane (Fig. 4b). The same pattern emerges, with the Chinese sample occupying the smallest area (area = 208) and the Caucasian sample the largest area (area = 665) hence differing by a factor of 3, which implies a relatively large skin lightness range within the Caucasian group. Lightness in the Caucasian sample ranges from approximately 29 to 73 *L** units, whereas in the Chinese sample the lowest lightness is level is 43 *L** units. The chroma range is significantly reduced in the Chinese, Kurdish and Thai sample when compared to the Caucasian group. In the former groups, high lightness values are associated with low chroma values, and vice versa.

To quantify the colour gamuts for different body locations, area (in the *a*b** plane) and volume (in the *L*a*b** 3D space) are calculated separately for each body location and each ethnicity. Figure 5a shows that the largest gamut area occurs for the cheek and the smallest area for the inner arm; the same pattern is observed for the volume (Fig. 5b). For both measures (area and volume), there is significant variation across body locations, except for the Chinese sample where the gamut is equally small for all locations. Relative differences between the Caucasian and the Chinese samples are larger for volume, compared to area, suggesting that the luminance variation is larger in the Caucasian group.

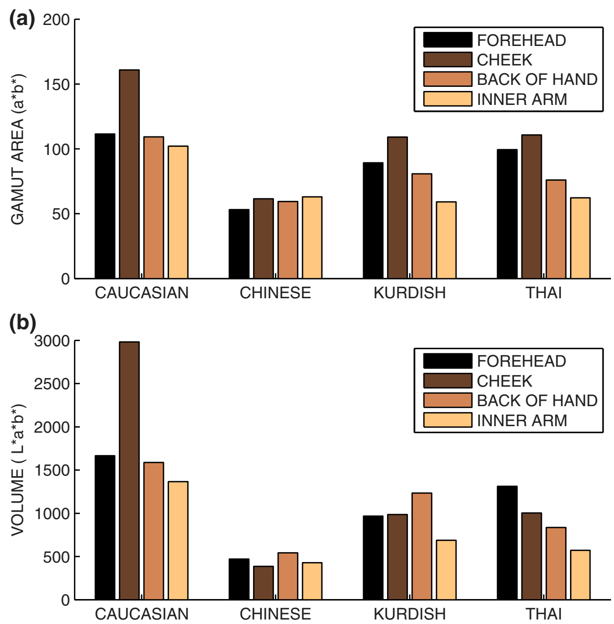

*Fig. 5. (a) Values for gamut areas (in the a*b*) and (b) volumes (in L*a*b*) are shown for the four body locations (forehead, cheek, back of hand and inner arm) for each of the four ethnicities.*

Variation in skin colour

It is important to note that gamut area and volume reflect the entire range of skin colours measured and are therefore sensitive to extreme values, in contrast to mean deviation measures (Equation 2). Mean skin colour variation takes into account variations along all three dimensions (*L**, *a**, *b**) and is calculated for each

TABLE 3. Mean skin colour variation for three ethnic groups (mean ± SD)

ΔE^*_{ab}	Forehead	Cheek	Back hand	Inner arm	All
Caucasians	5.4 ± 3.3	5.6 ± 4.0	5.6 ± 5.4	5.3 ± 3.8	6.2 ± 3.5
Chinese	3.6 ± 1.9	3.6 ± 1.8	3.7 ± 2.2	3.5 ± 2.3	4.3 ± 2.3
Kurdish	4.8 ± 2.5	4.9 ± 2.3	5.1 ± 3.4	4.9 ± 2.8	5.5 ± 3.0
Thai	4.3 ± 2.5	4.4 ± 2.4	4.5 ± 2.7	3.8 ± 2.4	5.0 ± 2.6

ethnic group and each body location. The overall mean variation for each group, irrespective of the body area is shown in Table 3, in the last column ('ALL'). Mean variation is largest in the Caucasian group ($\Delta E = 6.2$) and smallest in the Chinese group ($\Delta E = 4.3$); variation in the Thai and the Kurdish group is 5.0 and 5.5 ΔE units respectively. Mean variation calculations demonstrates the same pattern as the skin colour boundaries, with the smallest variation seen in the Chinese sample and the largest variation seen in the Caucasian sample. Mean variations are smallest for the inner arm and largest for the back of the hand (Table 3).

Discussion

Human skin colour is controlled by both genetic and environmental influences. Skin pigmentation has evolved primarily to regulate the amount of ultraviolet radiation penetrating the skin (11). The single most important pigment affecting skin colour is melanin which is the main determinant of skin colour in darker-skinned individuals. For lighter-skinned individuals, skin colour is partly determined by the bluish-white connective tissue under the dermis and by the haemoglobin circulating in the veins and capillaries of the dermis. Broadly speaking, melanin controls the lightness and yellowness of the skin, whereas haemoglobin is related to skin redness. To a smaller extent, skin colour can be modulated by diet (12).

A reliable data base of the variety of human skin shades is of vital importance for numerous medical applications including the diagnosis of cutaneous disease and maxillofacial soft tissue prostheses. The purpose of this study was to quantify the variation in skin tones within and across individuals. To that end, the skin colour of four different body areas in almost 1000 individuals from different ethnicities, across four geographical locations, is measured. To ensure that these measurements from the different laboratories were commensurate, a strict measurement protocol is used to sample all values.

Ethnic skin appearance differences have been documented in previous studies. De Rigal et al. (6, 13) measured the skin colour in four different ethnic groups (African-American, Mexican, Chinese and Caucasian) at two facial locations. Our results are in broad agreement with findings of de Rigal et al, apart from facial skin redness. De Rigal et al. report a larger redness value (of about 10% in terms of a^*) in the Caucasian compared to the Chinese group whereas in our sample, facial redness differences are within measurement error (cf Table 2). These differences could be due to environmental factors; in the de Rigal et al. study, an inclusion criterion was a 2-year residency in USA, whereas our participants were measured in their native countries. Furthermore, de Rigal et al. measured only female skin which could also account for these small differences in redness (14), in addition to the effects of smoking and diet. Yun et al. (7) measured similar body locations to our study, i.e. forehead, cheek, back hand and arm, in a Korean sample; they show that skin redness depends strongly on body location with the forehead showing the highest redness values and the inner arm the lowest which is consistent with our results (Fig. 3b) and can therefore be generalised to other ethnicities. While virtually all previous studies have either studied a single ethnic group or different ethnic groups residing in their non-native surroundings, our data base provides a more veridical reflection of skin differences and variability in skin colour since it eliminates the well-documented environmental factors influencing skin appearance (e.g. sun exposure, diet).

One of our most interesting findings was that variation in skin colour across individuals can be – to a first approximation – explained by two simple factors: differences in yellowness (a^*; Figs 2 and 3c) are mostly due to ethnicity: the Thai sample has the highest a^* value (~18) and the Caucasian sample the lowest value for a^* (~14). Differences in redness (b^*) on the other hand were primarily due to different body locations (Figs 2 and 3b) with the inner arm having the smallest redness value (~7 b^* units) and the forehead the highest value (~12 b^* units). Variations in lightness (L^*) are more idiosyncratic and depend on both ethnicity and body area (Fig. 3a): Caucasians are on average lighter-skinned than any of the other groups, but for all ethnic groups, facial areas tend to be darker than the arm areas. This may be attributed to the fact that this area is subject to the significant environmental influence.

Second, in the a^*b^* chromaticity plane, the skin gamut of the Chinese sample was completely contained within the Caucasian gamut (Fig. 4) and the Caucasian gamut was approximately twice as large as the Chinese skin gamut. When lightness was included in these calculations by calculating the volume in $L^*a^*b^*$ space for each ethnicity (Fig. 5b), this ratio was even larger, and the volume occupied by the Chinese skin sample was approximately 1/4 of that occupied by the Caucasian sample, suggesting that lightness variation is larger in the Caucasian sample compared to the other ethnic groups. Similarly, skin colour variation within each of the ethnic groups was smallest in the Chinese sample, for all four body areas (Table 3) and largest in the Caucasian group, hence corroborating the finding that the gamut (in $L^*a^*b^*$ space) is largest in the Caucasian sample compared to the other groups. This large variation in skin colour in the Caucasian group could be due to environmental factors (e.g. sun exposure) or, alternatively, to the fact that the Caucasian group was less homogenous in terms of their genetic make-up compared to the other groups.

Our extensive data base and analysis of colour shifts and colour variation for different ethnic groups and body areas provides useful guidance for medical applications. For applications requiring a specific, consistent and accurate skin colour representation, the mean colour differences in different ethnicities and body areas need be taken into account. These applications include skin disease diagnosis, skin imaging and identification, and medical skin manufacturing processes. Skin colour schemes developed, for example, for a Caucasian sample, will be unsuitable for a large proportion of a Chinese sample. Differences in the mean skin variation provides useful information on the accuracy that needs to be achieved for a particular application and could be used to derive a skin tolerance metric based on the variation occurring in each ethnic group.

Acknowledgements

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Appendix

*Table A1. Statistical significance of skin colour differences between the four ethnic groups (** indicates P < 0.01)*

	Chinese	Kurdish	Thai
LIGHTNESS *L**			
Forehead			
Caucasian	**	**	**
Chinese	–	n.s	n.s
Kurdish		–	n.s
Cheek			
Caucasian	n.s	**	n.s
Chinese	–	n.s	**
Kurdish		–	**
Back of Hand			
Caucasian	**	**	**
Chinese	–	n.s	n.s
Kurdish		–	n.s
Inner Arm			
Caucasian	**	**	n.s
Chinese	–	n.s	n.s
Kurdish		–	**
REDNESS *a**			
Forehead			
Caucasian	n.s	n.s	n.s
Chinese	–	n.s	n.s
Kurdish		–	n.s
Cheek			
Caucasian	n.s	n.s	**
Chinese	–	n.s	n.s
Kurdish		–	n.s
Back of Hand			
Caucasian	**	n.s	**
Chinese	–	n.s	n.s
Kurdish		–	n.s
Inner Arm			
Caucasian	n.s	**	n.s
Chinese	–	n.s	n.s
Kurdish		–	n.s
YELLOWNESS *b**			
Forehead			
Caucasian	n.s	n.s	**
Chinese	–	n.s	**
Kurdish		–	**
Cheek			
Caucasian	n.s	n.s	**
Chinese	–	**	**
Kurdish		–	**
Back of Hand			
Caucasian	**	**	**
Chinese	–	n.s	**
Kurdish		–	**
Inner Arm			
Caucasian	n.s	**	**
Chinese	–	n.s	**
Kurdish		–	n.s

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