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Colour differences in Caucasian and Oriental women face illuminated by LED white sources

M. Melgosa*,1, N. Richard[2], C. Fernández-Maloigne[2], K. Xiao[3], H. de Clermont-Gallerande[4], S. Jost-Boissard[5], K. Okajima[6]

[1]*Department of Optics, University of Granada, Granada, Spain,

[2]XLIM Laboratory, UMR 7252 CNRS, University of Poitiers, Poitiers, France,

[3]School of Design, University of Leeds, Leeds, United Kingdom,

[4]Chanel Parfums Beauté, Pantin, France, ¶LGCB Laboratory, ENTPE,

[5]University of Lyon, Vaulx-en-Velin, France,

[6]Faculty of Environment and Information Sciences, Yokohama National University, Japan

Abstract.

OBJECTIVE. To provide an approach to facial contrast, analysing CIELAB colour differences ($\Delta E^*_{ab,10}$) and its components in women's faces from two different ethnic groups, illuminated by modern white light-emitting diodes (LEDs) or traditional illuminants recommended by the International Commission on Illumination (CIE).

METHODS. We performed spectrophotometric measurements of spectral reflectance factors on forehead and cheek of 87 young healthy women (50 Caucasians and 37 Orientals), plus 5 commercial red lipsticks. We considered a set of 10 white LED illuminants, representative of technologies currently available on the market, plus 8 main illuminants currently recommended by the CIE, representative of conventional incandescent, daylight, and fluorescent light sources. Under each of these 18 illuminants we analysed the magnitude and components of $\Delta E^*_{ab,10}$ between Caucasian and Oriental women (considering cheek and forehead), as well as for cheek-forehead and cheek-lipsticks in Caucasian and Oriental women. Colour-inconstancy indices for cheek, forehead, and lipsticks were computed, assuming D65 and A as reference illuminants.

RESULTS. $\Delta E^*_{ab,10}$ between forehead and cheek were quantitatively and qualitatively different in Orientals and Caucasians, but discrepancies with respect to average values for 18 illuminants were small (1.5% and 5.0% for Orientals and Caucasians, respectively). $\Delta E^*_{ab,10}$ between Caucasians and Orientals were also quantitatively and qualitatively different both for forehead and cheek, and discrepancies with respect to average values were again small (1.0% and 3.9% for forehead and cheek, respectively). $\Delta E^*_{ab,10}$ between lipsticks and cheek were at least 2 times higher than those between forehead and cheek. Regarding $\Delta E^*_{ab,10}$ between lipsticks and cheeks, discrepancies with respect to average values were in the range 1.5% - 12.3%, although higher values of up to 54.2% were found for a white RGB LED. This white RGB LED provided the highest average colour-inconstancy indices: 17.1 and 11.5 CIELAB units, under reference illuminants D65 and A, respectively.

CONCLUSION. Colour contrasts in women's faces under CIE standard illuminants for outdoor and indoor conditions may be strongly altered by using specific white LEDs. More research needs to be done on the impact of spectral power distribution of light sources with high colour rendering indices on visual colour appearance of cosmetic products.

Introduction

The colour of a given object can be considered the result of the combination of three factors: The spectral power distribution (SPD) of the light source illuminating the object, the optical properties of materials the object is made of (represented by the so-called spectral reflectance factor), and the spectral sensitivity of the human visual system (represented by what are called colour-matching functions) [1]. These three factors lead to the primary numerical colour specification proposed by the International Commission on Illumination (CIE): the so-called X, Y, Z tristimulus values [2], which provide an objective (instrumental) method for colour measurement of any object. From tristimulus values, using additional information (e.g. tristimulus values of a reference white), it is possible to achieve improved colour specifications (e.g. CIELAB colour coordinates), establishing numerical correlates of the perceptual colour attributes of a given object. For example, CIELAB lightness (L^*), chroma (C^*_{ab}) and hue angle (h_{ab}) are correlates of the three main colour attributes we can distinguish in objects colours, as illustrated by the chips in colour atlases such as the Munsell Book of Color [3]. Ultimately, the main goal of colorimetry is to specify colour, allowing objective instrumental colour measurements in agreement with subjective human colour perception. The current study deals with objective colour measurements, considering the influence of two of the three previously mentioned factors:

1) A relevant set of modern illuminants (white light-emitting diodes, LED). New solid-state lighting products are rapidly gaining the lighting market. Especially, white LED sources are replacing banned incandescent lamps and other lighting technologies in most general lighting applications. However, the SPDs of white LEDs are quite different from those of conventional light sources, raising questions concerning possible risks of deterioration (or improvement) in contrasts or colour appearance of specific objects such as, for example, human skin. It is necessary to compare colour rendition properties of modern white LEDs with that of lamp types that they are intended to replace [4].

2) A set of objects of particular interest to the cosmetic industry (skin in two regions of women's faces and some representative lipsticks). Skin colour is one of the most important factors influencing the acceptability of a light source and is often used, consciously or not, as a criterion to evaluate the colour quality of light sources [5]. CIE TC 1-92 is currently working to provide a skin-colour database, investigating uncertainty in skin-colour measurements and some influential factors in skin colour, such as ethnicity, gender, age, and body location [6, 7]. On the other hand, one of the most important components of cosmetic use is the application of lipsticks. Lips of the female face are associated with femininity and attractiveness [8], and red shades are commonly used for lipsticks to change the natural pinkish colour of lips. In this work, we also consider a representative set of lipsticks in relation to the overall appearance of women's faces under different light sources.

"Facial contrast", defined as "the luminance and colour differences between the facial features and the skin surrounding those features" [9], has been considered important because of its association with attractiveness, health, and perceived age, mainly for women's faces [9-13]. Some papers on facial contrast have focused on only one dimension of colour, considering lightness [14] or luminance contrast [15]. However, recent works have demonstrated the importance of considering colour contrast (i.e. 3 dimensions) between the features and the surrounding skin for sex classification and related face-perception tasks [16, 17], and the use of an adapted version of Michelson contrast for CIELAB L^*, a^*, b^* coordinates has been proposed [9]. The present study proposes another approach to facial contrast, by analysing the magnitude of CIELAB colour differences between specific regions of women's faces (forehead, cheek and lips), as well as the three components (lightness, chroma, and hue) of such colour differences [2], under traditional CIE illuminants and a representative set of modern white LEDs. In addition, colour-inconstancy indices [18] are also used to measure the magnitude of changes in skin-colour regions and lipsticks, when they are observed under different white LEDs, daylight, and fluorescent illuminants, assuming as reference the colours of these objects under the two main CIE illuminants, D65 and A, considered by CIE as the main representatives of outdoor and indoor lighting, respectively.

Our approach to facial contrast in women's faces is based on objective instrumental colour measurements, in such a way that other useful subjective measurements of facial contrast (e.g. measurements based on preferences), lie beyond the scope of the current paper. While some researchers have tried to identify critical spectral components for the preferable appearance of the skin in women's faces [19], or preferable LED lamps for the appearance of skin in daily lives [4, 20], the need persists for objective colour measurements assessing colour shifts in faces under different illuminants. In agreement with our current purposes, a recent work concluded that it would be valuable to investigate skin-colour shift for more than one illumination, the magnitude of colour change with illumination, and the differences in skin-colour distribution due to illumination, using the most recent colour-appearance models [21].

In summary, the main goal of the present work is to provide a simple approach to facial contrast, analysing CIELAB colour differences in women's faces from two different ethnic groups, and comparing the results found when they are illuminated by modern white LEDs and the main traditional illuminants recommended by the CIE. The structure of this paper is as follows: Section Materials and methods describes the selected set of 10 white LEDs to be compared with 8 CIE traditional illuminants, as well as the spectral reflectance factor measurements performed for the facial skin in 87 women wearing 5 commercial lipsticks. In addition, this section provides basic information on CIELAB colour space and associated colour-difference formula, and the concept of "colour-inconstancy index" (CII), which are relevant to measure colour shifts generated by a change of illuminant or light source. Section Results is divided in four different subsections, analysing the effects of change of illuminant in: Colour differences between skin in two regions of the face (forehead and cheek), both for Caucasian and for Oriental women's faces; colour differences between Caucasian and Oriental skin colour, considering only one region of the face (cheek or forehead); colour differences between cheeks and lipsticks for Caucasian and for Oriental women's faces; and CII values for lipsticks, and for forehead and cheek in Caucasian and Oriental women, assuming as the reference one of the two main CIE standard illuminants (D65 and A). Finally, Section Conclusions and future work summarizes the main findings and recommends directions for future work.

Materials and methods

From measurements of SPDs of 1298 white LED sources [22], it is likely that CIE will propose in the forthcoming edition of its main publication on colorimetry [23] a set of 10 white LED illuminants, as representatives of current typical white LED technologies, close to those shown in Figs. 1 and 2: 5 phosphor-converted blue LEDS (BLEDs) with correlated colour temperatures (CCTs) from approximately 2700 K to 6500 K, 1 hybrid LED mixing a phosphor-converted blue LED and a red LED, 2 RGB LEDS mixing red, green, and blue LEDs, and 2 two phosphor-converted violet LEDs (VLEDs) with very different CCTs. In addition to these 10 white LED illuminants, we will also consider 8 traditional illuminants already established by the CIE [2]: The CIE standard illuminants A and D65 (considered as main representatives of indoor and outdoor lighting, respectively), 3 daylight illuminants with different CCTs (D50, D55, and D75), and the 3 fluorescent illuminants (F2, F7, and F11), considered by CIE as priority when only a few typical fluorescent illuminants must be selected. Overall, we have used 18 illuminants (10 white LEDs plus 8 traditional illuminants already established by CIE), with their SPDs normalized to consistently achieve Y=100 for an ideal sample with a spectral reflectance factor equal to 1.0 at all visible wavelengths (reference white).

Figure 1. Representative SPDs of 5 phosphor-converted blue LEDS (BLEDs), with CCTs from approximately 2700 K to 6500 K [22].

Figure 2. Representative SPDs of 5 with LEDs using three different technologies (hybrid, RGB, and phosphor-converted violet) [22].

Spectrophotometric measurements of human skin have been carried at two different places of the face (forehead and cheek) for a set of 87 healthy young (20-35 years old) women from two different ethnic groups: 50 Caucasians and 37 Orientals [24]. Specifically, we employed a CM2700d (Konica Minolta) spectrophotometer with 8 mm aperture size and a plate to fit the aperture window with low pressure on subject's face. Individual spectrophotometric measurements were made in the morning, at room temperature (20-25 °C), at least 10 min after the subject arrived to the laboratory. From these measurements, we calculated the average spectral reflectance factors (range 400-700 nm, at intervals of 10 nm) for forehead and cheek of Caucasian and Oriental women, as shown in Fig. 3. In addition, using a CM-2600d (Konica Minolta) spectrophotometer we also measured spectral reflectance factors of 5 representative lipsticks, from the company Chanel, in this case not applied into any specific woman's face, nor measured on the lipsticks, trying to avoid inconsistent measurements related to their glossy and curved surfaces. Each lipstick was melted at 90 °C (these lipsticks contain a wax with a fusion temperature of 85 °C, and we wanted to avoid any residual solid crystal), and then it was spread as a film of 500 µm thickness on a flat white card (Leneta 6495), in order to perform 3 repeatable spectrophotometric measurements of the spectral reflectance factor of the material, which were finally averaged. In practical situations, women apply lipsticks at a temperature around 32 °C, and perhaps they use a lower thickness than

500 µm. Anyway, the relevant point for the current research is that we have accurately specified colours of all lipsticks employed (see next Figure 4 and Table 1), and such colours can be considered as realistic or representative of true colours in lips of women faces. For spectrophotometric measurements of lipsticks we used the same wavelength range and interval than for the spectroradiometric measurements of human skin, and the results found are shown in Fig. 4. These lipsticks have the commercial names of "Louise", "Coco", "Olga", "Gabrielle" and "Erik", although in the current article they will be designated as lipsticks #1 to #5, respectively. The INCI list corresponding to the lipsticks employed (Rouge Coco) is provided as "supporting information" to this article. While measurements in other regions of women's faces would be desirable, our current approach to facial contrast will be based only on average colours for forehead, cheek, and lipsticks. For example, measurements of iris colour [25], or the effect of make-up [19] may be relevant aspects to be examined in future works on facial contrast.

Figure 3. Measured average spectral reflectance factors for the skin of forehead and cheek in a set of 50 Caucasian and 37 Oriental healthy young women [24].

Figure 4. Measured spectral reflectance factors for five representative commercial lipsticks.

Using the standard procedure [1, 2], from spectral reflectance factors of the above-mentioned objects (Figs. 3 and 4), we computed CIELAB colour coordinates for each object, under each of the 18 illuminants considered, assuming the CIE 1964 standard colorimetric observer, recommended for visual fields subtending more than 4°. This standard procedure implies that, in a first step, we must compute the CIE tristimulus values of the samples (X_{10}, Y_{10}, Z_{10}), and then we can compute the corresponding CIELAB colour coordinates of the sample (L^*_{10}, a^*_{10}, b^*_{10}), assuming as reference white the illuminant employed. While Cartesian CIELAB colour coordinates L^*_{10}, a^*_{10}, b^*_{10} were computed first, we used the 3 polar CIELAB coordinates, lightness (L^*_{10}), chroma ($C^*_{ab,10}$), and hue-angle ($h_{ab,10}$), because they are related to the perceptual colour attributes of lightness (relative amount of light), chroma (intensity of colour) and hue (attribute leading to names such as red, pink, yellow, etc.), respectively. CIELAB colour space can also be used to compute the total colour difference between two objects (e.g. forehead and cheek), assuming that both objects are under the same viewing conditions, using the so-called CIELAB colour-difference formula ($\Delta E^*_{ab,10}$). We should emphasize that the use of colour-difference formulas like $\Delta E^*_{ab,10}$ requires that the light source or illuminant for both objects be the same, to have a single reference white for the computation of colour differences. CIELAB colour differences below around 1.0 CIELAB units can be considered close to just perceptible colour differences by the human eye [25, 26]. The total CIELAB colour difference can be split in its three intrinsic components —i.e. lightness difference (ΔL^*_{10}), chroma difference ($\Delta C^*_{ab,10}$), and hue difference ($\Delta H^*_{ab,10}$)— [1, 2], which will be given here as percentages ($\%\Delta L^*_{10}$, $\%\Delta C^*_{ab,10}$, $\%\Delta C^*_{ab,10}$) of the total CIELAB colour difference ($\Delta E^*_{ab,10}$), defined as follows:

$\%\Delta L^*_{10} = 100\ (\Delta L^*_{10} / \Delta E^*_{ab,10})^2$

$\%\Delta C^*_{ab,10} = 100\ (C^*_{ab,10} / \Delta E^*_{ab,10})^2$

$\%\Delta H^*_{ab,10} = 100\ (\Delta H^*_{ab,10} / \Delta E^*_{ab,10})^2$.

The addition of these three percentages is equal to 100:

$\%\Delta L^*_{10} + \%\Delta C^*_{ab,10} + \%\Delta H^*_{ab,10} = 100$.

From values of the lightness-difference, chroma-difference and hue-difference components, we can achieve a better understanding of the characteristics of total colour difference between two given objects (e.g. how much darker, more chromatic, and more yellowish one is compared to the other). As a way of providing a better correlation with visual differences perceived by observers with normal colour vision under most usual viewing conditions, the CIEDE2000 colour-difference formula has been recently recommended by ISO and CIE [27], because it significantly improved $\Delta E^*_{ab,10}$. However, we cannot use CIEDE2000, because it was recommended for the illuminant D65, colour differences below 5.0 CIELAB units, and objects in contact (no gap), and these restrictions are not compatible with situations in current study.

Table I offers a preliminary idea of the different colours of the objects under analysis (Figs. 3 and 4), from their corresponding CIELAB colour coordinates under CIE illuminants D65 and A. The results in Table I show that for both illuminants the facial skin of Oriental women is darker (lower L^*_{10}), more saturated (higher $C^*_{ab,10}$), and more yellowish (higher $h_{ab,10}$) than that of Caucasian women. Comparing Oriental and Caucasian women's faces, Table I shows that for both illuminants the aforementioned lightness decrease and chroma increase are smaller for cheek than for forehead, while the increase in hue-angle is higher for cheek than for forehead. Regarding the lipsticks, Table I also shows that they cover a wide colour gamut, considerably broader than for skin colour. The lipsticks selected have similar or lower lightness than facial skin, but they are much more saturated and reddish (except lipstick #5) than the skin. The analyses of colour differences between cheek and forehead, or cheek and lipsticks, considering each of the 18 tested illuminants will be described in the Results section.

Table I. CIELAB polar coordinates, lightness (L^*_{10}), chroma ($C^*_{ab,10}$), and hue-angle ($h_{ab,10}$), under the two main CIE illuminants (D65 and A) and CIE 1964 standard observer, for cheek and forehead in Caucasian and Oriental women, as well as for 5 commercial lipsticks.

If we consider only one object successively illuminated by two different illuminants (e.g. lipstick #1, first under D65 illuminant and next under BLED6500 illuminant), in general the colour appearance of such object will change, because of the change in the SPDs of the illuminants, but, as mentioned above, we cannot directly use a colour-difference formula (e.g.

$\Delta E^*_{ab,10}$) to measure such change, because there is no common reference white. In this situation, colour-inconstancy indices (CIIs) must be employed as follows: first, a chromatic adaptation transform (CAT) allows the so-called "corresponding colours" to be computed under a fixed reference illuminant [18]; and next we can use a colour-difference formula under such a reference illuminant. In our current study, corresponding colours were computed using the chromatic adaptation transform named CAT16 [28], with complete adaptation (*D* factor = 1), using as reference illuminants both, D65 and A illuminants. From corresponding colours under the reference illuminant, the CII will be computed using $\Delta E^*_{ab,10}$. The use of CAT16 is justified because it is an improvement of CAT02, embedded in current CIE colour-appearance model, CIECAM02 [29].

Our approach suggests as objective measurements of changes in facial contrasts: 1) the change in the magnitude and components of CIELAB colour differences for two points of a woman face (e.g. cheek and forehead) under different illuminants; 2) the change of CII for one point in a woman face (e.g. lipstick or cheek) when the illuminant changes. Hypothetical null/high values of mentioned changes in CIELAB colour differences or in CII values indicate no/high changes in women facial contrasts when illuminant changes.

Results

Colour differences between forehead and cheek in Caucasians and Orientals

Figure 5 shows CIELAB colour differences between forehead and cheek for Caucasian and Oriental faces under the 18 illuminants tested. The average colour differences for the 18 illuminants in Fig. 5 are considerably lower for Caucasian than for Oriental faces (2.7 against 4.9 CIELAB units), as should be expected from the similitude of spectral reflectance factors plotted in Fig. 3, with almost negligible standard deviations in both ethnic groups (0.2 and 0.1 CIELAB units for Caucasian and Oriental faces, respectively). It should be remembered that colour differences below around 1.0 CIELAB units are hardly perceptible to the human eye [25, 26]. The mean deviations with respect to average values of colour differences using the 18 illuminants were 5.0% and 1.5% for Caucasian and Oriental faces, respectively. The highest deviations with respect to the average values from the 18 illuminants were found for the illuminants F11 (19.4% in Caucasians and 3.2% in Orientals) and for the illuminant white LED RGB1 (10.2% in Caucasians and 2.5% in Orientals).

Figure 5. CIELAB colour differences between forehead and cheek for Caucasian and Oriental women under 18 illuminants.

Figure 6 shows the percentages of the three components (lightness, chroma, and hue differences) in total CIELAB colour differences between forehead and cheek shown in Fig. 5, for each of the 18 illuminants tested. Fig. 6 indicates that colour differences between forehead and cheek are predominantly in hue for Caucasian faces, but not for Oriental faces, where lightness and chroma differences are present in similar proportions, and the percentages of hue differences are minimal. As in Fig. 5, the results shown in Fig. 6 are quite similar for the 18 illuminants, the highest discrepancies being found for Caucasian faces under white LEDs RGB1 and RGB2 and under illuminant F2.

Figure 6. Percentages of three components in total CIELAB colour differences between forehead and cheek for Caucasian (top) and Oriental (bottom) women under 18 illuminants.

From Figs. 5 and 6, we conclude that the magnitude (i.e. total value) and characteristics (i.e. percentages of the 3 components) of CIELAB colour differences between forehead and cheek are very different in Caucasian and Oriental women, indicating that facial contrasts are different in these two ethnic groups. However, in general, there are only small discrepancies between the results found for the 18 illuminants in Figs. 5 and 6, indicating that illuminant changes induce minor changes in contrast between forehead and cheek.

Colour differences between Caucasian and Oriental faces in forehead and cheek

Figure 7 shows CIELAB colour differences between Caucasian and Oriental women's faces for forehead and cheek under the 18 illuminants tested. For the 18 illuminants, the average CIELAB colour differences in Fig. 7 were 6.6 units for forehead (with a standard deviation of 0.1 units), and 3.3 units for cheek (with a standard deviation of 0.2 units). Therefore, the colour differences between these two ethnic groups are higher for forehead than for cheek, and the results are similar for all 18 illuminants tested. More specifically, in Fig. 7 the mean deviations with respect to average values of colour differences for the 18 illuminants were quite small, 1.0% and 3.9% for forehead and cheek, respectively. The highest deviations with respect to average values from 18 illuminants, in the case of forehead, were found for the white LEDs BLED5000 (2.1%) and RGB1 (1.9%), and, in the case of cheek, for illuminants F11 (13.2%) and white LED RGB2 (6.7%).

Figure 7. CIELAB colour differences between Caucasian and Oriental women's faces, considering separately the results for forehead and cheek, under 18 illuminants.

Figure 8 shows the percentages of the three components (lightness, chroma, and hue differences) of total CIELAB colour differences between Caucasians and Orientals for forehead and for cheek (Fig. 7) under the 18 illuminants tested. Fig. 8 indicates that colour differences between Caucasian and Oriental faces are predominantly in hue for cheek, but not for forehead, where lightness and chroma differences have similar proportions and hue differences represent only a tiny percentage. The results shown in Fig. 8 are markedly similar for the 18 illuminants, and small deviations with respect to average results are noticeable only for cheek, under illuminants F2 and white LEDs RGB1 and RGB2.

Figure 8. Percentages of three components in total CIELAB colour differences between Caucasian and Oriental faces, for forehead (top) and cheek (bottom), under 18 illuminants.

From Figs. 7 and 8 we conclude that the magnitude (i.e. total value) and the characteristics (i.e. percentages of the 3 components) of CIELAB colour differences between Caucasian and Oriental women's faces differ sharply for forehead and cheek. However, only small differences appear between the results for the 18 illuminants in Figs. 7 and 8, indicating that in general the change of illuminant induces minor changes in colour appearance of Caucasian against Oriental faces, in comparisons of the same part of the face (forehead or cheek).

Colour differences between cheeks and lipsticks in Caucasians and Orientals

Figure 9 shows CIELAB colour differences between each of the 5 lipsticks and cheeks of Caucasian and Oriental women, under the 18 illuminants tested. The reason for the preference of cheek in the current comparison is that the cheeks and lips are closer regions in the face in comparison with the forehead and lips. The colour differences in Fig. 9 are considerably higher than those previously reported in Fig. 5 (two regions of the face for each ethnic) or in Fig. 7 (the same region of the face in two different ethnics). Specifically, for the 18 illuminants tested, the average CIELAB colour differences in Fig. 9 range from 10.0 (lipstick #1, Caucasian cheek) to 43.7 (lipstick #2, Oriental cheek). From Fig. 9, we also note that the results from cheeks in Caucasian and Oriental faces are very similar (average discrepancy below 0.2 CIELAB units), except for lipstick #3, where discrepancies are higher (average of 2.5 CIELAB units). Therefore, as expected, the colour differences between lipsticks and cheek (Fig. 9) are higher than those between forehead and cheek (Fig. 5). Another difference between the results in Figs. 5 and 9, is that in Fig. 9 some illuminants score CIELAB colour differences as considerably different from the average of the 18 illuminants. Specifically, in Fig. 9 the mean deviations with respect to the average values of the 18 illuminants are 12.3%, 8.1%, 11.0%, 6.7%, and 1.5%, for lipsticks #1 to #5, respectively, considering as a reference the cheek in Caucasian faces (similar results are found using cheek as a reference in Oriental faces). Perhaps the most relevant finding in Fig. 9 is that for some illuminants the CIELAB colour differences are markedly different from the average of 18 illuminants. This is true of white LED RGB2 and all lipsticks (except for lipstick #5), where the deviations with respect to the average of 18 illuminants ranged from 25.6% (lipstick #4, Caucasian cheek) to 54.2% (lipstick #1, Oriental cheek).

Figure 9. CIELAB colour differences between each of the 5 lipsticks and the cheek in Caucasian and Oriental women, under 18 illuminants.

Figure 10 shows the percentages of the three components (lightness, chroma, and hue differences) in total CIELAB colour differences between each of the 5 lipsticks and the cheek in Caucasian or Oriental faces (Fig. 9), for the 18 illuminants tested. For lipsticks #1 and #2 the differences in chroma predominate, for lipstick #3 the differences are almost only in chroma and hue, for lipstick #4 the differences are mainly in lightness and chroma, and, finally, for lipstick #5 the differences are mainly in lightness and slightly in hue. These discrepancies between the 5 lipsticks in Fig. 10 are because they were selected to cover a wide (and commercially representative) colour gamut. Regarding differences among the results for the 18 illuminants, Fig. 10 shows that they are relatively small for all 5 lipsticks, although some exceptions are evident (e.g. for the lipstick #4, the white LEDs RGB1 and RGB2 achieve percentages of chroma difference which are higher than those found for the remaining illuminants).

Figure 10. Percentages of three components in total CIELAB colour differences between each of the 5 lipsticks and cheek in Caucasian and Oriental faces, under 18 illuminants.

In summary, from Fig. 9 we conclude that colour differences (associated with contrasts in our approach) between lipsticks and cheeks have a higher magnitude and a wider range than colour differences between cheeks and foreheads (Fig. 5). Specifically, considering the average of the 18 illuminants, the lowest average colour difference between lipsticks and cheeks was 10.0 CIELAB units (lipstick #1 and the Caucasian cheek), while the highest colour difference between foreheads and cheeks was 4.9 CIELAB units (Caucasian faces), indicating that the lowest ratio between these two kinds of colour differences was a factor of 2. The characteristics or components of the two colour differences may also be considerably different, as reflected by the comparison of Figs. 10 and 6. Meanwhile, Figs. 9 and 10 show that some white LEDs (e.g. RGB2, RGB1, and BLED2700) result in colour differences between lipsticks and cheek that substantially differ from the average of the 18 illuminants.

Colour inconstancy for cheek, forehead, and lipsticks (reference illuminants D65 and A).

Another method to evaluate the change in facial contrasts caused by the illuminant change is to consider the individual objects we have examined before (i.e. cheek and forehead of Caucasian and Oriental women, plus the 5 lipsticks) and compute colour-inconstancy indices (CIIs). Under the assumption of a given reference illuminant, a null value of CII for a given object and test illuminant means that the colour of that object is the same when illuminated by the reference and test illuminants. Alternatively, high CII values indicate a pronounced change in colour appearance when the object is illuminated by test and reference illuminants.

We computed CIIs (CIELAB units), applying the chromatic adaptation transform CAT16 with complete adaptation (*D* factor = 1), to determine the corresponding colours [18, 29]. For an object under a test illuminant, we established its corresponding colour, with one of the two main CIE illuminants (D65 or A) as the reference illuminant, and then we computed the CII of this object between the test and reference illuminants. The results found are given in Tables II and III, for reference illuminants D65 and A, respectively. The last two columns in Tables II and III show the average CII for the 9 objects considered in this article (4 skin colours plus 5 lipsticks), and the ranking of the illuminants according to this average. For example, in Table II, the low values of CII for illuminant D75 indicated that the objects considered have colours very similar to those exhibited under the reference illuminant D65, a result consistent with the fact that the SPDs of the D75 and D65 illuminants are relatively similar. On the other extreme, the high CII values shown in Table II for the white LED RGB2 indicate a substantial change in the colour of the objects when illuminated by this illuminant, in comparison with their colours under illuminant D65, which is also a reasonable result from the sharply different SPDs of LED RGB2 and illuminant D65.

Table II. Colour-inconstancy indices (CIELAB units), assuming D65 as the reference illuminant (outdoor lighting) for cheek (Ch.) and forehead (For.) in Caucasian and Oriental women's faces and 5 lipsticks. From the averaged results, the last column shows the ranking of the illuminants tested.

The highest average CII values in Table II correspond to the white LEDs RGB2 and RGB1 (note that these values are considerably higher than those found for the other illuminants), followed by VLED warm, A, Hybrid LED, and F2, showing also rather high values. Regarding the five illuminant BLEDs in Table 2, the highest CII corresponds to BLED2700, with a CCT close to 2700 K, which is far from the CCT of 6500 K of the D65 reference illuminant. In any case, the CII values in Table II are not well correlated with the differences of the CCTs of the illuminants with respect to 6500 K (the CCT of the reference illuminant D65): For example, BLED6500 and D65 have similar CCTs around 6500 K, but the colours of the 9 objects under BLED6500 and D65 are considerably different, with an average colour difference of 3.9 CIELAB units. This result is not surprising, because CCT is an indicator of the colour appearance of illuminants/sources (e.g. low CCT can be associated with a reddish appearance), but not an indicator of colours of real objects under such illuminants/sources. As mentioned in the Introduction, the colour of real objects is the result of the combination of the SPD of the illuminant, the spectral reflectance factor of the illuminated object, and the sensitivity of the photoreceptors of the human visual system. In general, the results in Table II indicate that colours of women's faces under the D65 illuminant (outdoor lighting) may be noticeably altered by certain white LEDs, mainly by white LEDs RGB2 and RGB1, as well as for illuminants with narrow peaks in their SPDS.

Table III. Colour-inconstancy indices (CIELAB units) assuming A as the reference illuminant (indoor lighting) for cheek (Ch.) and forehead (For.) in Caucasian and Oriental women's faces and 5 lipsticks. From averaged results, the last column shows the ranking of the illuminants tested.

The results in Table III have the illuminant A as reference, with a CCT of 2856 K (i.e. a reddish light, representative of indoor lighting), and therefore they are different from those in Table II. From the average values of CIIs in Table III, the greatest changes in colour appearance with respect to that under illuminant A are found for the white LED RGB2 (as in Table II), followed by illuminants F2, BLED6500, BLED 5000, and F7 (in that order). As in Table II, from Table III we also conclude that some white LEDs may lead to marked changes in the facial contrast of women.

Conclusions and future work

From experimental measurements of skin colour in cheek and forehead of Caucasian and Oriental women, plus a set of 5 lipsticks, we have reported on the magnitude and components of CIELAB colour differences in women's faces, under 18 illuminants (10 of them representative of white LEDs technologies currently available in the market), with the following results:

1) CIELAB colour differences between forehead and cheek were quantitatively and qualitatively different in Orientals and Caucasians, but the discrepancies with respect to average values for the 18 illuminants were small (5.0% for Caucasians and 1.5% for Orientals).

2) CIELAB colour differences between Caucasians and Orientals were also quantitatively and qualitatively different in forehead and cheek, but the discrepancies with respect to average values for the 18 illuminants were again small (3.9% for cheek and 1.0% for forehead).

3) CIELAB colour differences between lipsticks and cheek were higher than those between forehead and cheek by at least a factor of 2. With respect to CIELAB colour differences between lipsticks and cheek, the discrepancies with respect to average values of 18 illuminants depended on the lipstick selected and were in the range 1.5% - 12.3%, although higher values of up to 54.2% were found for a RGB white LED.

4) RGB LEDs provided the highest colour-inconstancy indices, considering the average values of 9 objects (cheek and forehead in Caucasian and Oriental women, plus 5 lipsticks): 17.1 and 11.5 CIELAB units under reference illuminants D65 and A, respectively.

Some white LEDs, particularly the so-called RGB LEDs, generated higher colour differences between points of women's faces than traditional light sources (e.g. illuminants D65 and A). This may induce variations in perceived contrasts in women's faces using some white LEDs. While we understand and share the interest about determining whether white LEDs are or not advisable for colour applications in cosmetics, unfortunately, our current results do not allow to make a general recommendation to manufacturers or users. Our results only indicate that colour contrasts in women's faces under CIE standard illuminants for outdoor and indoor conditions, may be strongly altered by using some white LEDs, not all LEDs. This alteration may be a factor in favour or against the use of some white LEDs, depending, for example, on aesthetical effects we may want to achieve.

The relevant colour differences found between forehead and cheek (as well as between Orientals and Caucasians) require further investigation: While in the present paper we used only average skin colours, variability and non-uniformity of human skin must also be accounted for in future works. Research on human skin as complex images, and objective tools based on spectral metrics [31] should be tested. Facial contrasts in women's faces, (e.g. highest contrasts between lipsticks and skin) under different light sources should also be investigated in future works from the standpoint of colour harmony [32], or using new colour rendering indices, like those currently studied by CIE TC 1-91 [7]. It should be desirable, future research provides new approaches and indices related to users' preferred contrasts in women faces. As a general rule for cosmetic applications, the use of light sources with high colour rendering indices (e.g. the so-called 'colour fidelity index' [33]) is recommended. This recommendation is in agreement with poor results achieved in our current paper for two RGB LEDs and the F2 illuminant, which have low values of CIE colour rendering index, R_a (below 65). Anyway, beside advances in lighting research, nowadays the study of preferences and specific visual effects produced by light sources is an open problem [34, 35].

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