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DOI:

[10.1364/JOSAA.35.00B324](https://doi.org/10.1364/JOSAA.35.00B324)

Document Version

Accepted author manuscript

[Link to publication record in Manchester Research Explorer](#)

Citation for published version (APA):

Amano, K., Linhares, J. M. M., & Nascimento, S. M. C. (2018). Color constancy of color reproductions in art paintings. *Journal of the Optical Society of America A: Optics, Image Science & Vision*, 35(4), B324-B333. <https://doi.org/10.1364/JOSAA.35.00B324>

Published in:

Journal of the Optical Society of America A: Optics, Image Science & Vision

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Color constancy of color reproductions in art paintings

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Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

Popular color reproductions of art paintings such as postcards are intended to remind viewers of the original works. It is, however, unclear how well the quality of the reproductions is preserved under various illuminations. Color constancy of the reproductions in relation to colors in the original paintings was estimated computationally with hyperspectral images of the 15thc Flemish paintings, the 20thc modern abstract paintings and their corresponding postcards with a series of illuminants: the CIE daylight D65 with correlated color temperature (CCT) 6500 K, daylight D40, fluorescent lamps F2 and F11, a LED lamp designed for museums with CCTs approximately 3500-4000 K. Despite large colorimetric differences between the types of art-paintings and between the illuminants simulated, local areas showed good color constancy: skin areas in the Flemish paintings ranged from 0.76 to 0.81, whereas non-skin areas ranged from 0.19 to 0.68. This result suggests that viewers may be able to achieve color constancy with the reproduction postcards disregarding inconsistent colors representations from the original paintings caused by changes in illumination conditions.

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OCIS codes: (330.1690) Color; (330.1710) Color, measurement; (330.1715) Color, rendering and metamerism; (330.1720) Color vision

<http://dx.doi.org/10.1364/#####>

1. Introduction

It is common that visitors at museums or art-gallery would purchase the reproduction of the art-paintings in the form of postcards. Color reproductions on the postcards are intended to remind viewers of the original works and viewers' appreciation of their colors. It is, however, unclear how good the quality of the reproduction is.

Since colors usually provide a signature of the painting and express emotions of the subject in the paintings, the quality of the color reproduction should be carefully managed. For example, skin coloration in the reproductions is crucial in capturing the color features of the original painting.

The postcards can be observed under any of viewing conditions, whereas the original art-painting is observed under controlled environment, in particular, the illumination. Even with such difference in the viewing environment, can viewers obtain the similar appreciation of colors to the original art painting with the postcard?

This question can be rephrased by the notion of color constancy. Color constancy refers to the effect where the perceived or apparent color of a surface remains constant despite changes in the illumination which may have different spectral composition [1]. Thus, the question to address in this study is how well color appearance is preserved on the reproduction postcard under different illuminations when compared with the original paintings.

Two types of art-paintings and corresponding postcards were selected to evaluate the color constancy: two of the 15thc Flemish

paintings and three of the 20thc modern paintings, (Figure 1). The corresponding postcards were obtained at the museums where the original paintings belonged. Each of the two Flemish paintings included skin areas of human faces and hands. One of the paintings represents joy and happiness with a lady holding an infant, and another represents sadness with a lady holding a deceased male. These emotions might have been expressed by elaborated use of color tone and shade. In contrast, the three modern paintings are almost abstract, consisted of color patches with various shapes and colors. Thus, there is no explicit representation of emotion in the modern paintings.

The hyperspectral images of the original paintings and the corresponding postcards were used to obtain precise color rendering of the surfaces under spectrally different illuminations, with which colorimetric analysis were undertaken. The use of the hyperspectral imaging for the color vision sciences has been reported elsewhere [2-4].

Since there is a large interval between the creation dates of the Flemish and modern paintings, it is very likely that color pigments used in these paintings could be physically different, whereas color pigments in the modern paintings may be closer to those used in the color printing of the postcards. It is the spectral properties by the hyperspectral imaging that enables to estimate the differences and lead to colorimetric analysis. The pigments in the modern paintings have been analyzed for the purpose of the conservation process in elsewhere [5].

The design of lightings for the art-paintings at museums and galleries vary between the institutions, although they follow the

standards [6-8]. Correlated color temperatures (CCTs) of the lightings are usually approximately 4000 K or lower [7, cf.9]. The use of LED lamp at the museums has been increased rapidly along with the technological advancement, because of its advantages in the stability of light emission, performance of color rendering, and energy consumption [10]. In contrast, the postcards could be observed under any of illuminations, even under direct sunlight or bright daylight.

Considering these facts, the illuminants simulated in this study were the CIE standard illuminant D65 with CCT 6500 K, fluorescent lamps F2 and F11 with CCT approximately 4000 K, and a LED lamp designed for the art materials with CCT approximately 3500 K and a daylight D40 with CCT 4000 K.

Color constancy of human vision has been studied mainly in psychophysical experiments, for example, with color matching task or operational judgements [1, 11, 12]. Observers' performance in color constancy tasks has been usually estimated by a standard color constancy index [11]. The same principle is applicable to estimate color constancy computationally. Here, by introducing the reproduction color constancy index (RCCI) [13, 14], color constancy between the original painting and the reproduction postcard under varied illuminants was estimated. The RCCI is defined by regarding the colors on the postcards as an estimate of observer's matched colors, then, applying the calculation of the standard color-constancy index. The index unity represents perfect constancy and the lower the index, the greater the error.

Mean RCCI over the local areas selected was as high as 0.81 under illuminants with lower CCTs. The result suggests that viewers can achieve fairly good color constancy, although there are variation between the local areas and the type of the paintings. The levels are close to the color constancy indices achieved by human psychophysics[1].

Spectral and colorimetric properties such as Chroma and lightness between the original paintings and the postcards and between the illuminants were analyzed as the course of the variations in RCCI. Statistics of color properties quantified by estimating chromatic contrast and color difference [e.g. 15]. Depending on the type of the paintings, the characteristics in the transformation of chromaticity distributions (color gamut) were different [e.g. 16, 17]. The Flemish paintings had an expansion of color gamut between the media, as if the effects of memory color and color preference [e.g. 18, 19] were taken into account. But the modern paintings had an opposite effect. These results suggest that, despite the colorimetric differences, viewers may be able to achieve good color appreciation by the reproductions of the original art-paintings.

2. Methods

A. Materials

Two of the 15thc Flemish paintings were belonged to Edição Do Museu Nogueira Da Silva, Braga, Portugal and three of the modern paintings by Amadeo de Souza-Cardoso (1887-1918) were belonged to Museu Calouste Gulbenkian, Lisbon, Portugal. The Flemish paintings, "Senhora com Christ morto" (a close English translation may be "Lamentation Over the Body of Christ") and "Senhora do leite da meia laranja" (a close English translation is "Madonna With Child"), were dated as 15thc made by unknown painter(s) ("desconhecido" in Portuguese). For the modern paintings by Amadeo de Souza-Cardoso since the titles of the paintings were not given formally, we use the labels P172, P200, and P38. The labels were based on the catalogue [20] (it should be noted that the museum has another set of coding for the three paintings, 86P21, 77P9 and 77P3, respectively). Each of the paintings was dated approximately 1915, 1917 and 1912, respectively. The detailed information of the paintings of Amadeo de Souza-Cardoso

and the procedure of the hyperspectral imaging was given in elsewhere [20, 21]. The sample images rendered under D65 are shown in Fig. 1 (the first and third rows).

In the manufacturing process of the postcards, it is common that the images of the original painting can be adjusted or the edges of the image can be removed so that the image can fit to the postcard format. In this study, the images of the original modern paintings were cropped so that the image size can be almost the same as the image content of the corresponding postcards (the original size were: P172: 21.4cm × 27.3cm, P200: 93.5cm × 75.5cm, P38: 33.9cm × 27.4cm). Since the details of the adjustments made in the manufacturing process are unknown, the areas of the removals were made by authors' judgements.

The final images of the original paintings and the postcards had different pixel resolution. Therefore, instead of the pixel-by-pixel comparison, analyses in this study were mainly made on local areas chosen to cover almost the same image contents between the original painting and the postcard.

This study considered only surface colors on the two-dimensional digitized image of the paintings and postcards. There may be often three-dimensional geometrical structures, such as a bump of paint or brush strokes, on the real paintings. Those may well create an effect of immersive-ness of the real paintings but were not concerned in this study, as they were not represented in the postcards.

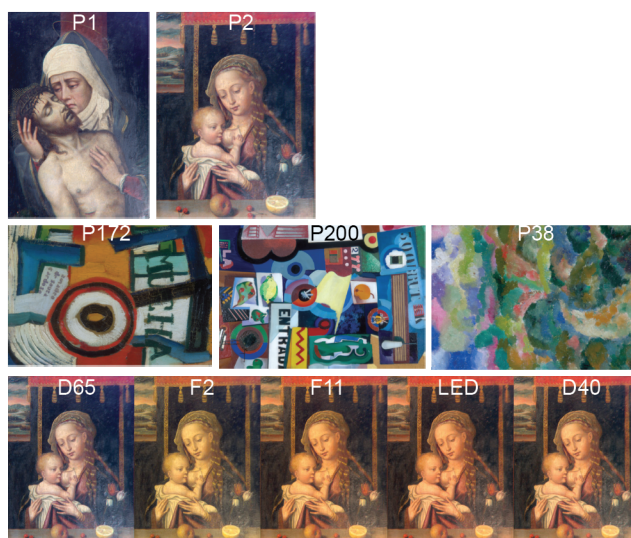


Fig. 1. Sample images of the art-paintings. The first and second rows show two Flemish paintings (P1 and P2) and three modern paintings by Amadeo de Souza-Cardoso (P172, P200 and P38), respectively. The color images were generated from the hyperspectral data with illuminant D65. The images on the third row show the color renderings with different illuminants (D65, F2, F11, LED and D40) on the Flemish painting P2.

B. Hyperspectral imaging and reflectance estimation

The hyperspectral image of the paintings and the postcards was acquired by a custom-build hyperspectral imaging system. The technical details of the system and imaging procedure have been reported elsewhere [21, 22]. Some of the essential details are given here.

The system consisted of a low-noise Peltier-cooled monochromatic digital camera (Hamamatsu, model C4742-95-12ER, Hamamatsu Photonics K. K., Japan) and a tunable liquid crystal filter (Varispec, model VS-VIS2-10-HC-35-SQ, Cambridge Research & instruments, Inc.,

MA). The wavelengths of the hyperspectral imaging ranged over visible range from 400 to 720 nm in 10 nm interval. FWHM of the tunable filter is 10 nm at 550 nm. The spatial resolution of the camera was 1344×1024 pixels. A small neutral surface (Munsell N7) was placed in the scene of the artefacts at the image acquisition to be served as a spectral reference to process the data to estimate the spectral surface reflectances.

Each of the paintings and postcards was imaged separately. Thus, the hyperspectral image acquisitions of the original paintings were undertaken at each of the museums, and those of the postcards were undertaken at a specially designed laboratory at University of Manchester. The image size of the real Flemish paintings subtended approximately $960 \text{ pixel} \times 690 \text{ pixel}$ for the original paintings and $785 \text{ pixel} \times 570 \text{ pixel}$ for the postcards; the modern abstract paintings subtended approximately $1120 \text{ pixel} \times 770 \text{ pixel}$ for the original and $820 \text{ pixel} \times 570 \text{ pixel}$ for the postcard.

C. Illuminant simulation

Colors under the four illuminations as well as the CIE standard daylight D65 were calculated. The simulated illuminants were two types of the CIE fluorescent illuminants F2 and F11, a LED lamp designed for art-materials, and the daylight D40.

Illuminant D65 corresponds to average noon daylight with a correlated color temperature (CCT) of approximately 6500 K and is defined as the standard illuminant for colorimetric calculations [40]. The fluorescent illuminant F2 is a common fluorescent lamp used for typical office illumination and is 'cool white fluorescent', with a CCT of approximately 4200 K. Another fluorescent illuminant F11 has three narrow peaks over the visible spectrum [26] with a CCT of approximately 4000 K and CRI approximately 83, which is mainly used as warehouse lighting. The LED lamp was specially designed for art materials (model XSM9535-1000-C, Xicato Inc, San Jose, CA; spectral data: <http://www.xicato.com>), whose CCT is approximately 3500 K. The difference from the conventional LED lamp is the fact that it does not have any strong power peak on the shorter wavelength, which is considered to harm color pigments. Illuminant D40 is close to a domestic incandescent or tungsten lamp. The spectral profile of the daylight D40 was obtained from three daylight spectral basis functions[23]. The spectral of the fluorescent lamps were obtained from the RIT dataset [24] in the range from 400nm to 720nm in 10nm interval. Luminance of each illuminant was simulated to be constant, in this study, set to 100 cd/m^2 . The sample images of the colour appearance under the different illuminants on the Flemish painting P2 are shown on the third row in Fig. 1.

D. Local Areas

Each of the two Flemish paintings includes two human figures. Coloration of human skin is of interest because they often represent individual's emotion which might correspond to the main theme of the paintings. To compare the color appearance of skin areas between the original paintings and the postcards, local skin areas of forehead, cheek and hand (or shoulder if any hand was not available) were selected from each figure (Fig. 2). These selections of the local areas were similar to those used in a dataset of human skin color [25]. The other non-skin areas were also selected (Fig. 2). The local areas selected in the modern paintings are shown in Fig 3. The local areas were selected pseudo-randomly but restricted not to have any non-uniformity of colors within the area.

The pixel size of each local area varied across the areas ranged from 12 pixels on lips area (area ns4 in Fig 2) to over 11,600 pixels (area ns3 in Fig. 2) in the Flemish paintings; from 160 pixels (area 5 in P38 in Fig. 3) to over 11,400 pixels (area 2 in P200 in Fig. 3).

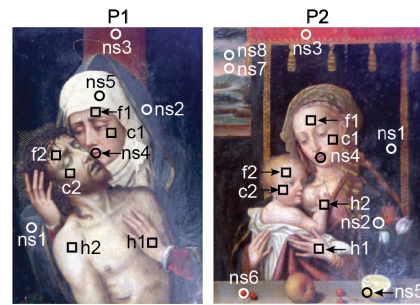


Fig. 2. Local areas on the two Flemish paintings P1 and P2. Local skin areas, forehead, cheek and hand/shoulder indicated by f, c and h with squares, respectively; non-skin local areas indicated by ns with circles. Size of the squares and circles were adjusted for visibility.

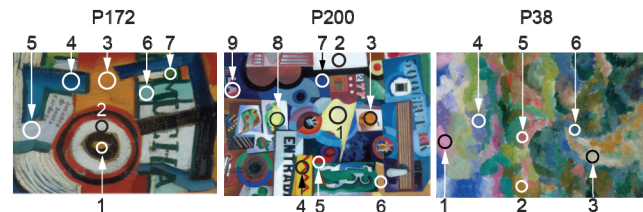


Fig. 3. Local areas selected on the modern paintings. Areas selected are indicated by circles. The sizes of circles were adjusted for visibility.

E. Colorimetric analysis

Colorimetric analysis was undertaken on the colors of the local areas in the original paintings and corresponding postcards under the simulation of different illuminations (Subsection 2C). Chromaticity coordinates were calculated in the CIELAB space. To estimate saturation of colors, Chroma was defined with a^* and b^* coordinates:

$$\text{Chroma} = \sqrt{a^{*2} + b^{*2}} \quad (1)$$

F. Reproduction color constancy index

Color-constancy performance has been assessed by the reproduction color-constancy index (RCCI) which is defined analogous to the standard color-constancy index established in vision sciences [1, 11]. Thus, in a uniform color space CIELAB, where the chromaticity coordinates of the local areas selected in an original painting and the corresponding areas in the postcard were located, let s be the Euclidian distance between the color of the original painting and color of the postcard under a test illuminant and t be the Euclidian distance between the original painting under the reference and test illuminations. Then, the RCCI is $1 - s/t$. Perfect constancy corresponds to unity, and the index is lower for a higher error level. Illuminant D65 was either the reference or test illuminant. That is, the directions of the illumination changes between the reference and test were considered, one of which is always paired with D65.

3. Results

A. Spectral analysis

Spectral reflectances on the selected local skin areas in the Flemish painting P2 are shown in Figures 4a–d.

Skin areas in the original painting and the postcard are shown in Figs. 4a and b, respectively. There are clear difference in the spectral profiles between the original painting and the postcard. Spectra of the original painting are smoother than those of the postcards. The surface

reflectances of the original paintings had almost 50% lower than the postcard, indicating the original has darker color than the postcard when they were illuminated by the same light source.

The evaluation of the spectral differences between two spectra, for example, one from the original paintings and another from the postcard, can be performed with root-mean-square error (RMSE) and spectral similarity values (SSV) [Eqns 7, 8 and 9 in 26]. Thus, let the spectrum of the original painting denote r_r and the spectrum from the postcard r_p ,

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (r_{r,i} - r_{p,i})^2} \quad (2)$$

$$SSV = \sqrt{RMSE^2 + S^2} \quad (3)$$

where i is the i -th spectral component of reflectances, and n is the total number of components. S^2 is defined by

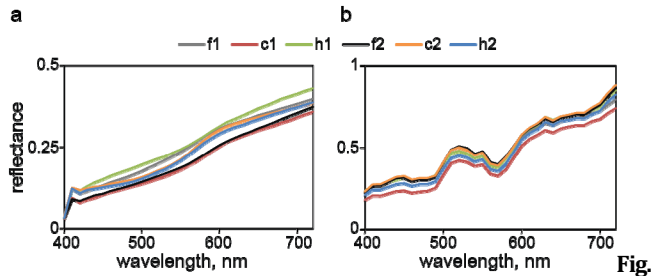
$$S^2 = 1 - \left[\frac{\frac{1}{n} \sum_{i=1}^n (r_{r,i} - \mu_r)(r_{p,i} - \mu_p)}{\sigma_r \sigma_p} \right]^2 \quad (4)$$

where μ_r and μ_p are the means of the reflectances of the original painting and the postcard, respectively, computed over wavelength, and σ_r and σ_p are the standard deviations of the reflectances of the original painting and the postcard, respectively.

The values of RMSE and SSV between the original painting and the postcards were similar to those reported in the similar comparisons [13], where the original human skin spectra was compared with artificial facial skin with a calibrated additive manufacturing process. Overall of skin areas and non-skin areas in both paintings, RMSE and SSV was not correlated ($R^2 = 0.54$). Since SSV include RMSE in its definition, the difference was caused by the covariance term between the original painting and the postcard (Eqn 4).

Spectral reflectances on the local areas in the modern paintings P200 are shown in Figures 5a and b. Similar to the Flemish paintings, the reflectance spectra of the original painting was smoother than the postcard. However, the level of reflectances was close to each other. The mean values of RMSE and SSV were similar to those for the Flemish paintings. There are bumps on spectra of postcards in both paintings, approximately 480nm and 580nm. These may be originated by the color inks in the manufacturing process. Similar characteristics have been reported in the additive manufacturing of colored skin [13, 14].

The correlation of the RMSE and SSV to reproduction color constancy RCCI is considered in Section 4.



4. Spectral reflectances of the Flemish painting P2. (a) the original painting and (b) the reproduction postcard. The local skin areas, forehead, cheek and hand/shoulder (f, c and h, respectively) correspond to those shown in Fig. 2.

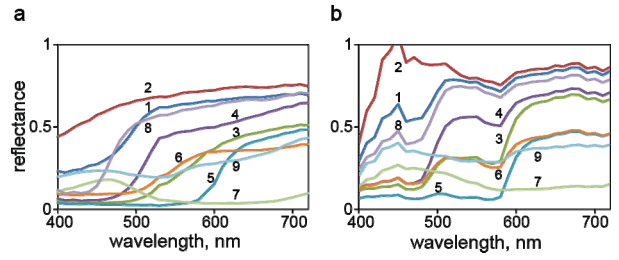


Fig. 5. Spectral reflectances of the selected local areas in the modern paintings P200. (a) the original painting and (b) the postcard. The numbers correspond to the areas selected, as shown in Fig. 3.

B. Colorimetric analysis

Chromaticity coordinates L^* , a^* and b^* in the CIELAB space at each local area were calculated with applying the illuminants of the daylight D65 and D40, fluorescent lamps F2 and F11, and a LED lamp (Subsection 2C). The chromaticity of each local area was defined by the spatial average within each local area.

The chromaticities of the skin areas in the two original Flemish paintings under the daylight D65 are shown in the CIELAB (a^* , b^*) coordinates in Fig. 6a and (Chroma, L^*) in Fig. 6b, respectively.

Skin colors in the Flemish painting P1 may have represented the emotion of sadness, while the paintings P2 may have represented the joy and happiness (Subsection 2A). Those emotion seemed to be reflected on the chromaticities; that is, the chromaticities of the skin areas in the painting P1 located towards greenish for the sadness (lower a^*), and those in the P2 towards more reddish (higher a^*) for the joy, and (Fig. 6a), whereas lightness of these areas are almost constant (Fig. 6b).

Figures 6c and d show the shift of chromaticities under different illuminants, in the CIELAB (a^* , b^*) coordinates in Fig. 6c and (Chroma, L^*) in Fig. 6d, respectively. Differences in the influence of the illuminants between the original and the postcard can be observed with comparing filled and open symbols. Arrows indicates the shifts of chromaticities due to the change of illuminants (from D65 to D40 or lower CCTs).

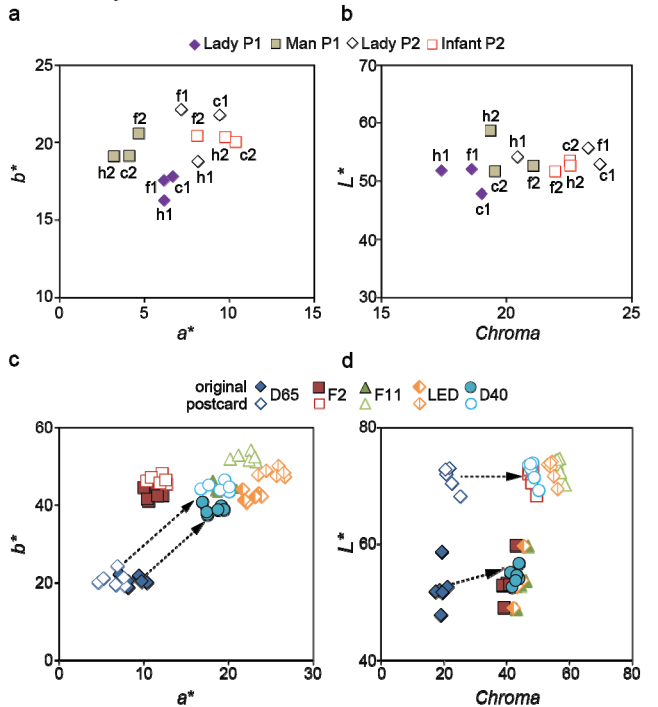


Fig. 6. Chromaticities of the local skin areas in the two of the Flemish paintings (P1 and P2). (a) Comparison of chromaticities of the skin areas in the Flemish paintings P1 and P2 under D65 on (a^*, b^*) and (b) on $(Chroma, L^*)$ space in the CIELAB. Labels f, c and h correspond to those in Fig. 2. (c) Comparisons of chromaticities of the skin areas under the different illuminants on (a^*, b^*) and (d) $(Chroma, L^*)$ in the CIELAB. Filled symbols show the chromaticities in the original paintings and open symbols show those in the postcards. Arrows indicates the shifts of chromaticities due to the change of illuminants (from D65 to D40 or lower CCTs).

The chromaticities of the postcard (open symbols in Figs. 6c and d) were similar to those in the original painting under the illuminant D65. However, the lightness levels are much higher, as expected from the reflectance profile in Fig. 4 (Subsection 3A). These characteristics were altered under different illuminants with the lower CCTs, i.e. fluorescent lamps F2 and F11, a LED lamp and daylight D40, (Subsection 2C). Chroma of the postcards was higher than the original paintings, while the lightness of the postcards was constantly higher than the original across the illuminants. On the non-skin areas, as with the skin areas (Figure is not shown), the chromaticities in the postcards have higher saturation and lightness than the original.

The shifts of Chroma of the skin colors between the original painting and the postcards of the Flemish paintings under the illuminants the lower CCTs, F2, F11, LED or D40 are markedly larger. With the Flemish painting P1 and P2, for example, mean differences in Chroma over skin areas between the original and postcard were 6.4 and 8.8 units under illuminant F11, respectively. The increment of the Chroma was also observed on the non-skin local areas in the Flemish paintings. Under illuminant F11, mean differences over the areas were 6.6 and 10.8 units in each of the paintings, respectively. Mean difference in Chroma between the original and postcard over the illuminants with lower CCTs and local areas are 4.3 and 6.1 units for P1 and P2, respectively.

chromaticities on the local areas in the postcard under the different illuminants on (a^*, b^*) and (d) on $(Chroma, L^*)$ in the CIELAB. The numbers inserted to diamond symbols D65 correspond to the areas shown in Fig. 2. Arrows indicates the shifts of chromaticities caused by illuminants (from D65 to D40 and lower CCTs).

The two of the modern paintings (P172 and P200) had different characteristics from the Flemish paintings. The chromaticities on the local areas in the postcards were desaturated and Chroma was smaller compared with those on the original paintings, while lightness were almost constant under the illuminants with lower CCTs. Figure 7 shows the chromaticities (a^*, b^*) and $(Chroma, L^*)$ of the painting P200. Filled symbols in Figs. 7a and b represent the chromaticities of the local areas in the original painting and open symbols in Figs. 7c and d represent the corresponding areas in the postcard, different symbols indicate different illuminants. The numbers inserted to diamond symbols D65 correspond to the areas shown in Fig. 2. Differences in the influence of the illuminants between the original and the postcard can be observed with comparing filled and open symbols, Figs. 7a and c and b and d, respectively. Arrows indicates the shifts of chromaticities caused by illuminants (from D65 to D40 and lower CCTs). The influence of the illuminants on the magnitudes and direction of the shifts varied across the local areas.

The direction of the Chroma shift was different between the Flemish and modern paintings. For the three modern paintings, the decrements in Chroma from the original paintings averaged over the illuminants with the lower CCTs, F2, F11, LED and D40 were -6.3 , -9.5 and -5.2 units, respectively. However, a reversed trend appeared for D65. Chroma of the original painting is higher than the postcard. These variations of characteristics may be originated in complex interactions of the surface reflectances and the spectra of the illuminants.

These shifts are in fact not limited in the local areas selected, but also the whole of colors in an image. This issue is to be discussed in Subsection 3D.

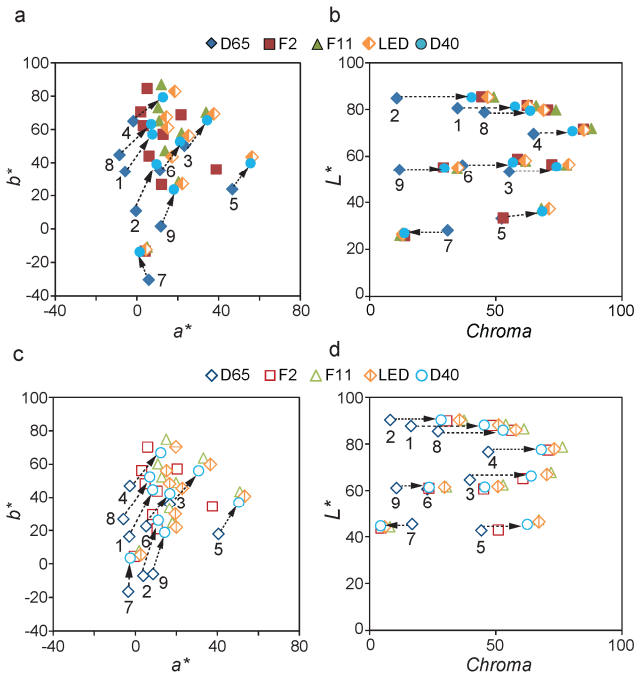


Fig. 7. Chromaticities of the local areas the modern paintings P200. The colors of the symbols indicate the difference of the illuminants. (a) Comparison of chromaticities of the local areas in the original painting under the different illuminants (D65, F2, F11, LED and D40) on (a^*, b^*) and (b) on $(Chroma, L^*)$ in the CIELAB. (c) Comparisons of

C. Reproduction color constancy index

The performance of color constancy was evaluated by the reproduction color constancy index (Subsection 2F). Here, 2 dimensional (a^*, b^*) color space was considered because of the large difference in the lightness (L^*) between the original painting and the postcard, in particular, the Flemish paintings (Fig. 4).

The RCCI on the skin areas in the Flemish paintings was relatively higher than the non-skin areas, except for the daylight D40. The average value over the skin areas (forehead, cheek, and hand in the two individuals in a painting) on the Flemish painting P2 ranged from 0.76 to 0.84 with a rank of the illuminants with the RCCI low to high, F11, LED and F2. RCCI with D40 was significantly low, with 0.22 (Fig. 8). The similar levels appeared with the Flemish painting P1, ranged from 0.78 to 0.84 with the same rank of the illuminants, whereas 0.18 with D40. The RCCIs on the non-skin areas were slightly lower than the skin areas. Among the selected non-skin local areas the RCCI ranged from 0.53 to 0.76 over the illuminants F2, F11, and LED. The RCCI with D40 was down to negative value, possibly because of the irregularity of color transformation.

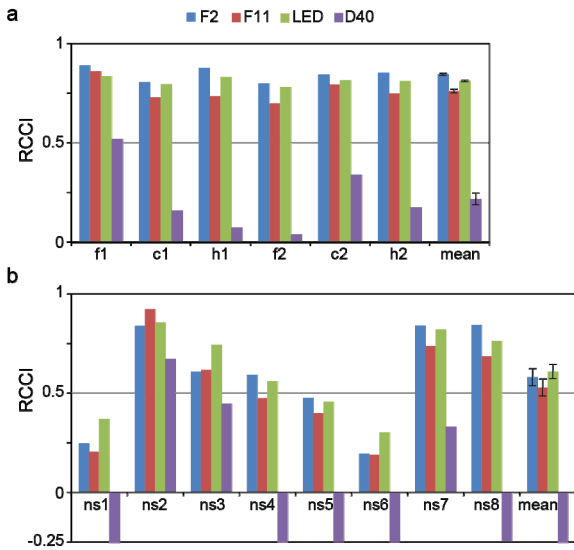


Fig. 8. Reproduction color constancy index (RCCI) of (a) local skin areas and (b) non-skin areas in the Flemish painting P2. To compute RCCI, the illuminant D65 was paired with one of the illuminants F2, F11, LED or D40. The RCCI with negative values were cut off at -0.25. Error bars represent standard error of mean. The labels correspond to the areas indicated in Fig. 2.

The RCCI on the local areas in the modern paintings were lower than the Flemish paintings. Mean RCCI over the local areas under different illuminants (excluding D40) ranged from 0.19 to 0.38 in P172, from 0.40 to 0.59 in P200, and from 0.59 to 0.68 in P38, respectively. RCCI varied largely across the local areas. Figure 9 shows the RCCI for the painting P200.

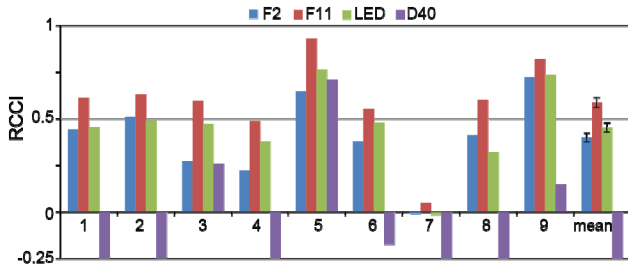


Fig. 9. RCCI on the local areas in the modern painting P200. The RCCI with negative values were cut off at -0.25. Error bars represent standard error of mean. The labels correspond to the areas indicated in Fig. 3.

Nevertheless, the reproduction color constancy obtained here are not so different from those achieved in color-constancy experiments by human observers[1]. In particular, the RCCI of the skin areas were relatively higher. But the RCCI on the non-skin areas had a large variation, depending on the chromaticity of the local areas. Thus, there seemed to be influenced by the irregularity in the transformation of chromaticities across the illuminants.

D. Color gamut

Distributions of chromaticities represented with (a^*, b^*) coordinates in the CIELAB space, color gamut, and with (Chroma, L^*) coordinates under the illuminants D65 and LED are compared in Figure 10 for one of the Flemish paintings P2 and one of the modern paintings P200,

respectively. In each Figure, labels (a) and (b) indicate the plots of (a^*, b^*) coordinates and (Chroma, L^*) coordinates, respectively.

Color gamut of the original paintings is markedly different from those of the postcards in both types of the paintings, as seen in Figures 11. Under the illuminant D65, for the Flemish painting P2, color gamut of the postcard appeared to be elongated toward higher a^* (reddish) than the original painting. For the modern painting P200, the gamut of the postcard is much smaller than the original. Along with the different illuminants with lower CCTs, the gamut for P2 tended to extend toward higher a^* as expected, and the gamut of the original paintings became rotated and skewed.

From (Chroma, L^*) coordinates, the difference in lightness distribution is clear. The distribution in the postcards has higher lightness and Chroma, compared with the original painting.

The difference in the size of the color gamut can be quantified by the chromatic contrast, i.e. color difference from the median chromaticity of (a^*, b^*) in the CIELAB space. Let C indicate chromatic contrast, C is defined as:

$$C = \sqrt{(L^* - L^*_{\text{med}})^2 + (a^* - a^*_{\text{med}})^2 + (b^* - b^*_{\text{med}})^2} \quad (5)$$

where a^*_{med} , b^*_{med} and L^*_{med} represent the median chromaticity of an image.

Table 1 lists the ratio of mean C over the local areas in the postcard under each illuminant to mean C over the local areas in the original painting. If the ratio is larger than unity, it indicates the increment of the chromatic contrast from that of the original under D65. The ratios on the Flemish paintings are larger than unity regardless of the type of the local areas, whereas those in the modern paintings P172 and P200 are less than the unity.

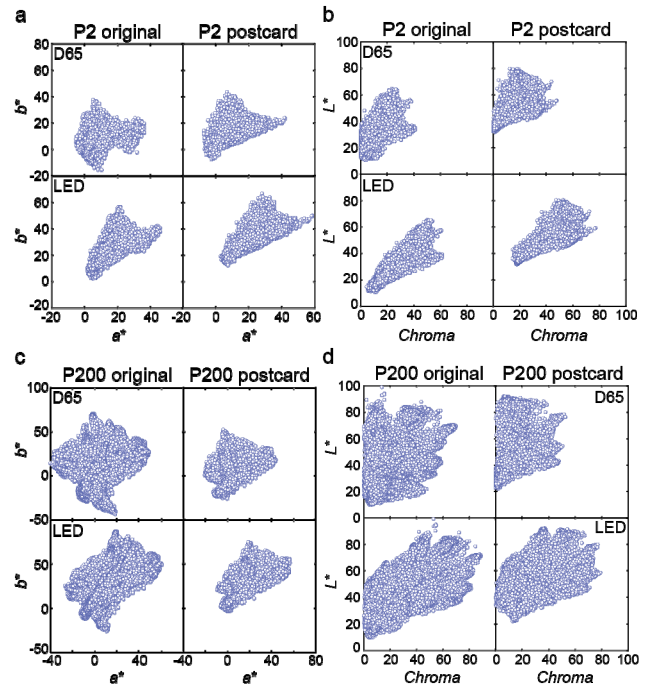


Fig. 10. Transformation of color gamut on (a) and (b) the Flemish P2 and (c) and (d) modern painting P200 under each of the illuminants D65 and LED, respectively. Color gamut of the original painting and the postcard (a) and (c) in (a^*, b^*) coordinates and (b) and (d) (Chroma, L^*) coordinates in the CIELAB, respectively.

Averaged over skin and non-skin areas in each of the Flemish paintings, by Analysis of variance without repetition for the five paintings and five illuminants, C values over the five paintings and five

illuminants, difference between the paintings are significantly different ($F(4, 16) > 200, p = 0.0$), so does the difference between illuminants ($F(4, 16) = 6.2, p = 0.0$).

Table 1. Ratios of chromatic contrast on the local areas in the postcard under each of the illuminants F2, F11, LED and D40 to the contrast in the original painting under illuminant D65.

Chromatic contrast is defined by color difference from the mean chromaticity (a^*, b^*) in the CIELAB. The ratio greater than unity represents the expansion of chromatic contrast.

Illuminant on postcard	Flemish painting				Modern painting		
	P1		P2		P172	P200	P38
	skin	Non-skin	skin	Non-skin			
D65	1.104	1.108	1.081	1.095	0.859	0.848	1.029
F2	1.081	1.114	1.059	1.067	0.881	0.901	1.077
F11	1.131	1.128	1.089	1.131	0.880	0.950	1.106
LED	1.135	1.124	1.077	1.115	0.876	0.930	1.089
D40	1.129	1.120	1.075	1.102	0.874	0.910	1.067

Table 2. Ratios of chromatic contrast of the postcard under each of the illuminants F2, F11, LED and D40 to the contrast of the original painting under illuminant D65.

The ratio greater than unity represents to the expansion of chromatic contrast.

Illuminant on postcard	Flemish painting		Modern painting		
	P1	P2	P172	P200	P38
D65	0.859	1.102	0.802	0.595	1.101
F2	1.189	1.248	0.795	0.621	1.046
F11	1.414	1.533	0.950	0.729	1.154
LED	1.381	1.503	0.935	0.716	1.139
D40	1.286	1.434	0.909	0.691	1.112

Instead of the local areas, C can be computed for all points in a whole image. Table 2 lists the ratios of mean C over all points in the postcard under each of the illuminants to mean C over all points under D65 on the original paintings. If the ratio is larger than unity, it indicates that the color gamut is larger than the gamut of the original painting under D65. In Table 2, it is clear that the increment and decrement of the ratio varied with the type of the paintings, i.e. the Flemish paintings and the modern paintings. The postcard of the Flemish paintings had almost 1.5 times larger gamut than the original under D65 illuminant, whereas those of the modern painting P200 had almost 0.6 times smaller. But the modern painting P38 seems to have larger gamut.

Analysis of variance without repetition for the five paintings and five illuminants showed that the effect of the illuminants was significant ($F(4, 16) = 7.73, p < 0.05$) and the difference between the paintings was significant ($F(4, 16) = 47.8, p < 0.05$).

The shape and size of color gamut varies along with the illuminants F2, F11 and D40, despite their CCTs are all approximately 4000 K and the LED with CCT 3500 K (the results with D65, F2 and LED are shown in Fig. 11). The transformation of color gamut had not only the expansion but also skewed toward higher a^* (reddish) and b^* (yellowish), as expected [15, 27, 28]. The skewness of the color gamut are summarized by tracing the median chromaticity in each of (a^*, b^*) coordinates under different illuminants.

The median chromaticity of a^* and b^* in the original painting under each of the illuminants against those in the postcard is shown in Figs. 11a and b for the Flemish painting P2 and the modern painting P200, respectively. The order of the illuminants in a^* and b^* coordinates are different, and their step-size are uneven across the illuminants. The magnitude of the skewness depends on the paintings.

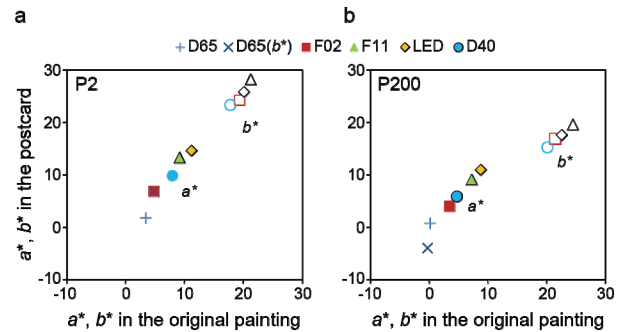


Fig. 11. Skewness over the transformation of color gamut for the Flemish painting P2 and the modern painting P200. Median chromaticities of a^* and b^* distributions of the original painting are shown as a function of those in the postcard along with the different illuminants, F65, F2, F11, LED and D40. The ordinate and abscissa are the chromaticities of the original paintings and those of the postcard, respectively. The rank of the illuminants is different between a^* and b^* .

Color gamut of the common color inks for printing (CMYK) is in general smaller than that of the colors available in RGB digital devices, and the RGB gamut is smaller than natural scenes and color pigments for the paintings [e.g. 21, 29]. Such technical constraints may have provided a limit on color available between media, and consequently color constancy between the original paintings and the reproduction postcards. Transformation of color gamut across media has been studied extensively, known as the color gamut mapping [16, 17, 30]. However, as observed the difference in colorimetric characteristics between the types of the paintings (e.g. Fig. 10), any of objective and scientific procedures, e.g. the gamut mapping, did not seem to be undertaken in the reproductions of the individual paintings used in this study. The colorimetric differences between the two types of the paintings may indicate that the reproduction processes might have been different between the institutions. In general practices, the reproduction process consists of digital imaging, color adjustments and printing. The color adjustments are usually based on empirical knowledge and subjective judgements by experts at the institutions.

4. Discussion

Colors of the original painting and the reproduction postcards may appear similar to our eyes, but colorimetric analysis revealed clear differences between them. Surface reflectances of the postcards of the historical Flemish paintings had much higher than the original painting, which produced the higher lightness and saturation. The distribution of colors in a color space, color gamut, was different between the original painting and the postcard. Depending on the type of the paintings, whether the historic Flemish painting or the modern abstract painting, by Amadeo de Souza-Cardoso the color gamut of the reproduction postcard is expanded or less in comparison to that of the original painting. The effects of the illuminants on the color gamut were observed by the skewness of the color gamut as well as its size.

Color constancy between the original painting and the postcard was quantified by RCCL. The RCCI was relatively high on skin color areas and modest on the non-skin local area with more saturated colors.

A. Consistency of colors

In imaging sciences, there are established standards to evaluate the color quality of illuminants, such as color fidelity and color rendering index (CRI), which examine the shifts of colors of specifically defined samples under a test illuminant are compared with those under a reference illuminant [6, 31, 32]. Analogous to these methods, it is possible to evaluate a consistency of surface color appearance of the local areas in the original painting and the postcard.

Three types of color differences are being examined. Thus, considering the illuminant D65 as a reference illuminant; (a) color differences at the local areas in the original painting between illuminant D65 and the illuminants with lower CCTs; (b) those in the postcards and (c) color difference at the local areas between the original painting and the postcards under different illuminants.

The ratios of (b) and (c) to (a) indicate whether the shift of colors is consistent between the original painting and the postcard. The ratio unity indicates the color shifts are similar to those within the original painting.

Table 3 shows the ratios of (b)/(a) and (c)/(a) for each painting. The ratios are mostly higher than unity, indicating the color differences or color shifts were larger in the postcards and with the changes in illumination from D65. With the Flemish paintings, the ratio (c)/(a) tended to be higher than the ratio (b)/(a), but it was reversed with the modern paintings.

Taking average of ratios between the skin and non-skin areas in the Flemish paintings, the two-factor analysis of variance without repetition for the five paintings and four illuminants showed that, for the ratio (b)/(a), each of the effects of the illuminants and paintings were significant ($F(3, 12) = 29, p < 0.05$; $F(4, 12) = 45, p < 0.05$); and for the ratio (c)/(a), the effect of the illuminants was not significant ($F(3, 12) = 2.6, p > 0.1$), but the difference between the paintings was significant ($F(4, 12) = 6.7, p < 0.05$).

B. Relationship between SSV and RCCI

The colorimetric properties which have been analyzed are originated in the spectral properties. It could be argued, therefore, whether the RCCI may be explained by the difference in spectral properties between the original painting and the reproduction postcard.

The similarity of spectral properties between the original paintings and the reproduction postcards were quantified by using RMSE and SSV (Subsection 3A). The RMSE and SSV of the surface reflectances at the selected local areas were regressed to RCCI to evaluate whether the variance of the RCCI may be explained by the variance of RMSE and SSV. These results suggest that the spectral similarity may not be able to explain solely the variance of the RCCI.

C. Color preference and color memory

The postcards of the Flemish painting had higher Chroma in the than the original when they were observed under the illuminants with the lower CCTs (Subsection 3B).

As discussed, the causes of the Chroma shifts and the transformations of color gamut between the original painting and the reproduction postcard may be attributed not only to the type of the paintings but also to the manufacturing process of the reproduction postcard. A conventional protocol of the reproduction process would include the digitization of the art-works, color adjustments and edits and color printing, at each of which color management would be undertaken.

Considering practical situation where viewers observe art-works at museums, they might memorize hundreds of paintings, and remembered with the reproduction postcards afterward. In such

circumstances, the influence of color memory could contribute to the color adjustments at the manufacturing process.

Shift of saturation of colors in color preference and color memory has been studied extensively. Preference color of the familiar objects and their memory color tend to be remembered as more saturated [18], and color memory of single color patches were shifted to more saturated [19], and categorical focal colors are generally located on saturated region in a color space [33, 34]. The shift can be extended to the expansion of color gamut or chromaticness caused by the memory of natural scenes [e.g. 15]. Performance of color constancy seemed to be robust with short term memory of natural scenes [4, 35, 36]. In one of the early studies [15], the expansion of chromatic contrast in natural images was reported by a memory recognition task. Even with involving memory, the color constancy seemed to be robust with a short-term memory of natural scenes [35, 36].

However, the expansion by the memory would not be applicable to the modern paintings used in this study as the color gamut in the reproductions are smaller than the original paintings, where the physical limitation of the color gamut may be taken into account (Subsection 3D).

Despite these transformations of color gamut and chromatic contrast, the postcard seems to be accepted by the viewers as an alternative to the original painting. This may suggest that human vision system may have an ability to maintain the constant appreciation of art paintings.

D. Skin color appearance

Although colors on the skin areas appeared to be "skin", the chromaticity coordinates are in fact less saturated and close to neutral color (see Figs. 6a and 7a). Surface color appearance is influenced by their surround [37] even if the surrounding surfaces are located remotely [38]. The color appearance of skin areas may be relevant to these phenomena.

The neutral colors would provide robust color constancy [1, 39, 40], as it may serve as an origin of color shift even with the changes in illuminants. However, the estimation of color constancy by RCCI used in this study is based purely on computation in the local areas. The effect of the surrounding colors was not considered.

As a reference, color of real Caucasian skin have higher a^* and b^* chromaticities than those in the Flemish paintings and the corresponding postcards. The mean (a^*, b^*) chromaticity coordinates in the CIELAB are approximately (a^*, b^*) = (12, 15) [25].

5. Conclusion

Spectral and colorimetric analyses were undertaken to assess color constancy on the reproduction postcards in relevance to the original paintings of the 15thc Flemish paintings and the 20thc modern abstract paintings by Amadeo de Souza-Cardoso. Reproduction color constancy across the daylight D65 and the common illuminants with lower CCTs approximately 4000K was assessed by the reproduction color constancy index (RCCI). The RCCI reached reasonably high, which was comparable to the human color constancy in psychophysics but varied depending on the colors in the local areas. The types of the paintings and illuminants influenced the statistics of color properties, such as the transformations of color gamut. The results suggest that viewers may be able to accept the reduction of color accuracy when illuminations were altered and to achieve good color appreciation of the original art-paintings with the reproduction postcards.

Funding Information. The European Cooperation in the field of Scientific and Technical Research, Action TD1201, Colour and Space in

Cultural Heritage: Short Term Scientific Missions (COST-STSM-TD1201-14213).

Acknowledgment. Authors thank Do Museu Nogueira Da Silva, Portugal and Centro de Arte Moderna da Fundação Gulbenkian, Lisboa, Portugal for their cooperation. The authors thank Osamu Masuda and Hélder Tiago Correia, and Cristina Montagner for helping in the spectral imaging of the paintings and thank David H. Foster for the use of the hyperspectral imaging system.

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Table 3. Color consistency from ratios of color differences between the original painting and the postcards.

Ratios of colour differences to estimate consistency of colors: (a) color differences at the local areas in the original painting between illuminant D65 and the illuminants with lower CCTs; (b) those in the postcards and (c) color difference at the local areas between the original painting and the postcards under different illuminants. The ratios of (b) and (c) to (a) indicate whether the shift of colors is consistent between the original painting and the postcard. The ratio unity indicates the color shifts are similar to those within the original painting.

Illuminant on postcard	Flemish painting P1				Flemish painting P2			
	skin		Non-skin		skin		Non-skin	
	b/a	c/a	b/a	c/a	b/a	c/a	b/a	c/a
F2	1.195	1.336	1.222	1.541	1.184	1.443	1.149	1.628
F11	1.349	1.457	1.390	1.616	1.345	1.523	1.374	1.758
LED	1.308	1.427	1.330	1.562	1.295	1.463	1.302	1.684
D40	1.319	1.509	1.334	1.693	1.295	1.564	1.303	1.831

Illuminant on postcard	Modern painting					
	P172		P200		P38	
	b/a	c/a	b/a	c/a	b/a	c/a
F2	1.245	1.039	1.122	0.906	1.080	0.980
F11	1.325	1.177	1.199	1.007	1.198	1.200
LED	1.290	1.220	1.164	1.565	1.157	1.111
D40	1.327	1.206	1.183	1.737	1.176	1.086