Color rendering of art paintings under CIE illuminants for normal and color deficient observers

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Color rendering indices are used to access the quality of lighting but, in addition to other well-known limitations, are not defined for color deficient observers. We evaluated the quality of lighting for normal and color deficient observers in the context of art paintings by estimating the number of colors they perceive when looking at the paintings. Hyperspectral data from 11 oil paintings were analyzed to compute the number of discernible colors when the paintings were assumed rendered under 55 CIE illuminants. Models of color perception for normal and color deficient observers were applied in the estimates. It was found that the number of discernible colors for normal and color deficient observers had low correlation with traditional color rendering indices and that some three-band illuminants, like HP4, were found to be good for most cases, except for tritanopes. These results suggest that it may be possible to obtain good lighting conditions for normal and color deficient observers with an appropriate choice of the light source.

OCIS codes: 100.4145, 110.2945, 220.2945, 330.1690, 330.1720, 330.6180.

1. INTRODUCTION

The visual impression of art paintings and their aesthetic appreciation are influenced by, among other factors, the intensity and spectral composition of the illumination used [1–6]. Although this is well established empirically, the relationship between the spectral composition of the light source on the paintings and its visual effects is not easily quantified or predicted.

For normal color vision, the color quality of a light source is typically evaluated by the color rendering index (CRI) standardized by the CIE [7,8]. This quantity compares the colors of a set of surfaces rendered under the given illuminant with the colors of the same surfaces under the reference illuminant, a daylight or blackbody radiation. The limitations of the CRI are well known [9–12], and other descriptors of the visual quality of a light source have been suggested, for example, the flattery or preference index [13–15], the color-discrimination index [16], and the gamut area index [17]. To obviate a reference illuminant, a method based on the volume of an object-color solid was recently proposed [18]. In the specific context of illumination of art paintings, the analysis of psychophysical experiments using hyperspectral data from paintings [3,4] indicated that observers' preference for specific conditions of illumination could have been influenced by the number of discernible colors in the paintings, and this quantity may therefore be used as a parameter for the evaluation of the effects of light sources on paintings.

Deficient color vision is usually not considered when assessing the color rendering of light sources. However, abnormal color vision affects a considerable fraction of the population. About 8%–10% of males lack the normal form of one or another of the long-, medium-, and short-wavelength-sensitive cone photoreceptors and have some form of congenital red–green color vision deficiency [19–21]. Protanopes lack the long-wavelength-sensitive pigment, and deuteranopes lack the medium-wavelength-sensitive pigment; together they represent about 2% of the male population. Red–green anomalous trichromats, protanomalous or deuteranomalous, represent about 6%–7% of the male population. Inherited defects in the short-wavelength sensitive cones are less frequent: tritanopes, lacking the short-wavelength sensitive pigment, represent less than 0.001 of the population, and tritanomalous have never been well documented. Acquired color vision deficiencies are of different nature and will not be considered here [22,23].

The availability of models allowing the conversion of dichromatic color vision to perceptions experienced by normal trichromats [24] enables computational estimations of the number of discernible colors by dichromats in specific scenes. In addition, there are reliable models of cone sensitivities of anomalous trichromats [25] that allow the simulation of their color perceptions and consequently the estimation of the number of discernible colors. The purpose of the present work was to use these models to evaluate the quality of lighting art paintings by estimating the number of colors normal and color deficient observers perceive when looking at the paintings and to compare these results with the quality assessed by more traditional indices, such as the CRI. We analyzed the effects of 55 CIE illuminants on 11 oil paintings from different époques by analyzing hyperspectral data from the paintings.

2. METHODS

Figure 1 represents the thumbnails of the 11 oil paintings of the collection of the Museu Nogueira da Silva, Braga, Portugal, that were digitized with a hyperspectral system. Seven are from the Renaissance period and are painted on wood (A–E, H, and I), and four (F, G, J, and K) are from the 20th century and are painted on canvas (for more details on the paintings see [4]). Figure 2 shows the color gamut of each painting represented in CIE (a^*,b^*) and CIE (C^*_{ab},L^*) [26] when assumed rendered under the CIE illuminant A. Panels (a)–(k) represent the gamuts in the CIE (a^*,b^*) of the paintings as labeled in Fig. 1, and (m)–(w) represent the corresponding information in CIE (C^*_{ab},L^*); (l) and (x) represent the data for all the paintings in CIE (a^*,b^*) and CIE (C^*_{ab},L^*), respectively. The representation of the eight colored samples used to compute the CRI and assumed rendered under CIE standard illuminant A are shown by crosses.

The hyperspectral system consisted of a low-noise Peltier-cooled digital camera with a spatial resolution of 1344×1024 pixels and 12-bit output (Hamamatsu, C4742-95-12ER, Hamamatsu Photonics K.K., Japan) and a fast-tunable liquid-crystal filter (VariSpec, model VS-VIS2-10HC-35-SQ, Cambridge Research & Instrumentation, Inc., Cambridge, Massachusetts, USA) mounted in front of the lens (for more details on the hyperspectral system see [27]). The focal length of the system was set to 75 mm and the aperture to f/16. With a line-spread function close to a Gaussian with SD of ≈1.3 pixels at 550 nm and an acceptance angle of the camera of ≈6 deg of visual angle, the spatial resolution of the system was at least as good as that of the human eye at the same viewing distance, that is, about 0.5 mm in the painting's surface. The hyperspectral digitalization was carried out over the range 400–720 nm at 10 nm intervals. The paintings were illuminated with low-level SoLux illumination with a correlated color temperature (CCT) of 4,700 K to avoid overexposure to high intensity levels and consequent painting damage. The spectral reflectance of each pixel of the paintings was estimated from a gray reference surface present near the painting at the time of digitizing. Illuminant spatial nonuniformities were compensated using hyperspectral measurements of a uniform surface imaged in the same location and under the same illuminating conditions as the paintings [3]. The accuracy of the system in recovering spectral reflectance functions was tested with oil-painted test samples [28], and the average spectral difference was 2%; the colorimetric error was on average 1.3 when expressed by the CIEDE2000 color difference equation [29] and 2.2 when expressed in the CIELAB color space, an accuracy level within the acceptable range for visualization purposes [30,31].

Fig. 1. (Color online) Thumbnail of the 11 oil paintings analyzed in this work (adapted from [4]).

The radiance spectrum reflected by each pixel of the paintings under several illuminants was computed using the spectral reflectance functions estimated as described above and a set of tabulated CIE illuminants [26]. The illuminants were CIE illuminant A, C, 21 D illuminants (CCT in the range 25,000 K to 3,600 K in steps of 1190.3 K), 27 FL illuminants (FL1, FL2, FL3, FL4, FL5, FL6, FL7, FL8, FL9, FL10, FL11*, FL12, FL3.1, FL3.2, FL3.3, FL3.4, FL3.5, FL3.6, FL3.7, FL3.8, FL3.9, FL3.10, FL3.11, FL3.12, FL3.13, FL3.14, and FL3.15), and 5 HP illuminants (HP1, HP2, HP3, HP4 and HP5). Figure 3 represents the normalized spectral power of some of these illuminants, and Fig. 4 represents their colors in the CIE 1931 (x,y) chromaticity diagram. These illuminants were selected because they represent a wide range of chromaticities and CCT, and almost any real light source can be approximated by one of the selections.

For normal trichromats, the CIELAB color volume for each painting assumed rendered under each illuminant was computed using the CIE 1931 2° standard observer [26]. The number of colors discernible in each case was estimated by segmenting the CIELAB color volume into unitary cubes and by counting the number of nonempty unitary cubes. This methodology gives an approximate but reasonable estimate [32] and was preferred over more complex approaches, such as spherical segmentation [18,33], for its moderate demand on computational power. In addition, as in this paper only relative values are considered, variations with color space, segmentation, or color difference formulas are likely to be minimized.

For dichromats, the CIELAB color volumes were computed using a computational algorithm simulating for normal trichromatic observers the appearance of the paintings for dichromats [24]. The algorithm is based on assumptions concerning the hues that appear the same to dichromats and normal trichromats [34–36]. Using the tristimulus values obtained from the radiance data as described above, the (L,M,S) coordinates were computed using the Vos [37] transformation and the Smith–Pokorny fundamentals [38]. In these transformations Judd's modified photopic luminous efficiency function was assumed to coincide with the nonmodified function. For protanopes,

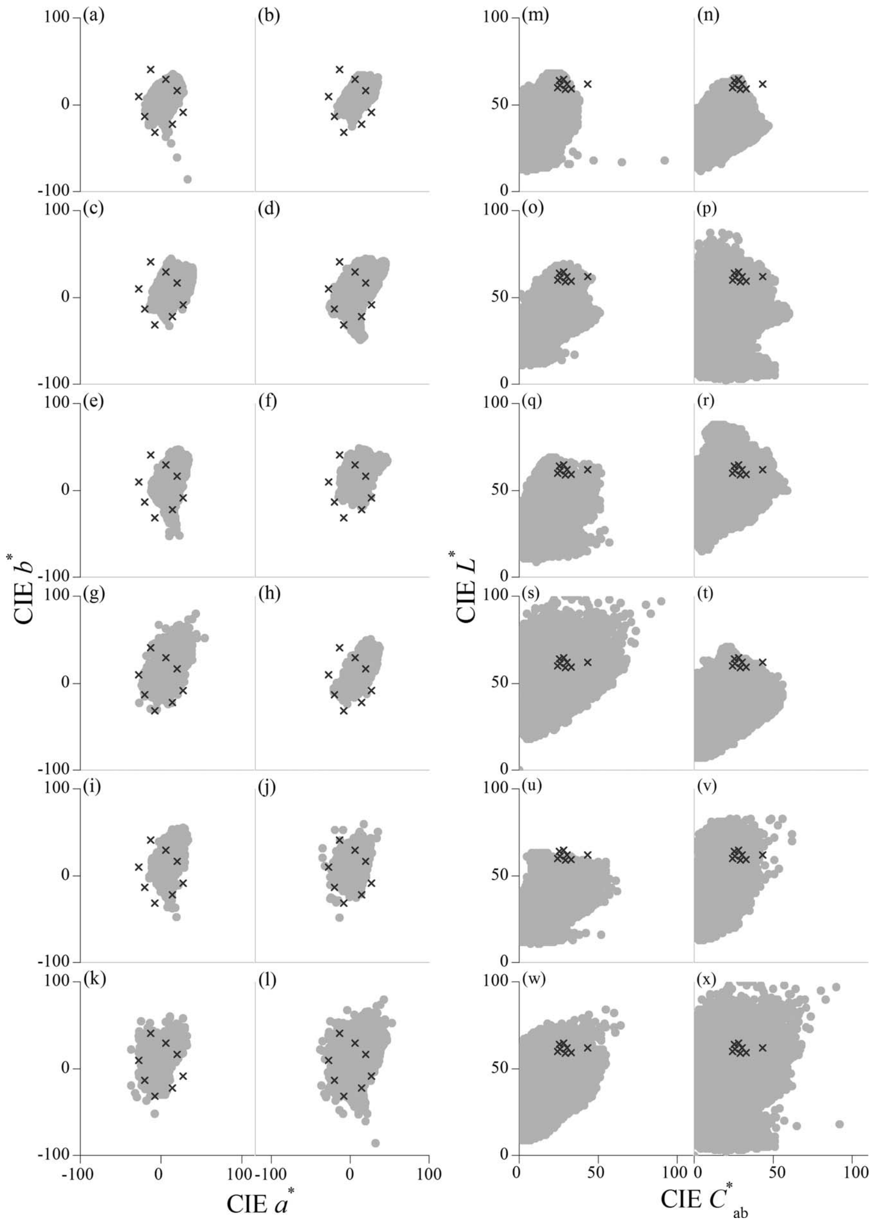

Fig. 2. Color gamut of each painting represented in CIE (a^*,b^*) and CIE (C^*_{ab},L^*) when assumed rendered under the CIE illuminant A. (a)–(k) represent the gamuts in the CIE (a^*,b^*) of the paintings as labeled in Fig. 1; (m)–(w) represent the corresponding information in CIE (C^*_{ab},L^*); (l) and (x) represent the data for all the paintings in CIE (a^*,b^*) and CIE (C^*_{ab},L^*), respectively. The representation of the eight colored samples used to compute the CRI and assumed rendered under CIE standard illuminant A are shown by crosses.

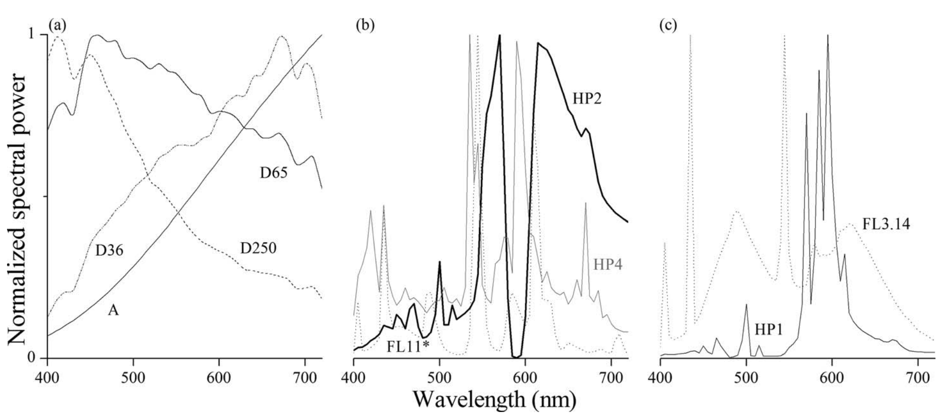

Fig. 3. Normalized spectral power of some of the CIE illuminants used in this work. CIE standard illuminant A was used as comparison illuminant in all computations.

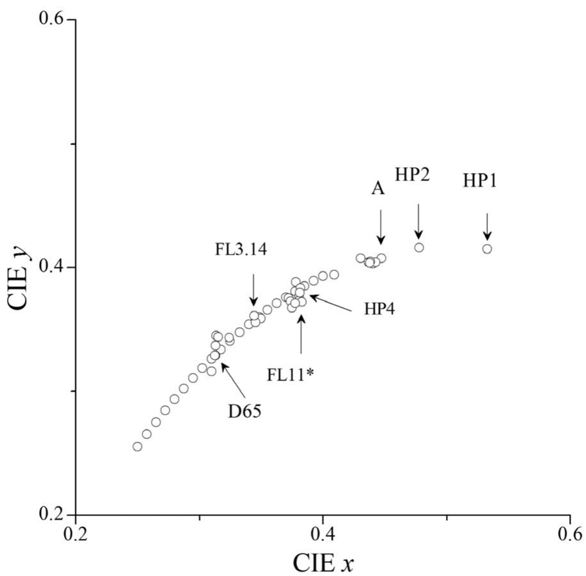

Fig. 4. Chromaticity coordinates of the 55 CIE illuminants used in this work represented in the CIE 1931 (x,y) chromaticity diagram. Arrows indicate some of the best and worst illuminants estimated for normal and color deficient observers.

deuteranopes, and tritanopes, the simulated (L',M',S') coordinates were obtained by replacing the undetermined cone signal with the corresponding value on the respective reduced-stimuli surface [24]. The (L',M',S') coordinates obtained in this way were then converted back into CIELAB coordinates using the inverse Vos transformation. In the above computations the reference white used to compute the CIELAB coordinates was also subject to the same transformation as the other stimuli.

For anomalous trichromats, the CIELAB color volumes were computed using anomalous cone spectral sensitivities estimated by shifting the normal M cone spectral sensitivity 10 nm toward long wavelengths to obtain the protanomalous sensitivity curve and the normal L cone sensitivity 6 nm toward shorter wavelengths to obtain the deuteranomalous sensitivity curve [25]. This model relies on the assumptions that anomalous observers can be characterized by average photopigments, that normal and anomalous trichromats have similar ocular media and optical densities of cone photopigments, and that photopigment spectra are relatively shape invariant when plotted as a function of the frequency [39].

The general color rendering index R_a [7] was computed for all 55 CIE illuminants, using the eight CIE test colored samples. The color representation of these eight colored samples when assumed rendered under the CIE illuminant A is shown in Fig. 2. The reference illuminant was obtained from the Planckian radiator if the CCT of the test illuminant was below 5000 K and from one of the phases of daylight if above.

All computations of the number of discernible colors were compared with the estimates obtained with CIE standard illuminant A. This illuminant was used for comparison because it probably still is the most frequently illuminant used in museum lighting [40]. Averages were computed across paintings.

3. RESULTS

In Fig. 5, open symbols represent relative variations on the number of discernible colors for each illuminant for normal observers, dichromats, and anomalous trichromats. Estimates were computed assuming CIE standard illuminant A as the reference illuminant. Each data point denotes the average across paintings, and error bars represent standard deviation. Arrows indicate, in each case, the points corresponding to the illuminant producing the maximum and minimum variations in the number of discernible colors. Gray solid symbols represent the ratio of the general color rendering index R_a between each of the illuminants tested and the corresponding index for illuminant A ($R^A{}_a$).

The relative number of discernible colors varies considerably across illuminants for all types of observers. For normal observers the maximum corresponded to an increase relative to the CIE standard illuminant A of about 14% obtained with illuminant FL11* and the minimum relative to a decrease of about 40%, obtained with illuminant HP1. As expected, patterns of variation are similar for deuteranopes and protanopes. A lesser degree of similarity was found between deuteranomalous and protanomalous observers, these being considerably different from tritanopes. The best illuminant for normal observers, FL11*, is also located in the best range for the other types of observers, but it is not necessarily the best for each specific category. The illuminant HP4 is the best for deuteranopes, protanopes, and protanomalous observers and very close to the best for deuteranomalous observers.

The average enhancements in the number of discernible colors for normal trichromats was 14% (with illuminant FL11*), for deuteranomalous observers was 6% (with illuminant HP2), for protanomalous observers was 26% (with illuminant HP4), for tritanopes was 12% (with illuminant FL3.14), for deuteranopes was 18% (with illuminant HP4), and for protanopes was 30% (with illuminant HP4).

To illustrate the effects of different illuminants on the paintings for the types of observers considered in this study, the color gamut of painting K (see Fig. 1) is shown in Fig. 6 rendered under the best and worst illuminants for normals, dichromats, and anomalous trichromats. The gamut for the best illuminant is clearly larger, hence the enhancement in the number of perceived colors.

For normal observers, some correlation between the general color rendering index R_a and the number of colors was found, but the former could not predict the latter reliably (see Fig. 5). For color deficient observers the two quantities show much less correlation, with maxima of one coinciding with minima of the other. To evaluate better the degree of correlation between these quantities, Fig. 7 represents the ratio between the color rendering index R_a for each of the illuminants and the corresponding value for illuminant A $R^A{}_a$ expressed as a function of the relative variations in the number of discernible colors. The straight line represents an unweighted linear regression, and the proportion of variance R^2 accounted for in the regression is given.

Consistent with the data obtained elsewhere for natural scenes [41], the absolute number of discernible colors estimated for dichromats for the paintings analyzed was

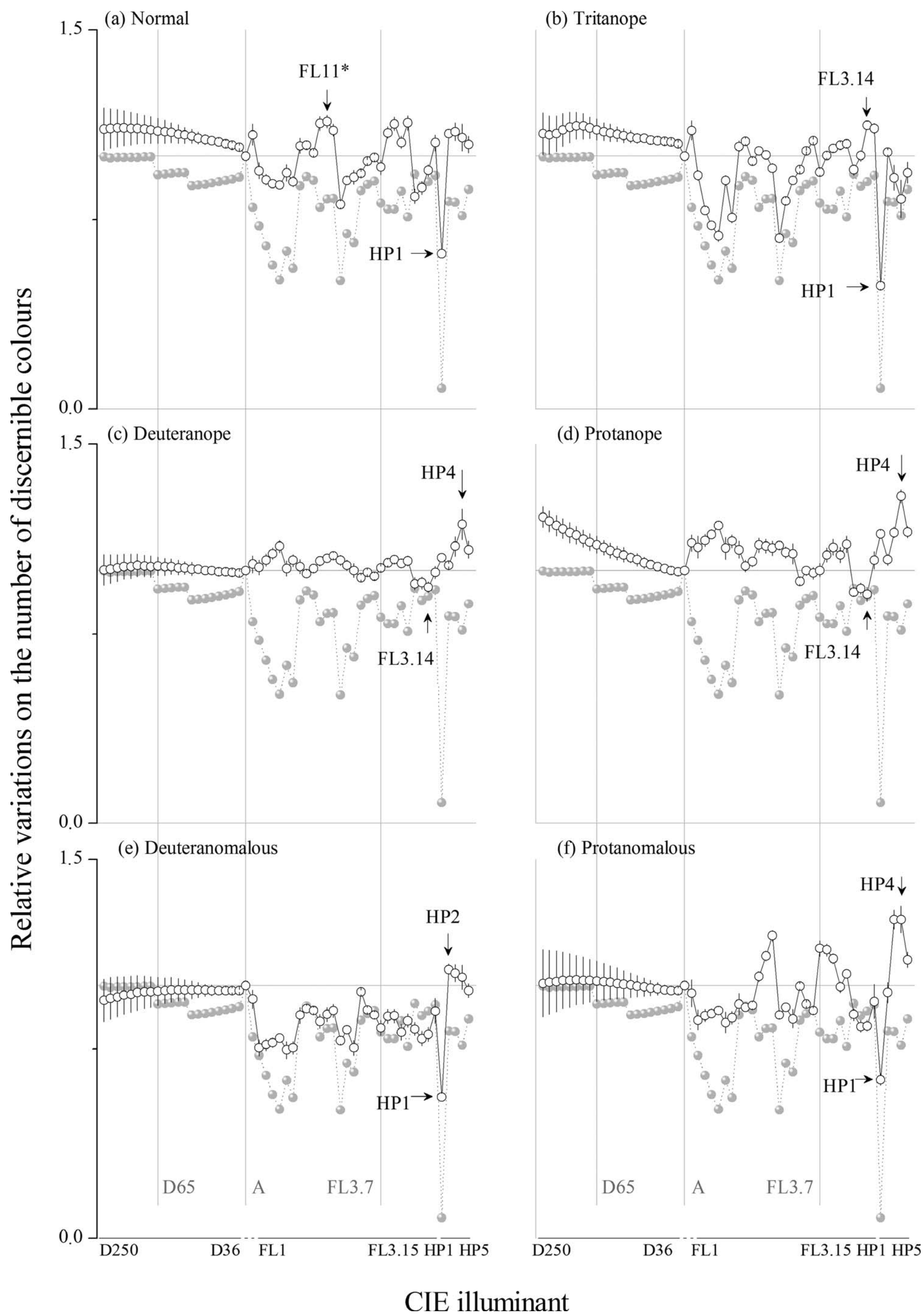

Fig. 5. Relative variations on the number of discernible colors for each illuminant for (a) a normal, (b) a tritanopic, (c) a deuteranopic, (d) a protanopic, (e) a deuteranomalous, and (f) a protanomalous observer (open symbols). Estimates were computed assuming CIE standard illuminant A as the reference illuminant. Each data point denotes the average across paintings, and error bars represent standard deviation. Arrows indicate, in each case, the points corresponding to the illuminant producing the maximum and minimum variations in the number of discernible colors. Also represented (gray solid symbols) is the ratio of the general color rendering index R_a between each of the illuminants tested and the corresponding index for illuminant A (R^A_a).

found to be considerably impaired compared with that of normal trichromatic observers. The reduction was on average to about 8%, 9.5%, and 9% for tritanopes, deuteranopes, and protanopes, respectively, and to about 70% and 78% for deuteranomalous and protanomalous observers, respectively.

To investigate whether the illuminants tested changed considerably the global appearance of the paintings, for each painting and type of observer the average color across the paintings was computed. Figure 8 shows the results represented in CIE (a^*,b^*), and Fig. 9 shows the results represented in the CIE (C^*_{ab},L^*). For comparison the data for normals is shown in all panels of the figure.

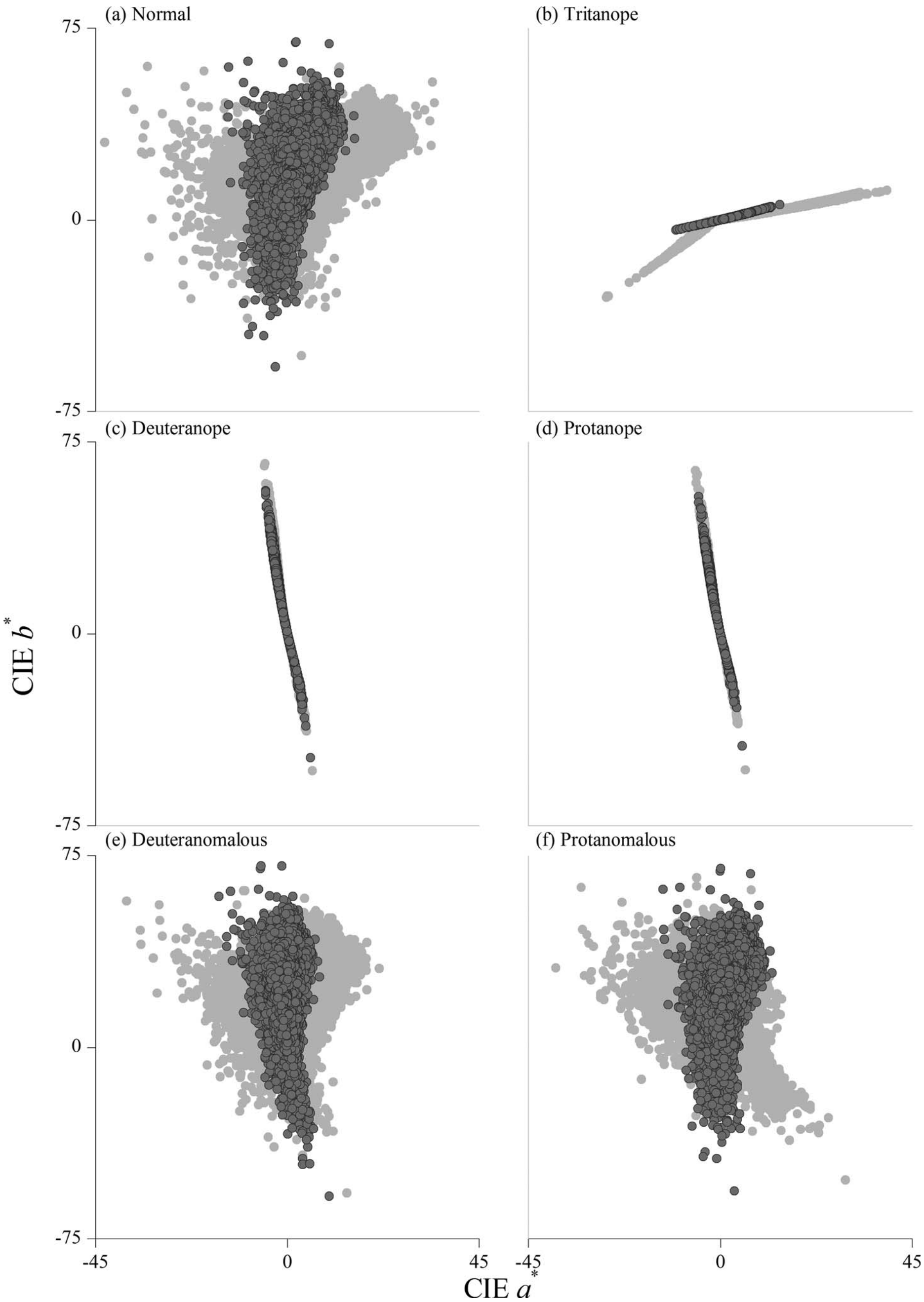

Fig. 6. Color gamut of painting K (see Fig. 1) rendered under the best (light gray symbols) and worst (dark gray symbols) illuminants for normals, dichromats, and anomalous trichromats.

Notice that what is represented is the actual color perceived by the observer, normal or color deficient. The variations of the average color with the illuminant are small, which suggests that no significant color distortions are introduced by any of the illuminants tested.

4. DISCUSSION

In this work we evaluated the color rendering of a collection of CIE illuminants, for normal and color deficient observers, by estimating the number of discernible colors in a set of paintings. The main result is that some illuminants were found to be good for all cases except for tritanopes, and, therefore, it may be possible to obtain good lighting conditions simultaneously for normal and color deficient observers with an appropriate choice of illuminant.

The impairment of the chromatic diversity perceived by dichromats obtained here is similar to the impairment estimated with natural scenes despite the differences in the color gamut between the two types of stimuli [41]. For anomalous trichromats the impairment is lower and in the range 70%–78%. Nevertheless, in all cases the number of discernible colors could be enhanced in relation to those obtained with illuminant A with an appropriate choice of illuminant.

The improvements in the number of perceived colors for some illuminants can be interpreted as an expansion

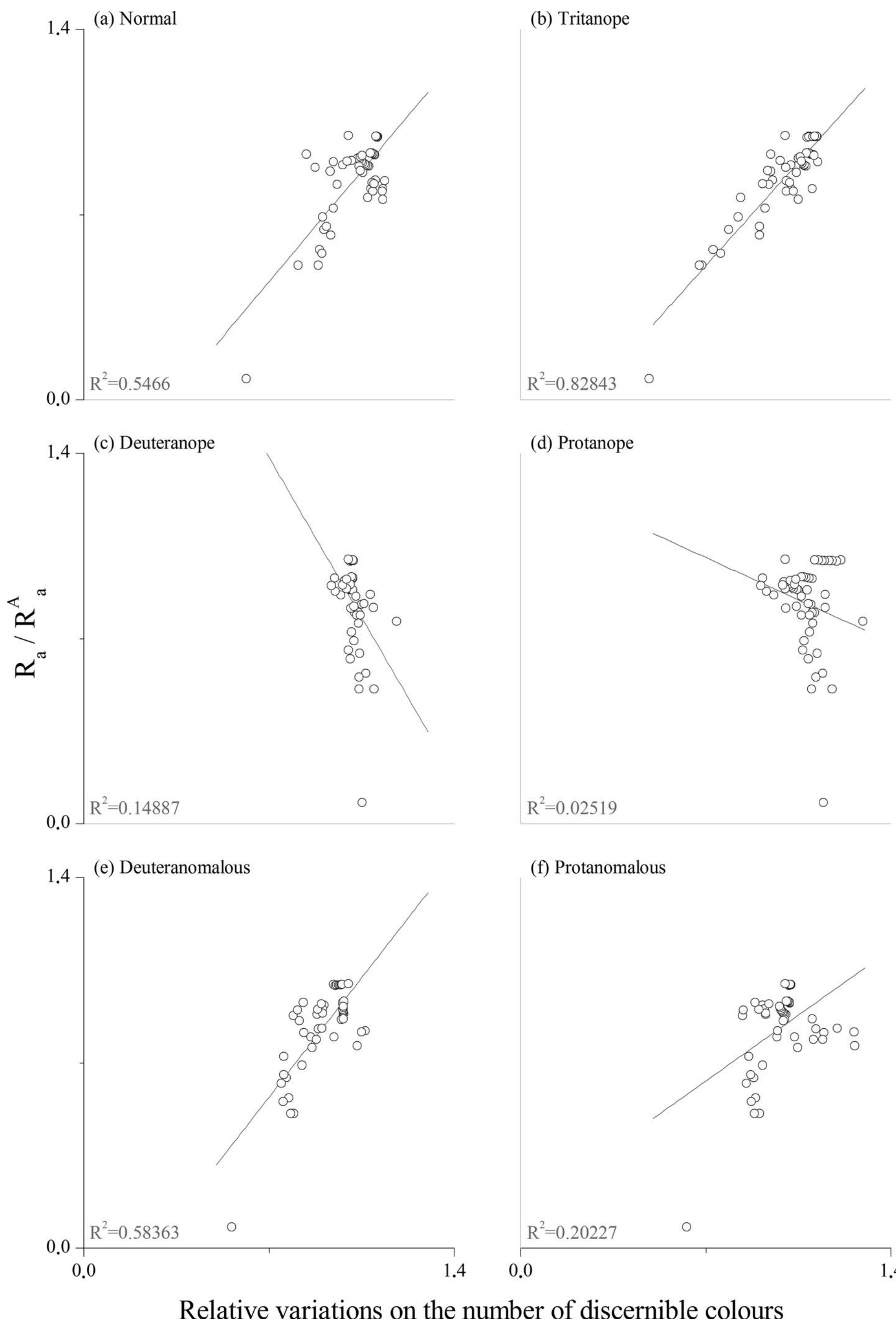

Fig. 7. Ratio between the color rendering index R_a for each of the illuminants and the corresponding value for illuminant A R^A_a as a function of the relative variations on the number of discernible colors for (a) a normal, (b) a tritanopic, (c) a deuteranopic, (d) a protanopic, (e) a deuteranomalous, and (f) a protanomalous observer. The straight line represents an unweighted linear regression, and the proportion of variance R^2 accounted for in the regression is given.

of the color volume and therefore an improvement in color discriminability, consistent with findings reported in previous research for Munsell surfaces [41], for optimal colors [18], and for samples of the Farnsworth–Munsell 100-hue test [17]. The illuminants FL11* and HP4 produced in almost all cases a considerable enhancement in the number of discernible colors. Both illuminants are three-band illuminants with spectral maxima in the red, green, and blue regions of the visible spectrum and were found to be the best ones for normals (FL11*), deuteranopes (HP4), protanopes (HP4), and protanomalous observers (HP4).

The correlation between the number of discernible colors for normal and color deficient observers and traditional color rendering indices was found to be rather low, in particular for color deficient observers. This suggests that the color rendering index may not be adequate to evaluate the color rendering quality of light sources for

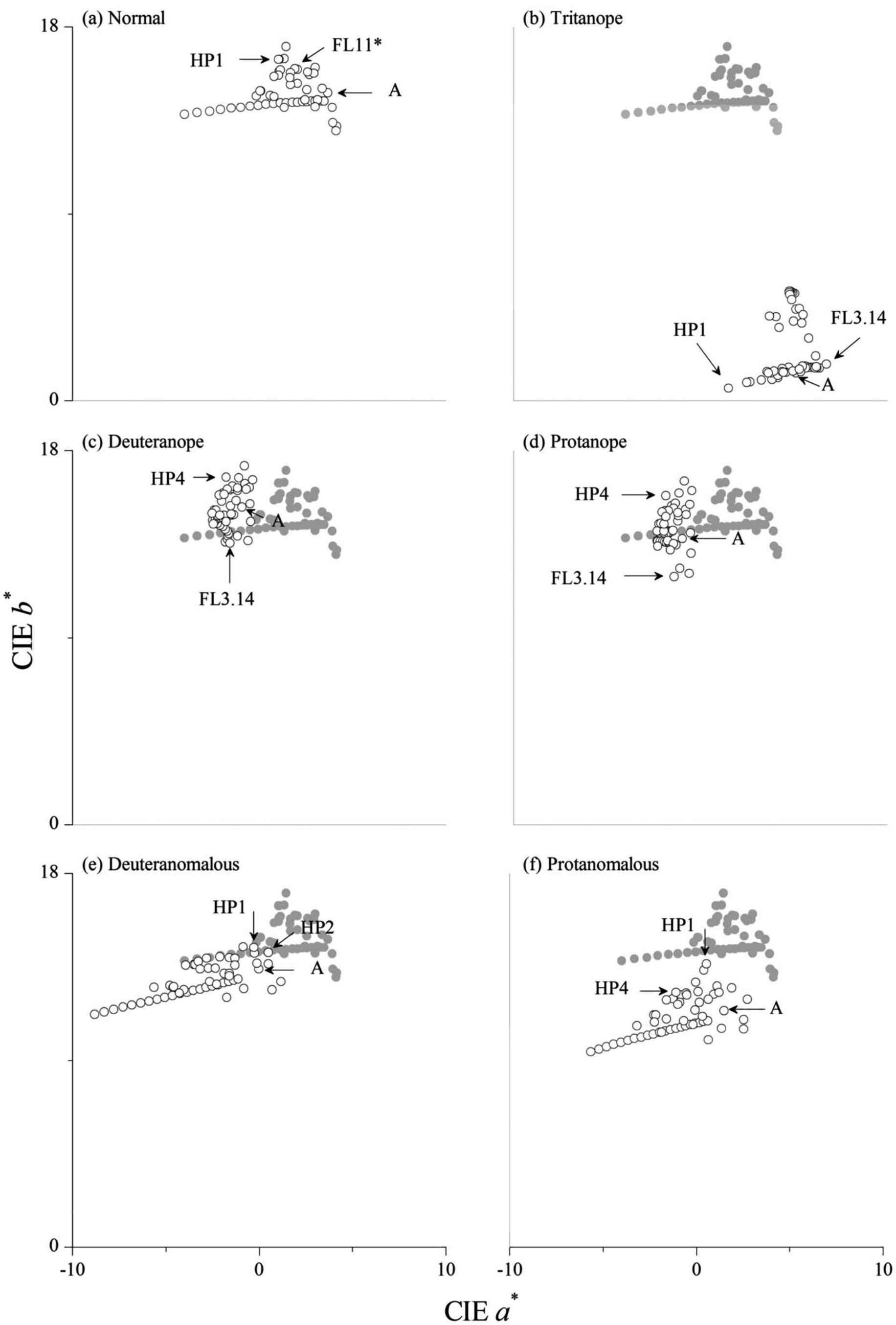

Fig. 8. Open symbols represent the average CIE (a^*,b^*) color coordinates for the paintings of Fig. 1 rendered by each 21 CIE illuminant D (in the range 25,000 K to 3,600 K), illuminant A, C, 27 FL illuminants and 5 HP illuminants, for (a) a normal, (b) a tritanopic, (c) a deuteranopic, (d) a protanopic, (e) a deuteranomalous, and (f) a protanomalous observer. Solid gray symbols represent the average CIE (a^*,b^*) color coordinates for normal observers. Data corresponding to the reference illuminant (illuminant A), the best illuminant, and the worst illuminant are represented.

color deficient observers. It is unlikely that a single index can encompass the complex visual effects of the light sources, and a multivariable metric may be necessary. However, color discrimination is a very important aspect for color deficient observers and may assume particular relevance in the appreciation of art paintings. These observers are already at a disadvantage, and therefore the number of discernible colors can constitute a useful guide to classify the effects of the light sources.

The results reported here were based on a model of dichromatic color perception that is known to describe dichromatic color vision incompletely [42]; furthermore, the computation of the number of discernible colors by segmentation of the color volume is done in the CIELAB color space known for its nonuniformity, in particular in blue and gray areas [29,43]. Also, the segmentation of the color volume into unitary cubes assumes that all colors inside the same cube could not be distinguished, but in fact

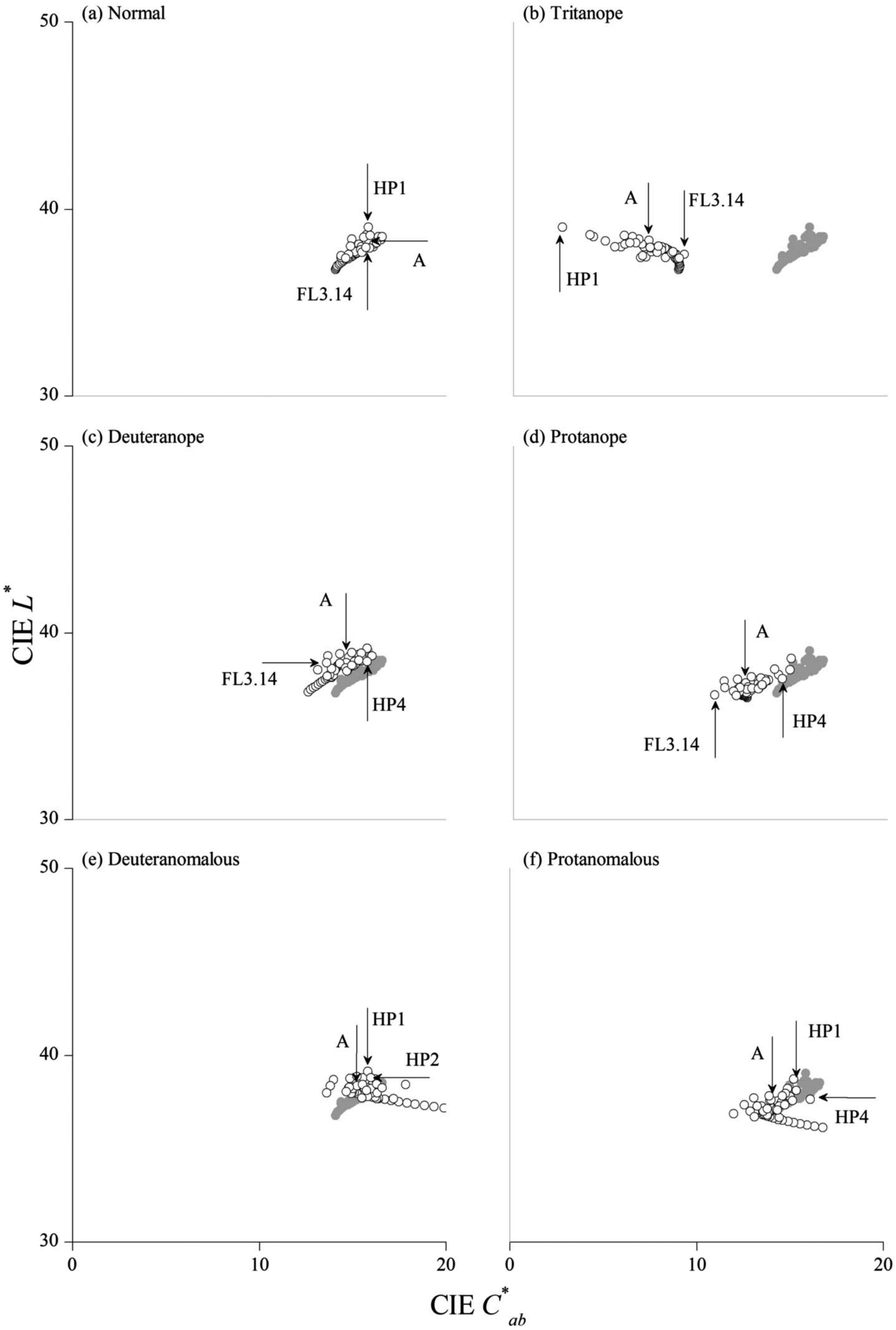

Fig. 9. Same as Fig. 9 but with data represented in CIE (C^*_{ab},L^*).

some pairs have a color difference $\Delta E^*_{ab} > 1$. The use of unitary spheres to segment the color volume can partially overcome this limitation, but some studies [33] suggest that relative estimates of the number of discernible colors are robust in relation to other methodologies that can be used to compute with great accuracy the number of discernible colors. Also, the sample of paintings is limited in number and type, and generalizations have to be made with care, but the paintings constitute a larger and more realistic sample than the limited number of surfaces used to compute color rendering indices.

Despite these limitations the data presented here suggest that good lighting conditions for all types of observers can be obtained with adequate choice of illuminant, information that may be very useful to the museums and art galleries.

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