# Correlated color temperature preferred by observers for illumination of artistic paintings

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The visual effects of lighting on art paintings is an important aspect that should be considered by museum curators. The aim of this work was to determine the correlated color temperature (CCT) of daylight illumination preferred by observers when appreciating art paintings. Hyperspectral images of 11 oil paintings were collected at the museum, and the appearance of the paintings under daylight illuminants with CCT from 25,000 K to 3600 K was computed. In a psychophysical experiment using precise CRT reproductions of the paintings, observers had to adjust the CCT of the illuminant such that it produced the best visual impression. It was found that the distribution of observers' preferences had a maximum at a CCT of about 5100 K and that this value did not depend on whether the observers were undergraduate students or museum visitors or on the degree of adaptation to the color of the illumination. These results suggest that observers prefer a more bluish-white light than that normally used in museums. © 2008 Optical Society of America

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## 1. INTRODUCTION

Illumination of artwork in museums and art galleries has specific requirements regarding aspects of conservation and visualization. As visible and invisible radiation can damage colored surfaces, the damaging potential of the illumination is the fundamental concern of museum curators. Because UV radiation causes photodegradation of pigments and IR radiation produces heat [1–4], filtering UV and IR light and controlling the overall illuminance levels and the periods of light exposure are the basic precautions taken to protect the artwork from the unwanted effects of radiation [5,6].

In spite of the fact that the human visual system is capable of partially compensating for variations in the spectral composition of the illuminant [7–9], the visual perception of objects is influenced both by the intensity of the light source and by its spectral composition [10–13]. Thus, the chromatic effects of lighting are important aspects to be taken into account in art exhibits.

There is a wide range of options for artwork illumination, from incandescent sources and gas discharge through solid-state devices. Natural daylight, tungsten halogen lamps, and fluorescent lamps are probably the most current types of lighting used in museums [5]; modern light sources, such as SoLux lamps with various correlated color temperature (CCT) and white LED lamps, are also becoming of relative common use [14,15]. The damaging aspects of these sources are generally well characterized but less so for their visual effects, in particular, in the context of visualization of artistic paintings.

The choice of a light source for visualization of artistic paintings may be motivated by specific aesthetic aspects, for example, to produce particular impressions for fidelity to the intentions of the artist. Many artists painted with natural light [16], as the ideal studio was a north-lit room [17]; but some used other light sources for specific effects, such as candlelight [18,19]. These cognitive aspects are certainly important in the contextualization of art. Another, more empirical way to decide about the light source is to take into account the observer's preference. Although this preference may be determined by several visual properties, such as the diversity and naturalness of colors or contrast, it may have practical use and provide cues to understanding how the illumination influences the visual impression produced by the painting.

Laboratory experiments using postcard reproductions of several types of paintings have shown that observers preferred illuminants with relatively low CCT, in particular, one of about 3600 K [10]. It was hypothesized that this CCT corresponds to light producing a sensation neither warm nor cool [13]. Results of experiments using hyperspectral data from paintings for precise display on a calibrated CRT monitor suggested that observers preferred illuminants with a higher color temperature [12]; this study also suggested that preference could have been influenced by chromatic diversity, a complementary quantification of color rendering properties [20,21]. Although these studies provided very useful empirical data, they were limited in color fidelity [10], in the range of illuminants used [12], and in the number of observers and paintings tested.

The aim of the present work was to determine psychophysically the CCT of daylight illumination preferred by observers when seeing oil paintings, old and modern. The study was carried out with a large sample of 80 observers, students and museum visitors, and 11 paintings of different époques. The experiment was based on stimuli obtained from hyperspectral data of the paintings, which allowed precise chromatic representation of the paintings in a calibrated CRT display.

## 2. METHODS

### A. Hyperspectral data

Figure 1 shows color pictures of the 11 oil paintings used in the study. They were selected from the collection of Museu Nogueira da Silva in Braga, Portugal. The set consisted of 11 oil paintings, 7 from the Renaissance époque painted on wood (A–E, H and I) and 4 (F, G, J, and K) from the 20th century painted on canvas. Two of the more recent paintings (J and K) are from Henrique Medina, one (F) from Carlos Reis and the other (G) from Veloso Salgado. All four are by Portuguese painters.

Each painting was digitalized in the museum with a hyperspectral system. Multispectral and hyperspectral imaging have been applied for complete spectral reconstruction of the paintings [12,22–24], a technique with a range of possible application in conservation [25]. The present system consisted of a low-noise Peltier-cooled digital camera with a spatial resolution of $1344 \times 1024$ pixels and 12-bit output (Hamamatsu, Model 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., Massachusetts, USA) mounted in front of the lens (for more details on the hyperspectral system see [26]). The hyperspectral digitalization was carried out over the range of 400–720 nm at 10 nm intervals. The paintings were illuminated with low-level SoLux illumination. The imaging distance and optical setup were such that the spatial resolution of the system was about 0.5 mm.

The spectral reflectance of each pixel of the paintings was estimated from a gray reference surface present near the painting at the time of digitalization. Illuminant spatial nonuniformities were compensated using measurements of a uniform surface imaged in the same location and under the same illuminating conditions as the paintings [12]. The accuracy of the system in recovering spectral reflectance functions was tested with oil painted test samples [27], and the average spectral difference was 2%; the colorimetric error was on average 1.3 when expressed by the CIEDE2000 color difference formula [28] and 2.2


Fig. 1. (Color online) Color pictures of the 11 oil paintings used in the study. They were selected from the collection of Museu Nogueira da Silva in Braga, Portugal. The set consisted of 11 oil paintings, 7 from the Renaissance époque painted on wood (A–E, H and I) and 4 (F, G, J, and K) from the 20th century painted on canvas. Two of the more recent paintings (J and K) are from Henrique Medina, one (F) from Carlos Reis and the other (G) from Veloso Salgado. All four are by Portuguese painters.

when expressed by the CIELAB color difference formula $\Delta E^*_{ab}$. [29], an accuracy level within the acceptable range for visualization purposes [30,31].

### B. Stimuli

The paintings were assumed to be illuminated by daylight illuminants with CCT from 25,000 K to 3600 K generated from a set of basis functions taken from a principal components analysis based on 622 samples of daylight [32,33] and corresponding to the D illuminants recommended by the CIE [29] except for the lower limit, which was slightly below the 4000 K recommended. The locus of natural daylights can be described by a line in CIE 1931 $(x,y)$ chromaticity space, and therefore each daylight can be represented by its $x$ coordinate. For the purpose of the experiment, a sample of 21 equally spaced illuminants in the CIE $x$ coordinate was selected. Thereafter, the illuminants will be referred either by the CCT or by the corresponding CIE $x$ coordinate, represented by $x_D$. The spectral radiance reflected from each painting under each illuminant was estimated by computing the product of spectral reflectance functions of the paintings by the spectral radiance of the illuminants.

Figure 2 (left) represents the normalized daylight spectra for CCT of 3600 K, 6500 K ($D_{65}$), and 25,000 K; on the right is the locus, represented in the CIE $(x,y)$ diagram, of the chromaticities of daylight illuminants used in this study. Daylight illuminants were selected because they span a wide range of CCT, with the extremes of the range being representative of the illumination at noon and evening [34]. Halogen and Standard Illuminant A have a lower CCT and were tested in another study [12].

Images of the paintings rendered under these illuminants were displayed on a 17 in. (1 in. = 2.54 cm) RGB color monitor with a flat screen (Trinitron, Model GDM-F400T9; Sony Corp., Tokyo, Japan) controlled by a computer raster-graphics card providing 24 bits per pixel in true-color mode (VSG 2/5; Cambridge Research Systems, Rochester, UK). The display system was calibrated in color and luminance with a telespectroradiometer (SpectraColorimeter, Model PR-650; Photo Research Inc., Chatsworth, California). Errors in the displayed CIE $(x,y,Y)$ coordinates of a white test patch were $<0.005$ in $(x,y)$ and $<3\%$ in $Y$ ($<5\%$ at lower light levels). Screen resolution was $750\times600$ pixels, and the refresh rate was 80 Hz. Images subtended to a 12–19 deg visual angle and were observed from a distance of 1 m from the screen. For display purposes all images were used with a spatial resolution that was half of the original resolution. All images were displayed with an average luminance of 8 $cd/m^2$. This luminance level corresponded to an illumination on the paintings in the range of 200–400 lux (depending on illuminant and painting) with an average of about 330 lux, which was close to the maximum levels recommended for museums [5].

Due to color gamut limitations of the monitor, not all pixels could be reproduced with accuracy. The percentage of pixels out of gamut was, on average, smaller than 2.3%; these pixels were displayed by clipping to the closest RGB values, producing on average an error of $\Delta E^*_{ab}=0.30$ in the CIELAB space. Figure 3 represents for two paintings, H (left) and K (right), the percentage of pixels out of gamut (solid curve) and the average chromatic error (dotted curve) expressed as $\Delta E^*_{ab}$ in CIELAB space resulting from clipping the out-of-gamut pixels. All values are expressed as a function of the CIE $x_D$ coordinate of the illuminant. The level of accuracy obtained is adequate for the purposes of this work, as the percentage of pixels out of gamut is small and the average color error is below the detectable magnitude [30,31].

### C. Procedure

Half of the experimental sessions took place in the laboratory with undergraduate students and half in the museum with museum visitors. In both locations the display system was the same and was located in a dark ambiance with average light levels lower than 2 $cd/m^2$. To investigate the influence of adaptation to the color of the illuminant, two spatial conditions were tested. In one, the paintings were observed on a black background; in the other, they were observed on a gray background subtending a 22 deg visual angle illuminated by the same illuminant as the painting and with a luminance of 8 $cd/m^2$.

The observers were instructed to adjust the CCT of illumination such that it produced the best visual impression of the painting. The instructions for the experiments were in written format (see the text below) and shown in

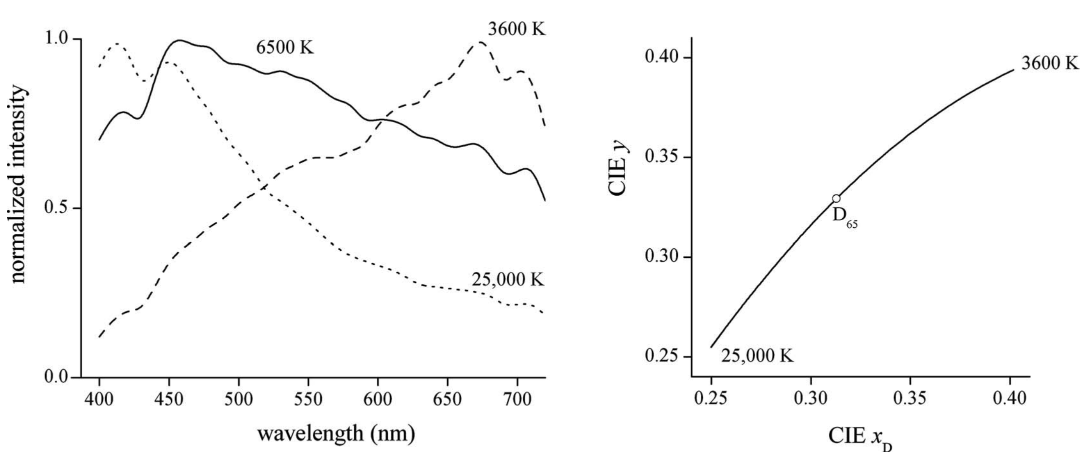


Fig. 2. (Left) Normalized daylight spectra for CCT of 3600 K, 6500 K ($D_{65}$), and 25,000 K. (Right) Locus of the chromaticities represented in the CIE $(x,y)$ diagram of the daylight illuminants used in this study.

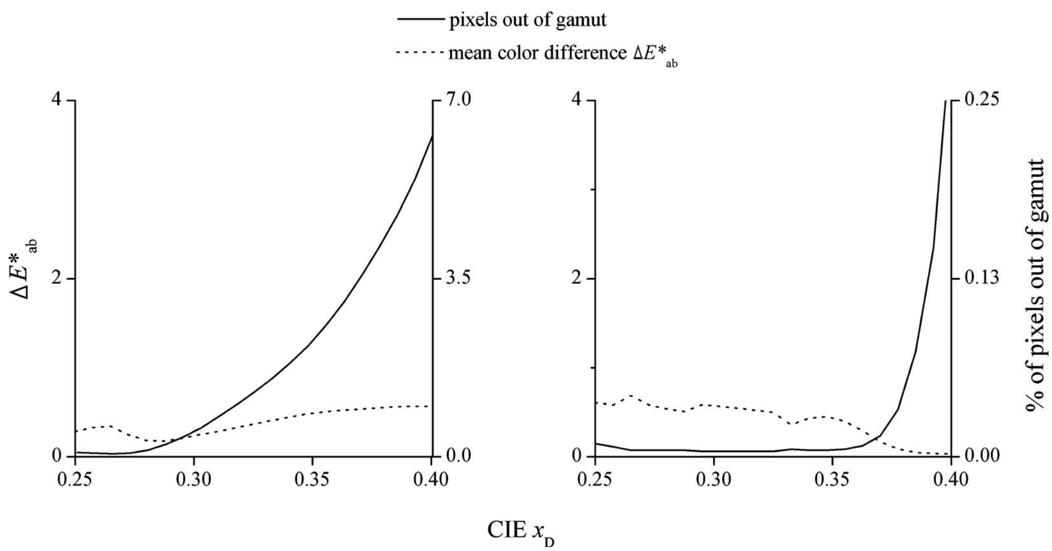


Fig. 3. Percentage of pixels out of gamut (solid curve) for two of the paintings, H (left) and K (right), used in the experiment and the average chromatic error (dotted curve) expressed as $\Delta E^*_{ab}$ in CIELAB space resulting from clipping the out-of-gamut pixels. All values are expressed as function of the CIE $x_D$ coordinate of the illuminant. Notice the difference in the scales on the left and the right axes.

the monitor display before each experimental session. In each trial, the observer selected the preferred illumination on the painting by using a remote device (CB6 Response Box, Cambridge Research Systems, Rochester, UK) that could change the illuminant on the painting within the CCT range selected. There was no time limit for the selection. In each session all paintings were tested in the two spatial conditions. Paintings and spatial condition were presented in a random order. The undergraduate students performed a total of three sessions on different days, and the museum visitors performed one session.

### D. Instructions

The text of the instructions was as follows: "With the available remote control it is possible to control the color of the illumination on the painting you are looking at. We invite you to select the illumination on the painting for your best appreciation."

### E. Observers

Two groups of observers participated in the experimental sessions. One group consisted of 40 undergraduate students, 12 males and 28 females, with an average age of 22 years old and a sample standard deviation of 1. The other group consisted of 40 observers, 20 males and 20 females, with an average age of 35 years old and a sample standard deviation of 13. These observers were selected from the visitors of the museum during the summer of 2006. They were all unaware of the purpose of the experiment and had normal or corrected Snellen acuity and normal color vision, as assessed by Rayleigh and Moreland anomaloscopy. Informed consent was obtained from all participants, and the research was conducted accordingly to the guidelines promoted by the Declaration of Helsinki.

## 3. RESULTS

Figure 4 shows observers' responses (open symbols) for two paintings (H and K on the left and right, respectively) represented by the frequency of illuminant selection expressed as a function of the CIE $x_D$ coordinate of the illuminant. Data based on 40 undergraduate observers and three trials per observer were obtained with the gray background. The solid curves represent Gaussian fits to the data, and the CCT indicated in each case represents the CCT corresponding to the maximum value of each Gaussian. The distributions of responses have clearly different maxima, but both could be reasonably fit with a Gaussian. The data for other paintings and conditions show similar patterns, although with different peak positions depending on the painting.

Figure 5 shows observers' responses (open symbols) represented in the same format as in Fig. 4 for the four conditions of the experiment. Data are pooled over observers and paintings. The solid curves represent Gaussian fits to the data, and the CCT indicated represents the CCT corresponding to the maximum value of each Gaussian. The peak positions of the Gaussian fits vary only a little with the conditions of the experiment, suggesting that they are equivalent. A Kruskal–Wallis test did not detect a significant difference between the conditions ($p > 0.9$). The width of the distribution of responses is larger for the measurements made in the museum than for the measurements in the laboratory. This may result from the fact that observers in the museum performed only one trial for each painting, whereas in the laboratory they performed three. Also, observers in the museum were less familiar with computer and computer controls than students were, which may have also contributed to more uncertainty and hence more noise.

In Fig. 5 are also represented (bars) the frequency of occurrence of the maxima of the distributions of observers' responses for individual paintings (for visualization purposes these frequencies were scaled by a factor of 10). These peaks were derived by fitting a Gaussian curve to the data for each individual painting and computing the CCT corresponding to the maximum of the fit. These data for individual paintings show that the observers' prefer-

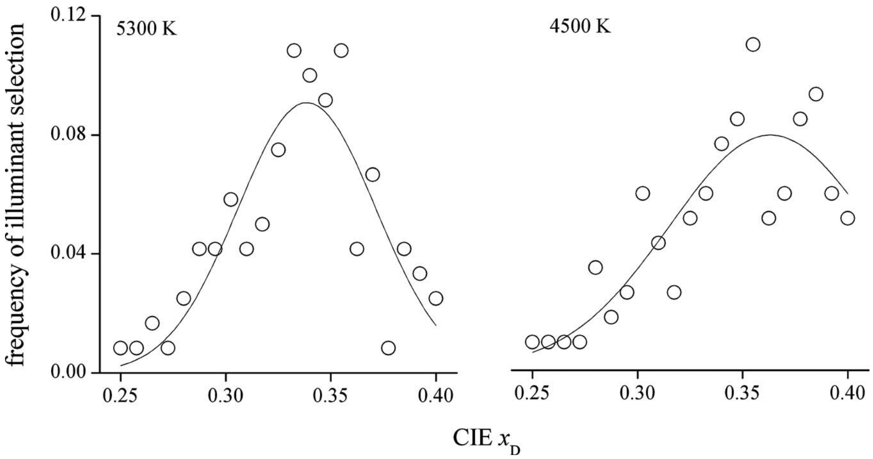


Fig. 4. Observers' responses (open symbols) for two paintings, H on the left and K on the right, represented by the frequency of illuminant selection expressed as a function of the CIE $x_D$ coordinate of the illuminant. Data based on 40 undergraduate observers and three trials per observer were obtained with the gray background. The solid curves represent Gaussian fits to the data, and the CCT indicated represents the CCT corresponding to the maximum value of each Gaussian. The data for other paintings and conditions show similar patterns, although with somewhat different peak positions depending on the painting.

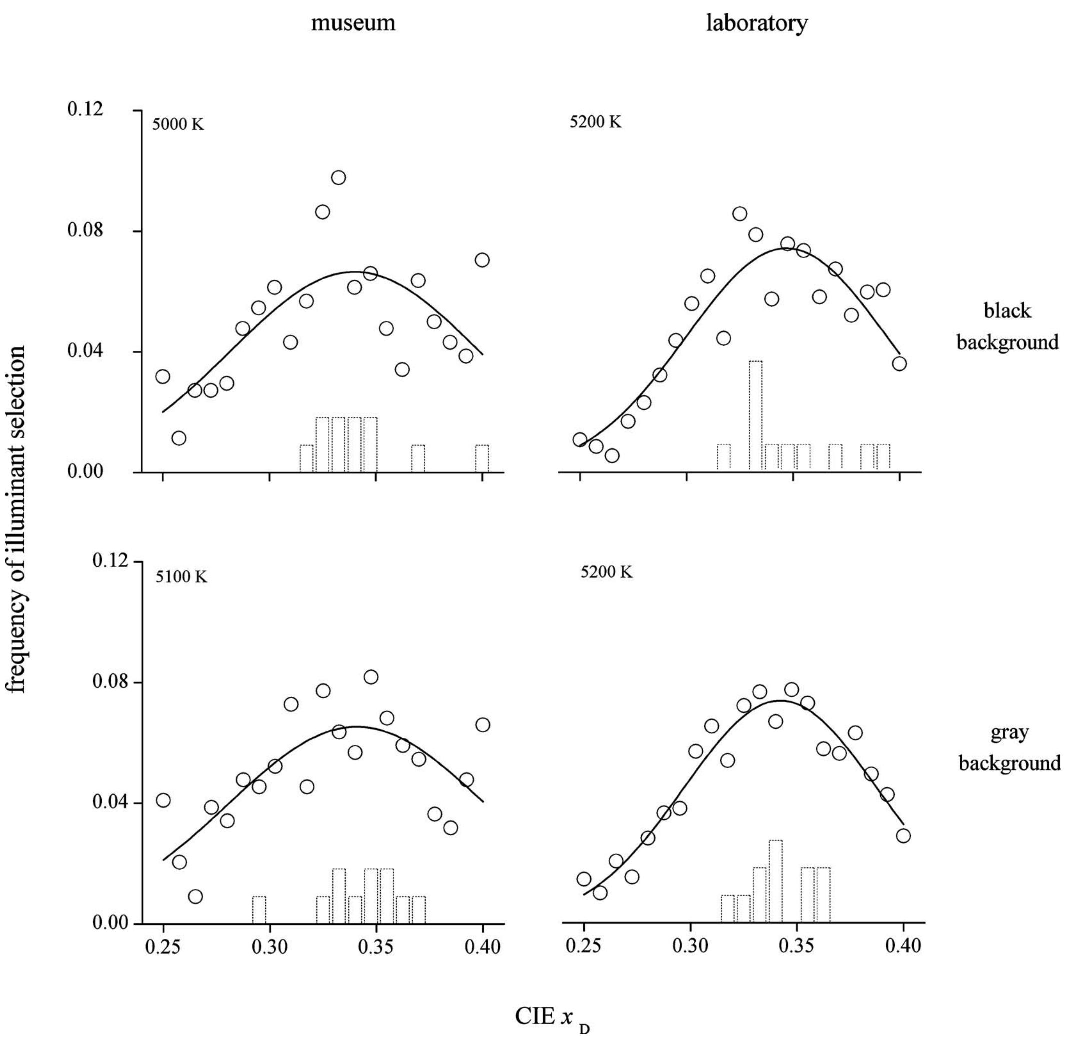


Fig. 5. Observers' responses (open symbols) represented by the frequency of illuminant selection expressed as a function of the CIE $x_D$ coordinate of the illuminant for the four conditions of the experiment. Data are pooled over observers and paintings. The solid curves represent Gaussian fits to the data, and the CCT indicated represents the CCT corresponding to the maximum value of each Gaussian. In the figure are also represented (bars) the frequency of occurrence of the maxima of the distributions of observers' responses for individual paintings (for visualization purposes the frequency was scaled by a factor of 10).

ences are close to the maximum obtained from the pooled data, suggesting a moderate variation across paintings.

To quantify further how well a light source with a CCT determined by the pooled data is suitable for individual paintings, the following computation was carried out. The ratio between the maximum frequency obtained for each individual painting and that corresponding to the CCT obtained for the pooled data was computed. The average value was 89% and 92% for black and gray backgrounds, respectively, for experiments carried out in the museum and 89% and 94% for black and gray backgrounds, respectively, for experiments carried out in the laboratory. These data show that a single CCT will be suitable for the set of paintings tested here.

## 4. DISCUSSION

Daylight illumination with a correlated color temperature of about 5100 K was found to represent observers' preferences adequately. Although some variation across paintings was observed, this CCT seems quite adequate for all paintings. This result was found to be robust in relation to the type of observers, undergraduate students or museum visitors, and in relation to adaptation to the illuminant. The results reported here are generally consistent with those of a previous study using a different methodology and a smaller selection of illuminants and paintings [12]. The present approach was better, as it allowed a wide range of CCT to be selected and used a larger sample of observers and paintings. Moreover, these results are consistent with a study where the color gamut associated with CCT lower than 5500 K was found to be smaller than that associated with higher temperatures [21].

In studies carried out with color reproductions of paintings [10], the illuminant with CCT of 3600 K was found to be optimal. The data reported here show that for this CCT (corresponding to a $x_D$ of about 0.40) the observers' frequency of illuminant selection drops to about 65% of the maximum, which makes it probably acceptable but not optimal for the paintings tested here. Significantly, it was suggested in a subsequent work [13] that due to large sampling intervals, the value of the optimized CCT could have been underestimated.

What determines observers' preferences? It was suggested that observers could chose an illuminant color neither cool nor warm [13]. With the setup described in Section 2 but with only the gray background present in the display, a group of 10 observers (none involved in the experiments with the paintings) was asked to adjust the color of the illuminant such that it appeared neither cool nor warm. A CCT of about 5100 K was in fact selected most often, suggesting that a subjective impression of cool–warm may have determined preference; it cannot, however, explain the variations of preference across paintings, as it refers to a single value.

A previous work [12] suggested that chromatic diversity, considered as the number of discernible colors that can be perceived in the paintings [35–37], could influence observers' preferences. To test for the influence of this factor, the number of discernible colors was computed for each painting and for each of the 21 illuminants used in the experiment. The chromatic representation of the paintings in the approximately uniform CIELAB color space was computed, and the number of nonempty unitary volumes in that space were calculated (for more details of this computation see [12]). This procedure computes an approximated but reasonable estimation of the number of discernible colors [21,35,38]. Figure 6 represents, as illustration, the relative variation in the number of colors for two of the paintings (A and B on the left and right, respectively) expressed as a function of the CIE $x_D$ coordinate of the daylight illuminant. Using other methods to compute the number of discernible colors, such as using spheres instead of cubes [37] or a color difference formula such as the CIEDE2000 [28], does alter the absolute numbers but not the relative changes. The correlation between observers' preferences for each painting, expressed as the CCT corresponding to the maximum of observers' responses, and the number of colors, corresponding to the maximum of the distribution of the number of colors, is represented in Fig. 7. The plot was based on the experimental data obtained in the laboratory. The straight line represents an unweighted linear regression. The proportion of variance $R^2$ accounted for in the regression was 0.68, which is statistically significant ($p=0.02$).

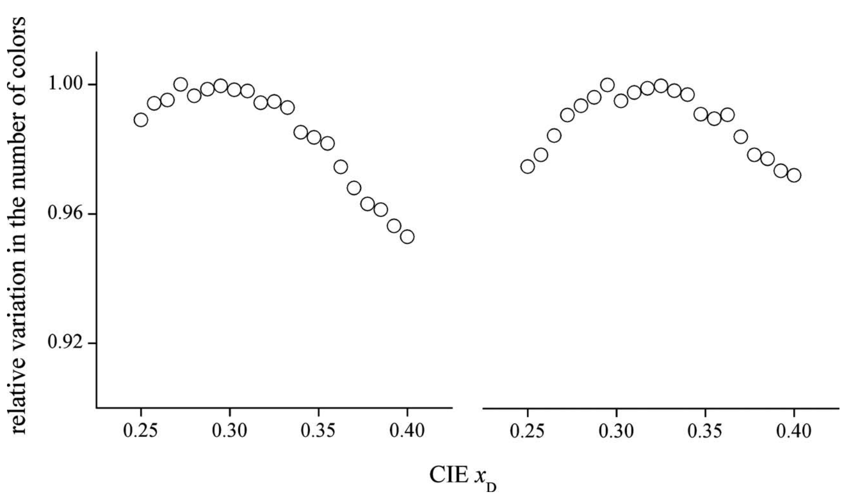


Fig. 6. Relative variation in the number of colors for two of the paintings (A and B) expressed as a function of the CIE $x_D$ coordinate of the daylight illuminant.

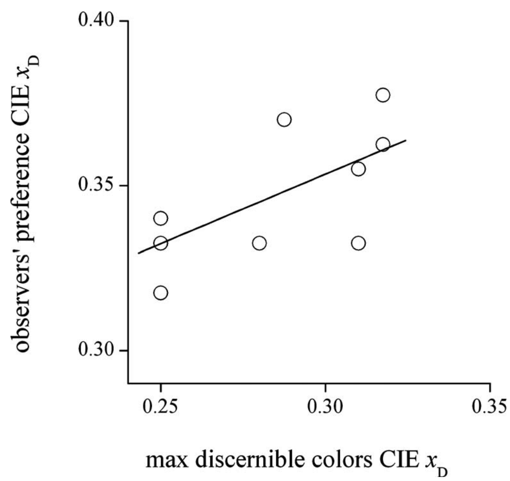


Fig. 7. Correlation between observers' preferences for each painting quantified as the CCT corresponding to the maximum of observers' preferences and the CCT estimated from the maximum of the number of colors for the corresponding painting. Only nine symbols are visible due to superposition. The plot was based on the experimental data obtained in the laboratory. The straight line represents an unweighted linear regression. The proportion of variance $R^2$ accounted for in the regression was 0.68, which is statistically significant ($p=0.02$).

These data suggest that chromatic diversity could be involved in determining an observer's preference.

The way chromatic diversity is quantified here represents a method to characterize the chromatic effects of a light source; another is by its color rendition capability, which is typically evaluated by the Color Rendering Index (CRI) defined by the CIE [39–41]. This index has, however, limitations, as it does not quantify the number of colors that can be perceived in a complex scene [42], and thus a complementary quantity may be necessary [21].

Several other factors, which are difficult to quantify, may influence observers' preferences. These could be luminance contrast, chromatic contrast, naturalness of the colors of natural elements in the scenes represented by the painters. These and other aspects may naturally be optimized for conditions of illumination similar to those present at the time of execution of the painting, which are likely to have been those of skylight [16,17], having a CCT of at least 5700 K [34]. This line of interpretation must, however, be explored with care because although many paintings were indeed painted under skylight following the advice of Leonardo da Vinci [43], artificial light sources were also used [18,19]. Another important aspect that may influence a painting's appreciation concerns the pattern of gaze positions of observers when they are looking at the paintings, which revels the perceptual saliency of specific features and which was found to be influenced by illumination [44].

Although paintings of several types were tested here, the sample is limited and care must be taken in generalizations to other types of paintings or works of art. Also, the experiment was carried out with a monitor display. Although it displayed the colors with very high precision, the stimuli were only a representation of the real paintings and viewing such paintings full size on a museum wall may produce different impressions. The effect of intensity was not investigated but may influence the preferred color temperature [11]; however, it seems that the perception of cool–warm is not influenced by intensity [13]. On the other hand, light levels in the museum are limited to approximately the corresponding illuminance levels used in this work.

## ACKNOWLEDGMENTS

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