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Psychophysical estimation of the best illumination for appreciation of Renaissance paintings

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Abstract

A variety of light sources are used in museum environments where the main concern is to prevent damaging effects of the light on paintings. Yet, the visual impression of an artistic painting is strongly influenced by the intensity and spectral profile of the illumination. The aim of this work was to determine psychophysically the spectral profile of the illumination preferred by observers when seeing paintings dated from the Renaissance époque and to investigate how their preferences correlate with the color temperature of the illumination and with the chromatic diversity of the paintings. Hyperspectral images of five oil paintings on wood were collected at the museum and the appearance of the paintings under five representative illuminants computed. Chromatic diversity was estimated by computing the representation of the paintings in the CIELAB color space and by counting the number of nonempty unit cubes occupied by the corresponding color volume. A paired-comparison experiment using precise cathode ray tube (CRT) reproductions of the paintings rendered with several illuminant pairs with different color temperatures was carried out to determine observers' preference. The illuminant with higher color temperature was always preferred except for one pair where no clear preference was expressed. The preferred illuminant produced the larger chromatic diversity, and for the condition where no specific illuminant was preferred the number of colors produced by the illuminant pair was very similar, a result suggesting that preference could have been influenced by chromatic diversity.

Keywords: Artworks illumination, Museum lighting, Chromatic diversity, Color of paintings, Color vision

Introduction

Artistic paintings in museums are illuminated by a variety of light sources such as natural daylight, tungsten halogen lamps, and light sources that approximate natural daylight, such as SoLux lamps (Thomson, 1986). The potential damaging effects of the light on paintings and the visual impression it produces to an observer are two aspects determining the type of illumination to be used. Protecting paintings from light damage normally implies light sources of low intensity and low ultraviolet content (Brill, 1980; Nassau, 1998; Taft et al., 2000). On the other hand, although the visual impression is influenced by the spectral profile and intensity of the local illuminant (Davis & Ginthner, 1990; Scuello et al., 2004*b*) few experimental data are available concerning observers' preferences. Given that concerns about damage still allow the illumination to be selected from a wide range of possibilities, psychophysical research on this issue may be of great relevance for museums and, more generally, for the artistic community.

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To investigate the illumination preferred by observers for appreciation of artistic paintings in real viewing conditions is difficult because it implies viewing and comparing the same painting under different test illuminations. Tests have been carried out in laboratory experiments using postcard reproductions of several types of paintings (Scuello et al., 2004*b*), and it was found that although illuminants approximating daylight were acceptable, observers preferred other illuminants with lower correlated color temperatures (CCT) and, in particular, one with a CCT of about 3600 K. The reason for this preference is not clear as this type of lighting is very different from the one under which the paintings are likely to have been executed; it has been hypothesized that it corresponds to light producing a sensation neither warm nor cool (Scuello et al., 2004*a*). Using postcards instead of real paintings may introduce artifacts related to chromatic distortions intrinsic to the reproduction process, and therefore data obtained under more chromatically faithful conditions may be necessary.

What quantifiable parameters may influence the visual impression of a painting and determine the preference for a specific illuminant? One possibility is that observers are influenced by the number of colors they can see in the painting or, in other words, by its chromatic diversity. Thus, a painting viewed under a light source producing a rich chromatic impression will be preferred to the painting viewed under a light source with poor color rendering.

The aim of this work was to determine the illuminant preferred by observers when seeing chromatically faithful cathode ray tube (CRT) reproductions of oil paintings and to investigate how their preferences correlate with the color temperature of the illumination and with the chromatic diversity of the paintings estimated from hyperspectral imaging data of the paintings. The paintings selected were all from the Renaissance époque, a selection determined by the compatibility of their color gamut with that of the CRT monitor display, a necessary condition for precise chromatic reproduction. Chromatic diversity was estimated by computing the representation of the paintings in CIELAB color space and by counting the number of nonempty unit cubes occupied by the corresponding color volume. A paired-comparison experiment using precise CRT reproductions of the paintings rendered with five illuminant pairs with different color temperatures was carried out to determine observers' preference. The illuminant with higher color temperature was preferred except for one case where no clear preference was expressed. The preferred illuminant produced the larger chromatic diversity, and for the condition where no specific illuminant was preferred the number of colors produced by the illuminant pair was very similar, a result suggesting that preference could have been influenced by chromatic diversity.

Materials and methods

Hyperspectral imaging

Hyperspectral images of five oil paintings on wood dated from the Renaissance époque were collected at the Museu Nogueira da Silva, Braga, Portugal. Fig. 1 shows color pictures of the paintings. The hyperspectral system (for details, see Foster et al., 2004) had 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., Hamamatsu City, Japan) and a fast-tunable liquid-crystal filter (VariSpec, model VS-VIS2-10HC-35-SQ, Cambridge Research & Instrumentation, Inc., MA) mounted in front of the lens. The wavelength of peak transmission could be varied over the spectral range 400–720 nm with a full width at half maximum (FWHM) of 10 nm at 550 nm, decreasing to 6 nm at 400 nm and increasing to 16 nm at 720 nm. Hyperspectral data were collected at the museum under low level Solux illumination.

The spectral reflectance of each pixel of the paintings was estimated from a gray reference surface present near the painting. 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. The accuracy of the system in recovering spectral reflectances of oil-painted test samples was on average within 1.3 when expressed by the CIEDE2000 color difference equation (Luo et al., 2001) or 2.2 when expressed in the CIELAB color space, and the average spectral error was 2% (Carvalhal, 2004). This accuracy in recovering the spectral data is within the acceptable range for visualization purposes (Berns, 2001).

The spectral radiance reflected from each painting under five illuminants, CIE standard illuminants A, B, and $D_{65,}$ with CCT of 2856 K, 4874 K, and 6500 K (Wyszecki & Stiles, 1982), respectively, Solux with a correlate color temperature of 4450 K, and Halogen with a correlated color temperature of 3000 K, was estimated by computing the product of the spectral reflectance functions of the paintings by the spectral radiance of the illuminants.

Chromatic diversity

Chromatic diversity was quantified by estimating the number of discernible colors in each painting rendered under each of the five illuminants. The chromatic representation of the paintings in the approximately uniform CIELAB color space was first computed using the spectral radiance reflected from each painting under each illuminant and the color-matching functions for the CIE 1931 standard colorimetric observer (2 deg). The corresponding CIELAB color volume was then segmented in unit cubes and the number of nonempty cubes computed and assumed to be equal to the number of discernible colors. In this counting procedure pairs of colors represented in different cubes are assumed to be distinguishable, but pairs represented in the same cube are not. The method approximates the assumption that in CIELAB space a just discernible difference is represented by a Euclidian distance of about 1.0 and computes an approximated but reasonable estimation of the number of discernible colors (Pointer & Attridge, 1998; Linhares et al., 2004).

Stimuli and procedure

Images of the paintings under each of the five illuminants were displayed on a 17-inch RGB color monitor with flat screen (Trinitron, model GDM-F400T9; Sony Corp., Tokyo, Japan) controlled by a computer raster-graphics card providing 24 bits per pixel in

Fig. 1. Color pictures of the five oil paintings on wood dated from the Renaissance époque from the collection of the Museu Nogueira da Silva, Braga, Portugal.

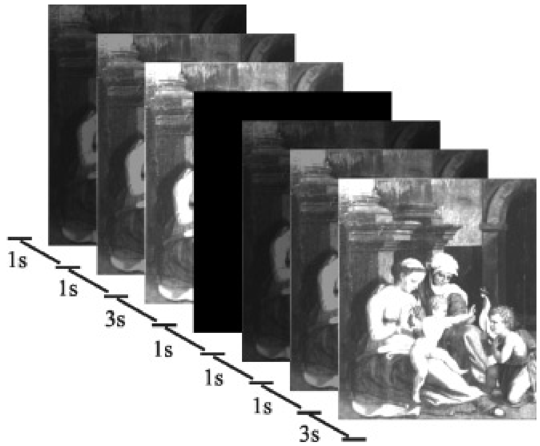

Fig. 2. Display sequence on the CRT monitor for stimulus presentation. In each experimental trial, the observer was presented sequentially with a pair of images corresponding to the same painting illuminated by two different illuminants. To allow for adaptation each image of the pair appeared as a linear temporal ramp with average luminance from 1 to 8 cd/m^2 during a total of 5 s. The image remained on the screen with its maximum luminance for 3 s. Between pairs and between trials the screen was black. The observers were instructed to indicate in each trial the preferred image of each pair.

true-color mode (VSG 2/5; Cambridge Research Systems, Rochester, UK). Screen resolution was 750 × 600 pixels, and refresh rate was 80 Hz. A telespectroradiometer (SpectraColorimeter, PR-650; Photo Research Inc., Chatsworth, CA) was used to regularly calibrate the display system. 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). Images subtended 8–15-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. The percentage of pixels out of gamut in the displayed images was, on average, smaller than 3.5%; these pixels were displayed by clipping to the closest RGB values.

In each experimental trial, the observer was presented sequentially with a pair of images, corresponding to the same painting illuminated by two different illuminants. Fig. 2 illustrates the display sequence for stimulus presentation. A sequential methodology was preferred to a side-by-side presentation because it allowed partial chromatic adaptation to the specific illuminant tested. To allow for adaptation each image of the pair appeared as a linear temporal ramp with average luminance from 1 to 8 cd/m^2 during a total of 5 s. The image remained on the screen with its maximum average luminance for 3 s. These temporal parameters are adequate as a significant part of adaptation takes place in the first few (5–10 s) seconds (Fairchild & Reniff, 1995; Werner et al., 2000). Between pairs and between trials the screen was black. Because the paintings were dark the maximum average luminance of 8 cd/m^2 corresponded only to an illumination on the paintings in the range 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 (Thomson, 1986).

Four pairs of illuminants were selected: D_{65}/Halogen, B/A, Solux/Halogen, and D_{65}/Solux corresponding to 209, 145, 108, and 71 mired shifts, respectively. An extra pair corresponding to D_{65}/D_{65} was used as a control. Although the pairs B/A and Solux/Halogen have similar CCT they represented different mired shifts; in addition, the latter represents spectra of real light sources used in museums rather than standard CIE illuminants.

The observers were instructed to indicate on each trial the preferred image of each pair. Responses were made with a switch box (CB6 Response Box, Cambridge Research Systems, Rochester, UK). There was no time limit for observers' responses, but they typically responded within the first second after the end of the image sequence. Each trial was initiated 2 s after the observer's response to the previous one. In each experimental session only one painting was tested, and the temporal ordering of the images in the trial was chosen randomly. Each observer performed 20 trials for each pair and therefore a total of 20 × 5 × 5 trials.

Observers

Five observers participated in this study. They were all unaware of the purpose of the experiment and had normal Snellen acuity and

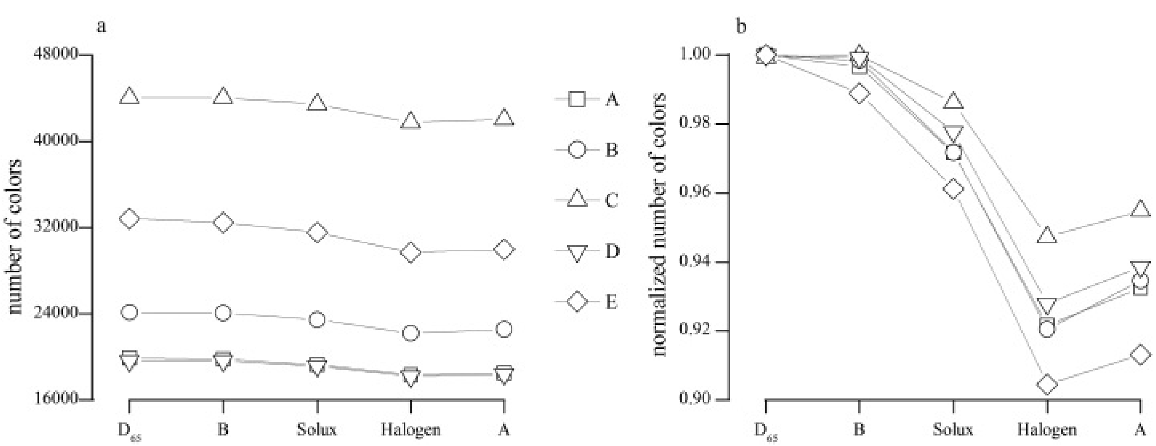

Fig. 3. Absolute (a) and relative (b) number of discernible colors estimated for each painting as a function of the illuminant under which it was rendered. Estimations were based on counting the number of nonempty unit cubes present in the representation of each painting in CIELAB space under each illuminant.

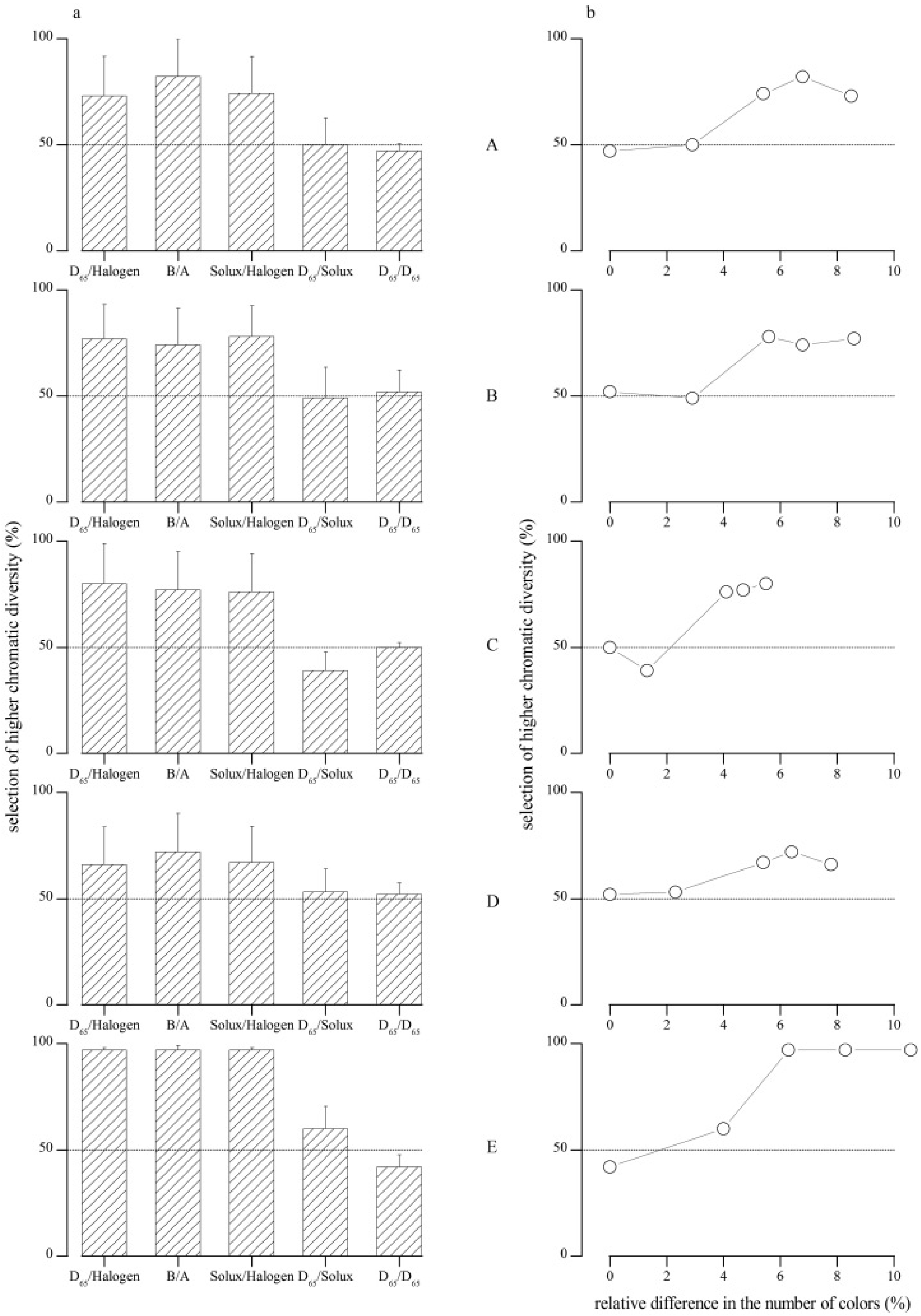

Fig. 4. Percentage of trials in which observers selected the image with higher number of colors as a function of the illuminant pair (a) and as a function of the relative difference in the number of colors (b). Data were averaged across observers, and error bars represent +1 SEM.

normal color vision, as assessed with the Farnsworth-Munsell 100-Hue test and by Rayleigh and Moreland anomaloscopy. Informed consent was obtained from all participants, and the research was conducted according to the guidelines promoted by the Declaration of Helsinki.

Results

Fig. 3a shows the number of discernible colors estimated for each painting as a function of the illuminant under which it was rendered. Fig. 3b represents the same data normalized at 1 at maximum. For all paintings D_{65} produced the largest number of discernible colors and Halogen the least. The variation of the number of colors across illuminants was about 10% and followed a similar trend for all paintings. The use of the color difference formula CIEDE2000 (Luo et al., 2001) to compute the number of discernible colors or the use of spheres of unit diameter rather than unit cubes produced different absolute numbers but similar trends and relationships between the illuminant pairs tested.

Fig. 4a shows for each painting the percentage of trials in which observers selected the image with higher number of colors as a function of the illuminant pair. Data represent averages across five observers, and error bars represent $+1$ SEM. Fig. 4b shows the same data but expressed as a function of the relative difference in the number of colors produced by the illuminant pair. With the pairs D_{65}/Halogen, B/A, and Solux/Halogen observers preferred the images with the higher number of colors, which corresponded to the illuminant with the higher color temperature. With the pairs D_{65}/Solux and D_{65}/D_{65} preference was about 50%. An analysis of variance showed a significant effect of the illuminant pair ($F(4,16) = 7.1$, $P < 0.01$) but no effect of the painting ($F(4,16) = 1.2$, $P > 0.1$). Figure 4b shows that when observer preference was about 50% the relative difference in the number of colors between the two images of the pair was small, up to about 3%. For larger differences preference was clearly above chance.

Discussion

For the illuminants and paintings tested in this study observers preferred the illuminants with higher color temperature except with the pair D_{65}/Solux, corresponding to CCT of 6500 K and 4450 K and a mired shift of 71, where no clear preference was expressed. The preferred illuminant also produced the larger chromatic diversity, a quantity assessed by estimating the number of discernible colors in the paintings. For the condition where no specific illuminant was preferred the number of colors with the two illuminants was very similar, a result suggesting that preference could have been influenced by chromatic diversity rather than by color temperature. Although it could be argued that the difference in color temperature for the pair D_{65}/Solux was too small to be perceived, this is unlikely as color constancy only holds approximately in these conditions (Arend & Reeves, 1986). Although the intensity level of the illumination is also important for the visual impression of a painting, this aspect was not considered in this work.

The illuminant with CCT of about 3600 K, found optimal in other studies (Scuello et al., 2004*b*), was not tested here. However, the chromatic diversity of a daylight with CCT of 3600 K was estimated for the paintings analyzed here and found to be between that produced by Solux and illuminant A (Carvalhal, 2004). Thus, from the point of view of chromatic diversity, this would not be the ideal illumination for the paintings tested here. Several factors may explain the differences between the results of the study of Scuello et al. and those presented here. They used paintings with different color palettes, a fact that may influence the ideal illuminant. Also, artifacts due to chromatic distortions of the printing process may have been introduced by the fact that they used postcard reproductions. The results of the present work are, however, consistent with the notion that preferred illumination is likely to be close to the illumination present at the time of painting. Concerning this issue, there is ample evidence that natural light was used in painting studios (Kemp, 1990) and that the studio was ideally a north-lit room (see, e.g., Turner, 1996).

The actual spatial context of the paintings in museum environments is variable. Paintings can be illuminated by a localized light source, by the diffuse illumination of the room, or by some combination of both. The visual stimuli provided by the CRT display are closer to the first of these conditions, and therefore the effects of an adaptation field like the one provided by the visual environment of the museum rooms were not tested. Although the color temperature and the overall lighting levels of the room may influence the impression observers have from the paintings, the results of this paper may only apply for the case where the illumination is uniform across the room and paintings.

The comparisons between different illuminants were carried out sequentially instead of side-by-side to allow for adaptation. Although it is likely that color memory may influence this type of comparison (Uchikawa & Ikeda, 1981) its effects are similar for all conditions of the experiment and therefore minimized by design.

The technique to estimate the number of colors is only approximated as it does not take fully into account the effects of adaptation and of spatial structure; the nonuniformity of the CIELAB space (Fairchild, 2005) was also not considered. Probably, it also underestimates diversity due to the cubic metric used. However, the important aspects in this approach are the relationships between the colors generated by different illuminants, and these are less susceptible to approximations than the computation of absolute numbers of colors.

These paintings all have the same type of pigments and style and the conclusions of the present work cannot be generalized to other types of paintings without further studies, but the notion that chromatic diversity may influence the visual impression and determine preference may be useful for museum lighting.

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