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Chromatic effects of metamers of D65 on art paintings

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Abstract

The visual impression of an artistic painting is influenced both by the colour and by the specific spectral structure of the rendering light source. The relationship between illuminant spectral structure and visual appearance assumes particular relevance with the advent of light sources with almost arbitrary spectral distribution, like modern LED based lighting. The aim of this work was to study, computationally, chromatic effects on paintings of illuminants with the same colour as D65 but different spectral profile. Hyperspectral data from twenty oil paintings were used in the analysis. A large collection of metamers of D65 was generated and the radiance reflected from each pixel of the paintings was estimated for each of the metamers. The number of discernible colours produced for each painting and illuminant was computed, and correlated with the spectral structure of the metamers. It was found that the number of colours generated varied considerably across the collection of metamers and that the metamers producing more colours were spectrally more structured, that is, less uniform. This result suggests that it may be beneficial to explore appropriate spectral tuning in practical illumination.

Keywords: chromatic effects, colour rendering, colour vision, D65 metamers

Introduction

Empirical studies have shown that observers prefer daylight illumination with specific correlated colour temperatures (CCT) to render artistic paintings (Scuello *et al*., 2004; Pinto *et al*., 2006, 2008). On the other hand, computational studies suggest that illuminants other than daylight may be necessary to optimize visualization of paintings (Linhares *et al*., 2009). These studies have been constrained to existing light sources and did not explore the potential properties of illumination with arbitrary spectral distributions. With the advent of modern LED-based lighting, light sources with almost arbitrary spectral distribution can be produced (Protzman and Houser, 2006) and the question of the relationship between spectral profile and visual effects assumes particular relevance. Experimental studies of the chromatic effects of LED lights have been carried out and suggest a number of limitations on colour rendering (Vienot *et al*., 2005; Mahler *et al*., 2009). However these studies used specific LEDs and generalizations to other lights are uncertain.

The goal of this work was to investigate, computationally, how the spectral structure of the illumination influences the chromatic perception of artistic paintings. The colour of the illuminants was that of D65 and the work was based on the analysis of hyperspectral data from twenty oil paintings. To evaluate the chromatic effects on paintings, both the number of discernible colours and the colour rendering index (CRI) were computed, since they represent complementary information.

Methods

A database with hyperspectral images of twenty oil paintings from the Museu Nogueira da Silva, Braga, Portugal was analyzed. *Figure 1* shows the thumbnails of the twenty paintings. The set consisted of seven paintings from the Renaissance époque painted on wood (a to d, h, n and 0), four from the 20th century painted on canvas (i, j, p, and q), two from the 20th

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Figure 1. Colour thumbnails of the 20 oil paintings analyzed.

century painted on wood (k and m), one from the Renaissance époque painted on copper (e), one from the 19th century painted on canvas (g), and five from an unknown period: of these, three were painted on copper (f, s and t), one on wood (r) and one on canvas (l).

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., Hamamatsu City, Shizuoka Pref., Japan) and a fast-tunable liquid-crystal filter (VariSpec, model VS-VIS2-10HC-35-SQ, Cambridge Research & Instrumentation, Inc., Woburn, MA, USA) mounted in front of the lens (for more details on the hyperspectral system see Foster *et al.* (2006) and for the specific application in artistic paintings see Pinto *et al.* (2008)). Image acquisition was over the spectral range 400–720 nm in 10 nm steps. The accuracy of the system in recovering spectral reflectance functions corresponded to an average spectral difference of 2%: by a colorimetric error, on average, of 1.3 when expressed by the CIEDE2000 colour difference equation (Luo *et al.*, 2001), and 2.2 when expressed in the CIELAB colour space (Carvalhal, 2004).

The CIELAB colour volume of each painting was first computed assuming the CIE standard illuminant D65 and the CIE 1931 standard colorimetric observer. The number of discernible colours was then estimated as follows: for each painting, the colour volume was segmented into cubes of unitary side and the number of colours was counted as the number of non-empty cubes. This methodology gives an approximate but reasonable estimate (Pointer and Attridge, 1998).

Given a standard observer, defined by three colour matching functions, there is an infinite number of spectral functions, the metamer set, that produce the same XYZ tristimulus (Wyszecki and Stiles, 1982). There are several ways of exploring metamer sets (Wyszecki, 1958; Takahama and Nayatani, 1972; Finlayson and Morovic, 2005), and for simplicity we choose Schmitt's simple elements approach to generate metamers of D65 (Schmitt, 1976). A metamer set of real positive functions F can be described by a convex hyperpolyhedron volume in an M-dimensional space, where M is the number of spectral bands considered. The apices of that hyperpolyhedron S_j are functions that have at most 3 non-zero coordinates, that is, no more than three spectral bands. Any element f_i of the set can be written as a positive barycentric combination of simple elements, i.e., for any $f_i \in F$ there is at least one set of $N \leq M$ positive numbers α_j such that:

$$f_i = \sum_{j=1}^{N} \alpha_j S_j$$

where,

$$\sum_{j=1}^{N} \alpha_j = 1$$

To generate an adequate sample of metamers the following approach was used. Considering δ_i, the absolute spectral differences between f_i and the equal energy illuminant E, defined by

$$\delta_i = \sum_{k=1}^{33} \left| f_{i,k} - E_k \right|$$

a total of 4844 metamers of D65 were generated by choosing the weights α_j such that the distribution of δ_i was approximately uniform in the range 0.3–2.0. All metamers were normalized in energy and generated in the range 400–720 nm with a spectral resolution of 10 nm. Note that because E is a uniform spectrum, δ_i is a measure of the degree of spectral structure which f_i has.

The CIELAB colour volume of each painting was also computed for each metameric spectrum and the corresponding number of discernible colours estimated as for D65. For each metamer the general colour rendering index R_a was computed accordingly to CIE (CIE, 1995).

Results

For illustration purposes *Figure 2* represents the CIELAB colour volumes of four of the paintings analyzed when rendered under D65. The notion of spectral structure used here can be illustrated by the metamers represented in *Figure 3*. *Figure 3a* represents two metamers M1 and M2 that are spectrally close to the equal energy illuminant E and *Figure 3b* represents two

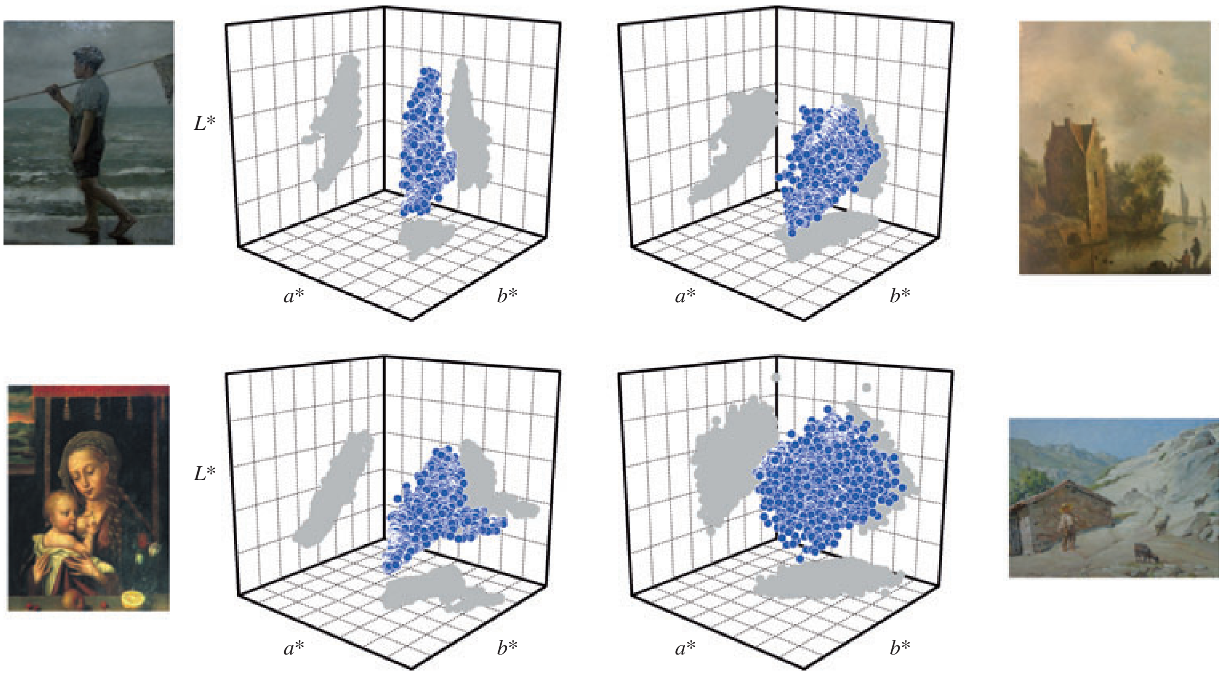

Figure 2. CIELAB colour volumes of four of the paintings analyzed when rendered under D65.

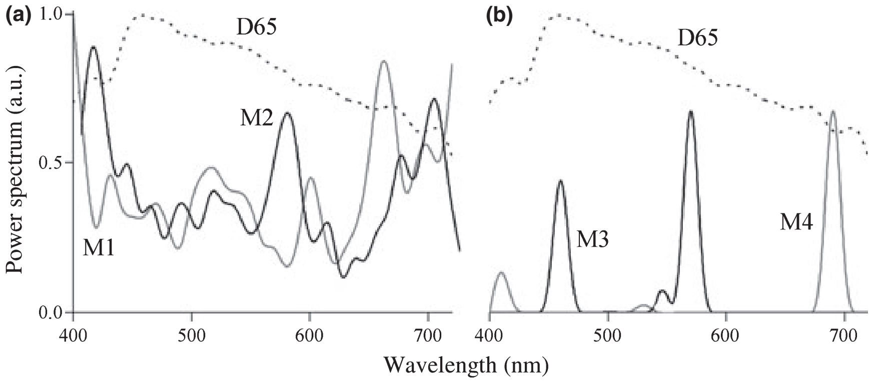

Figure 3. Power spectra of four of the metamers set of D65 used in this work. M1 and M2 represent two metamers that are spectrally close to the equal energy illuminant E and M3 and M4 represent two metamers that are spectrally distant from E. For representation the metamers were normalized at the wavelength of maximum energy.

Figure 4. Colour thumbnails of one of the paintings (a) under D65, (b) under a spectrally structured illuminant M3 producing a small number of colours, and (c) under a spectrally structured illuminant M4 producing a large number of colours.

metamers M3 and M4 that are spectrally distant from E. For representation the metamers were normalized at the wavelength of maximum energy.

To illustrate the visual effects of metamers, *Figure 4* shows the colour thumbnails of one of the paintings under D65, under a spectrally structured illuminant M3 producing a small number of colours, and under a spectrally structured illuminant M4 producing a large number of colours.

Figure 5a shows the variation of the average number of discernible colours across paintings expressed as a function of δ, the absolute spectral difference to illuminant E. As δ increases, the variability of the number of colours also increases, suggesting more extreme effects as the spectral structure of the illuminant becomes more marked. *Figure 5b* shows the general colour rendering index R_a of each metamer also expressed as a function of δ. As δ increases, lower values of R_a are obtained. To investigate how the average colour of the paintings varies across the metamer set, the distance in the CIELAB (a^*, b^*) plane between the average colour across paintings produced by D65 and that produced by each metamer of the sample was computed. *Figure 5c* shows this quantity as a function of δ. Although some colour changes can be observed with increasing δ the effects on average colours are relatively modest, being on average 3.0 expressed in the CIELAB colour space.

To clarify the relationship between δ and the spectral structure of the metamers, δ was compared against the number of non-zero spectral bands for each metamer. *Figure 6* shows the results. As δ increases the number of non-zero spectral bands decreases. These data together with the data shown in *Figure 5* suggests that the maximum number of colours is obtained with metamers which are more spectrally structured (that is, less uniform), and that is achieved with a spectral distribution with a low number of non-zero spectral bands.

The computations presented here were all carried out with a sample of metamers obtained with the method described above. To investigate the robustness of the pattern of results with sampling, the same computations were repeated with different samples obtained with the same method and using samples obtained with different sampling methods. The results obtained (not shown) were similar across conditions.

Discussion

The main result of this work is the mathematical possibility of producing a large chromatic diversity, that is, a large number of perceived colours, with a light source with a small number of spectral bands. This result may be useful in designing new light sources for optimal chromatic discrimination.

Why do spectra with a small number of spectral bands produce a large number of colours? Although this result is not obvious or intuitive, and seems to contradict empirical work on the chromatic effects of LEDs (Vienot *et al.*, 2005; Mahler *et al.*, 2009), it may be

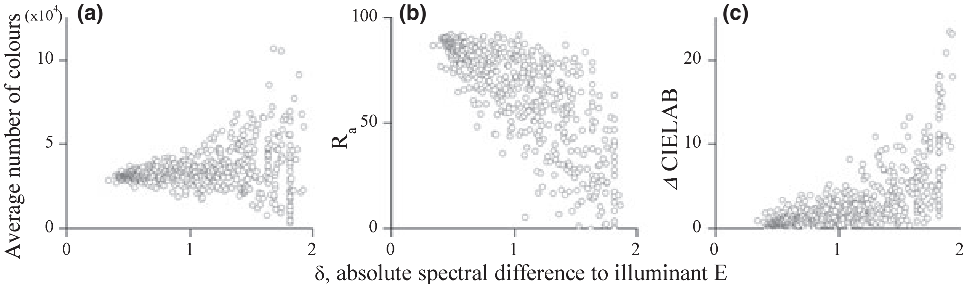

Figure 5. Chromatic quantities expressed as a function of δ, the absolute spectral difference to illuminant E: (a) variation of the average number of discernible colours across paintings, (b) the general colour rendering index R_a of each metamer and (c) distance in the CIELAB (a^*, b^*) plane between the average colour across paintings produced by D65 and that produced by each metamer of the sample.

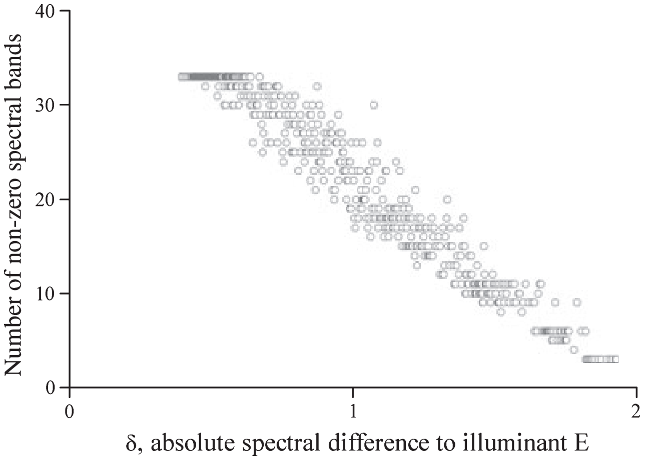

Figure 6. The number of non-zero spectral bands with a width of 10 nm for each metamer, expressed as a function of δ, the absolute spectral difference to the equal energy illuminant E.

explained by the spectral position of the bands. For example, in *Figure 3b* both spectra M3 and M4 have three spectral bands but M4 produces more colours by a factor of 10. Notice that M4 has spectral bands in the extreme and central position of the visible spectrum and, therefore, when illuminating a set of coloured samples has the potential to produce cone stimulations that are more dissimilar.

This is a computational study and its generalization to practical applications must be approached with care. The methodology to estimate the number of perceived colours is approximate. On the other hand, although there are some empirical data suggesting that the number of discernible colours may influence observers' preference for a specific illumination (Pinto *et al*., 2008), other factors also contribute to the aesthetic appreciation.

One of the findings of this work is that a high colour rendering index and large chromatic diversity are somewhat incompatible, but whether observers prefer daylight fidelity or good chromatic diversity is open to question. New developments in defining improved ways of computing the colour rendering index (Davis and Ohno, 2005) may change the pattern described here and improve the compatibility between fidelity and diversity.

In addition, it should be noted that the global impression of a painting is also influenced by other chromatic and non-chromatic aspects, like the contrast across borders, and these are not quantified here. Also, increasing the number of colours perceived by a global expansion of the colour gamut may lead to impairment of discrimination in some regions of the space (Vienot *et al*., 2008; Mahler *et al*., 2009). However, the results presented here suggest that appropriate spectral tuning may be explored to advantage in practical illumination.

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