Chromatic effects of metamers of daylights

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Abstract

The relationship between the spectral composition of light sources and the visual appearance of rendered scenes is a matter of practical relevance and assumes today particular significance with the advent of light sources of almost arbitrary spectral distribution, like modern LED based lighting. This relationship has only been studied for specific illuminants, like daylights, and systematic studies with other light sources are necessary. The aim of this work was to address this issue by studying, computationally, some chromatic effects of metamers of daylight illuminants. For each daylight with correlated color temperature (CCT) in the range 25 000 K – 4000 K a large set of metamers was generate using the Schmitt's elements approach. The metamers set was parameterized by the absolute spectral difference   to the equi-energy illuminant E and by the number of non-zero spectral bands. The chromatic effects of the metamers were quantified by the CIE color rendering index CRI and by the CIELAB color gamut generated when rendering the Munsell set. It was found that although CRI decreases with , that is, as the illuminant spectrum becomes spectrally more structured, the largest values for the color gamut could be obtained only for large values of . Furthermore, the relationship between color gamut and number of non-zero bands showed that the largest gamuts were obtained with a small number of spectral bands. Thus, spectrally structured metamers produced low CRI but larger color gamuts, a result suggesting that appropriate spectral tuning may be explored in practical illumination when obtaining large chromatic diversity may be important.

Introduction

Modern LED based lighting can have almost arbitrary spectral distribution [1, 2] and are increasingly present in the market and available to the general public. Studies of the visual effects of light sources have concentrated more on standard daylights [3-6] and some LEDs [7, 8]. In particular, empirical studies of the chromatic effects of LEDs have suggested a number of limitations on color rendering [7, 9]. These studies, however, used specific LEDs and their results are difficult to generalize to other lights sources.

The color quality of a light source is typically evaluated by the color rendering index (CRI) [10, 11]. This is a quantity that 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 [12-15] and other descriptors of the visual quality of a light source were suggested [16-18]. To obviate the need for a reference illuminant, a method based on the volume of the object-color solid was recently proposed [19]. Another index introduced recently was the Gamut Area Index (GAI) [20], a measure of the extension of the color gamut generated. In the present work the characterization of the chromatic effects of the illuminants was quantified by the CRI and by a generalization of the index GAI to quantify the gamut associated to each illuminant.

The aim of this work was to study, computationally, the relationships between illuminants with almost arbitrary spectral profile and their chromatic effects. Metamers of daylight were the class of illuminants selected. For each daylight with CCT in the range 25 000 K – 4000 K a large set of metamers was generate using the Schmitt's simple elements approach [21]. The metamers set for each CCT was parameterized by the absolute spectral difference   to the equi-energy illuminant E and by the number of non-zero spectral bands. The chromatic effects of the illuminants were quantified by the CRI and by the CIELAB color gamut generated when rendering the Munsell set.

Methods

For a given colorimetric observer defined by 3 color matching functions, there is an infinite number of illuminants that produce the same *XYZ* tristimulus on a white surface [22]. These constitute the metamer set. There are several ways of generating metamers [21, 23-25]. Here, for simplicity, we choose the Schmitt's simple elements approach [21]. 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 apexes of that hyperpolyhedron S_j are functions that have at most 3 non-zero coordinates, that is, no more than 3 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 $N \le M$ positive numbers α_j such that:

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

where,

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

Considering δ_i the absolute spectral difference between f_i and the equi-energy illuminant E defined by the formula,

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

a total of 10,000 metamers were generated for each daylight in the CCT range 25 000 K — 4000 K by choosing the weights α_j

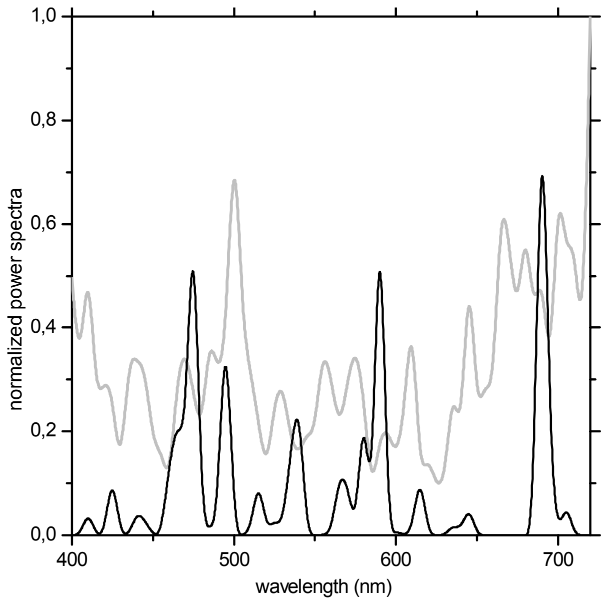

***Figure 1.** Two examples of metamers of D_{65}. The black line represents a metamer spectrally different from E and the grey line a metamer spectrally similar to E.*

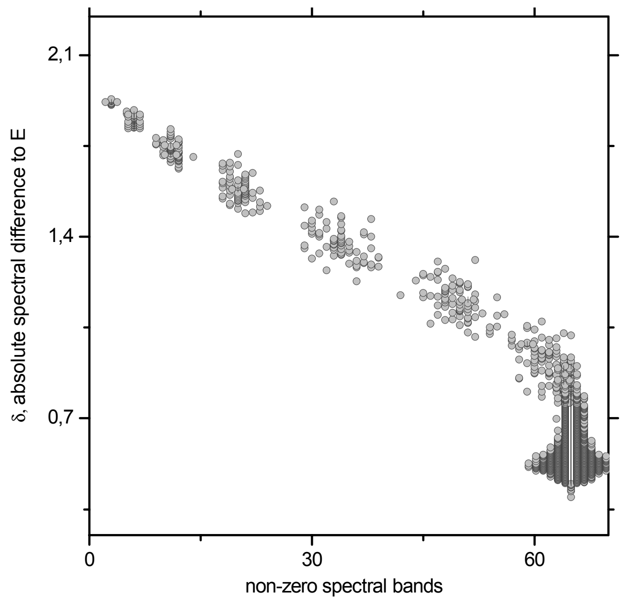

***Figure 2.** Absolute spectral difference to the equi-energy illuminant E expressed as a function the number of non-zero spectral bands. Data for a selection of metamers of D_{65}. Data for metamers sets of other daylight illuminants with different CCTs show similar patterns.*

such that the distribution of δ_i was approximately uniform over a reasonable range. All metamers were normalized in energy and were generated for the spectral range 400 nm - 720 nm, with 5 nm spectral resolution. Thus, the number of spectral bands M was 65. Note that because E is a uniform spectrum, δ_i is a measure of how much spectrally structured f_i is. The colorimetric observer used was the CIE 1931 Standard Colorimetric Observer.

For each metamer the general color rendering index CRI was computed accordingly to CIE [10]. To quantify the color gamut generated by each case, the CIELAB color volume occupied by the set of 1269 samples from the Munsell book of Color [26] was computed. The spectral reflectance set were used as tabulated by the University of Joensuu Color Group [27]. The set was assumed rendered by each metamer and the coordinates of each Munsell sample were computed in CIELAB color space. The volume was then computed using a three-dimensional convex hull routine. Note that this method gives the volume inside the envelope defined by the Munsell surfaces in the periphery of the set. This quantity is strongly correlated with the chromatic diversity or number of discernible colors produced in natural scenes and can be used as a Chromatic Diversity Index (CDI) [28].

For illustration purposes Figure 1 shows two metamers of D_{65}. The black line represents a metamer spectrally different from E and the grey line a metamer spectrally similar to E. Figure 2 represents for a selection of metamers of D_{65} the absolute spectral difference to the equi-energy illuminant E δ expressed as a function the number of non-zero spectral bands. As δ decreases the number of non-zero spectral bands increase, that is, the spectra become less structured. Data for metamers sets of other daylight illuminants with different CCTs show similar patterns.

Results

Figure 3 represents the CRI expressed as a function of δ for a selection of metamers of D_{65}. As expected, the maxima and minima CRI decrease as the illuminant becomes more structured, that is, less similar to the equi-illuminant E. Data for metamers of other daylights show similar pattern. This dependence of CRI with δ means that the colors produced by daylight illuminants cannot be reproduced by irregular or structured spectra. Yet, some spectra with δ values around 2,0 can still produce relatively high indices of the order of 80 equivalent to some fluorescent sources.

Figure 4 represents the volume of the Munsell set expressed as a function of δ for a selection of metamers of D_{65}. Data for the other daylights show similar pattern. The range of volumes obtained increases with δ and the maximum and minimum volumes are obtained for large spectral differences. The pattern of results presented in Figure 3 and Figure 4 suggests that large volumes and high CRI cannot be obtained by the same illuminant. In Figure 5 the volume of the Munsell set is expressed as a function of the CRI. High values of the CRI correspond to medium values of the volume and large volumes correspond to low CRI.

Figure 6 shows the volume of the Munsell set expressed as a function of the number of non-zero spectral bands of the metamer set of D_{65}. Data for other daylights show similar pattern. As the number of non-zero spectral bands increases the range of volumes that can be obtained decreases. The larger volume is obtained with metamers with a small number of spectral bands. Or, in other words, metamers spectrally similar to E generate only moderate volumes and only more spectrally structured illuminants generate larger volumes.

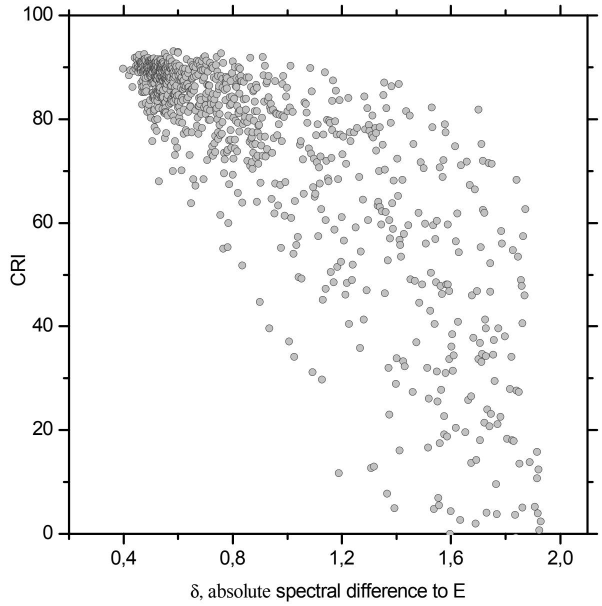

***Figure 3.** CRI expressed as a function of δ for a selection of metamers of D_{65}.*

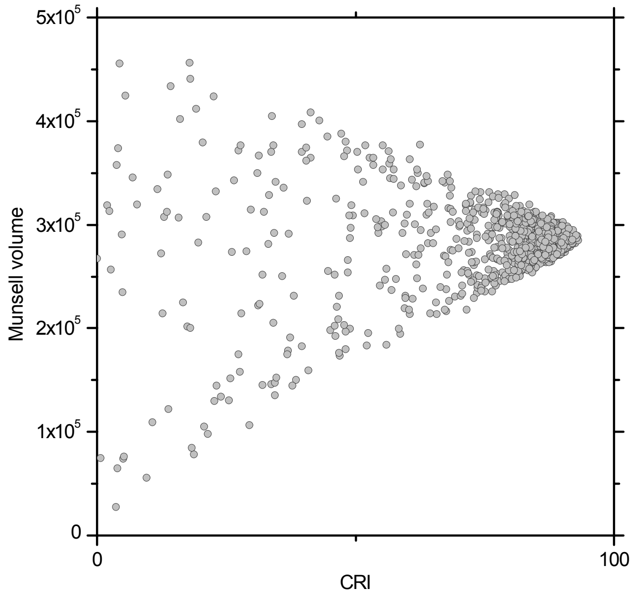

***Figure 5.** Volume of the Munsell set obtained with each illuminant expressed as a function CRI. Data for a selection of metamers of D_{65}.*

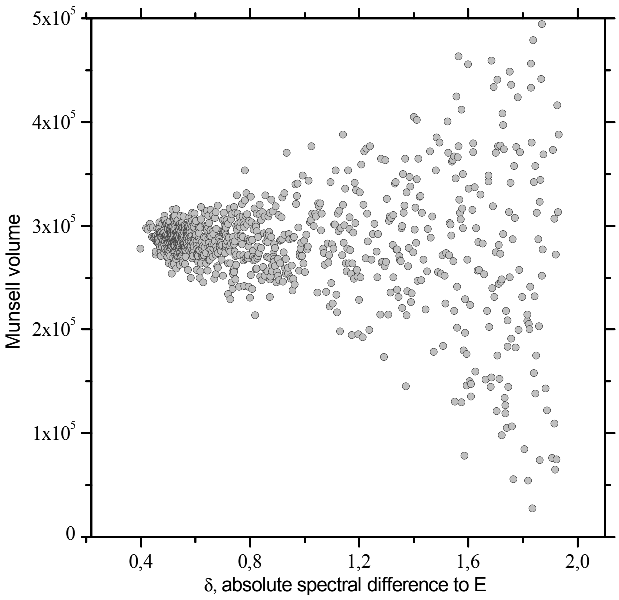

***Figure 4.** Volume of the Munsell set obtained with each illuminant expressed as a function δ. Data for a selection of metamers of D_{65}.*

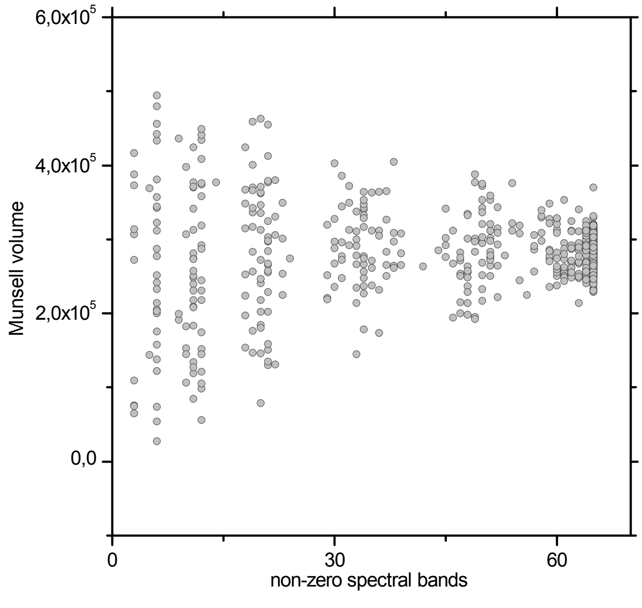

***Figure 6.** Volume of the Munsell set expressed as a function of the number of non-zero spectral bands of the metamer set of D_{65}.*

To illustrate the visual effects of a set of metamers of D_{65} Figure 7 shows the color thumbnails of one artistic painting under D_{65} and under two different metamers of D_{65}. The painting shows different colors in all cases. The one at the button displays more colors than the others but the colors may be seen as less natural.

Figure 7. *Color thumbnails of one artistic painting under D_{65} (upper picture) and under two metamers of D_{65} (middle and lower picture).*

Conclusions and comments

In this study the relationships between illuminant spectral structure, CRI and color gamut were explored, computationally, using metamer sets of daylight illuminants. It was shown that CRI tends to decreases as the spectrum becomes less uniform although values of CRI close to 80 can be obtained with structured spectra. The color gamut, quantified by the color volume in CIELAB enclosed by the Munsell set, has its maximum for highly structured spectra; high CRI and large gamuts cannot be obtained by the same light sources.

When CRI and color gamuts were expressed as a function of the number of non-zero spectral bands as an alternative measure of the spectral structure, it was found that spectra with a small number of non-zero spectral bands produce the maximum color gamut. Thus, one of the main results of this work is the theoretical possibility of producing large color gamuts with light sources with a small number of spectral bands. This result is consistent with the results obtained for the effects of colored filters in the perceived chromatic diversity of natural scenes where a lens with transmittion in three broad spectral bands produced the maximum number of discernible colors [29].

The two types of aspects approached here are both relevant to color rendering, one refers to what colors appear and the other to how many colors appear. These two aspects have been considered often in color rendering research [15, 30, 31] and represent complementary information about the effects of light sources on the rendering scenes and together may be useful in designing new light sources for optimal chromatic discrimination.

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 [32] may change the pattern described here and improve the compatibility between fidelity.

But why do spectra with a small number of spectral bands produce large gamuts? This seems to be inconsistent with experimental work on chromatic effects of LEDs [7, 9] but may be explained by the spectral position of the bands: only three spectral bands appropriately localized in the visible spectrum may stimulate the cone photoreceptors optimally for maximum chromatic diversity or color gamut. On the other hand, a small number of spectral bands may produce also low chromatic diversity, as show in Figure 6. This is because of the position of the spectral bands, for example, if they are close it is expected that the number of perceived colors is lower than if they are apart.

The work presented here is of a computational nature and its generalization to practical applications must be approached with care. In particular, the methodology to estimate the gamut uses the CIELAB space which is known for its non-uniformities [33]. However, they may be explored with advantage in practical illumination when large chromatic diversity may be important.

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Author Biography

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