De-entangling colorfulness and fidelity for a complete statistical description of color quality

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In this Letter, the main attributes known to affect color quality are treated statistically over a set of 118 spectra representing the current mainstream lighting technology. The color rendering index (CRI) is used to assess color fidelity while colorfulness is used to complement CRI-R_a, supported by the growing evidence that assessment of light spectra cannot overlook color preference inputs. Colorfulness is evaluated by our optimal color (O_c) index, through a code that computes the (MacAdam) theoretical maximum volumetric gamut of objects under a given illuminant for all the spectra in our database. Pearson correlation coefficients for CRI-R_a, the (Y. Ohno's) color quality scale (CQS) and O_c show a high correlation (0.950) between CRI-R_a and CQS-Q_a, while O_c shows the lowest correlation (0.577) with CRI-R_a, meaning that O_c represents the best complement to CRI-R_a and Q_a for an in-depth study of color quality. © 2012 Optical Society of America

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Different quality color dimensions for light sources in general lighting have been studied for more than 40 years. Despite the fact that the CIE general color rendering index (CRI-R_a) [1] is in a re-evaluation stage, it is widely accepted among the different players in the general lighting sector. The CIE-CRI-R_a index compares test and reference illuminants over 14 reflectance samples. However, beyond the CRI-R_a, there exists another dimension of color quality, colorfulness, that is being intensively studied in recent years due to the market growth of the LED technology, which is known to enhance object chroma. Chroma affects subjective aspects of color perception.

Guo and Houser [2] made a comparison of nine color quality indices and Akashi (in his comment to this work [3]) proposed dividing these nine indices into at least two groups: The first group would be driven by fidelity, i.e., how similarly test and reference illuminants render object colors, while the second relies on geometric attributes of objects in color spaces such as the gamut area or volume, as quantifiers of the colorfulness that the light source is able to provide. Subjacent to this is the idea that color fidelity schemes are not sufficient, and colorfulness information are required in order to have a complete description.

Smet *et al.* [4] found that predictive performance in terms of naturalness is negatively correlated with the predictive performance for preference. Therefore, a metric that rates naturalness attributes well necessarily has to rate attractiveness poorly. This assertion confirms the finding of Rea and Freyssinier [5], where a complete description of all aspects of color quality of a light source would likely require more than one metric. Previous results of Smet in [6] are in agreement with Bartleson's findings [7] and several other studies, confirming that colors of familiar objects are remembered as being more vivid and saturated than in reality are, and that the recalled color (termed "memory color") is usually preferred than the real one.

In this way, the statistical analysis proposed by Šukauskas *et al.* [8] through the use of color rendering vectors also concluded that color quality of solid state white lamps "should not be rated by a single figure of merit and require at least two: for color fidelity and saturation." Object color saturation indexes could also be a good complement to color rendering maps [9].

Further evidence in Davis and Ohno's work [10,11] suggests that increases in object chroma, as long as they are not excessive, are not detrimental to color quality and may even be beneficial. To quantify this, Davis and Ohno proposed the Gamut AreaScale (Q_g) [10], as a support to the general color quality scale (Q_a). Figure 1 shows their color saturation icon for an RGB 3000 K white LED that has a $Q_g = 111$. A Q_g greater than 100 reflects the ability of a light source to increase the object saturation in the regions where the plot exceeds the circumference boundary, as compared to the D65 CIE-standard illuminant ($Q_g = 100$), represented by the white circumference in Fig. 1(b).

Thus, it becomes clear that color quality has at least two quasi-orthogonal dimensions that give complementary information. The volume in the CIELAB space has been recently used to calculate spectra maximized

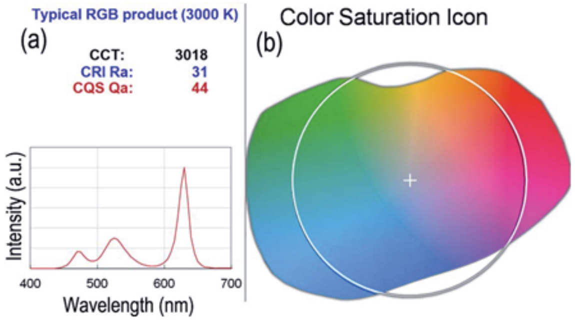

Fig. 1. (Color online) (a) Spectrum of a noncommercial 3000 K white RGB LED and (b) 2D saturation plot for the same 3000 K RGB LED with $Q_g = 111$ as compared to a CIE D65 standard illuminant (perfect circumference). Figure composed of images adapted from NIST spreadsheet *Color Quality Scale* ver 9.0.a 2011.

for colorfulness [12]. The theory underlying the spectral properties of optimal colors, i.e., the colors with maximum purity for a given luminance factor, was developed by Schrödinger [13], and their chromaticities were computed later by MacAdam in 1935. His theory of the maximum visual efficiency of colored materials [14,15] resulted in what we now know as the MacAdam limits for optimal colors.

The development of indices to characterize the complex visual effects of illuminants is an actively studied topic that has been intensified by the need to characterize LEDs with almost arbitrary spectral profiles. In particular, the relationships between chromatic diversity and fidelity have been studied computationally with outdoor and indoor scenes [16] and with artistic paintings [17]. Psychophysical studies have been also carried out for naturalness and chromatic diversity [18]. An explicit relationship between CRI and the MacAdam volume was derived by Verdu for a set of selected illuminants [19].

In this work, by using the convex hull method, we calculate the volume of the optimal colors of all light sources contained in a 118 spectra database (from Ohno's spreadsheet v9.0.a 2011). This database is large enough to represent all the currently available technologies, and will help us in the determination of the limits of the proposed index.

For each spectral power distribution of the 118-spectra database, we start from the the calculation of the optimal colors solid through the computational method proposed by Masaoka [20]. Figure 2 shows the optimal color solid calculated for a 3000 K RGB-LED light source.

The method in [20] provides a relatively fast and accurate manner to calculate the solid comprised within the MacAdam limits. After obtaining the 118 optimal color solids, the convex hull volume (V_{ch}) subtended within the CIELAB color boundaries is calculated. The V_{ch} ratio between the test light source and its reference light source as defined in CIE-CRI-R_a [1] was calculated (and termed O_c), in analogy to the CQS-Q_g that is calculated in a similar manner from gamut areas, as seen in Eqs. (1) and (2):

$$Q_g = 100\left(\frac{\text{Gamut Area}_{\text{test}}}{\text{Gamut Area}_{\text{ref}}}\right)_{\text{CIELAB}} \qquad (1)$$

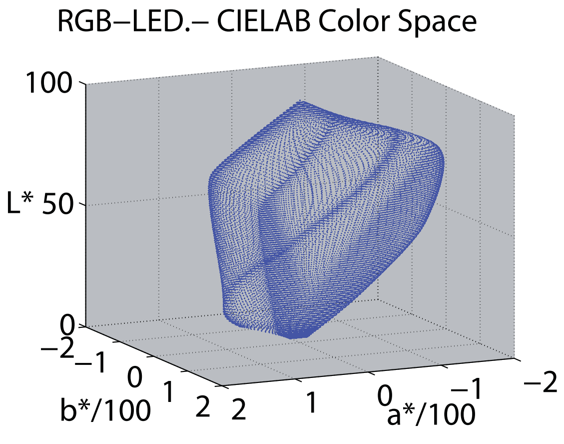

Fig. 2. (Color online) Optimal color volume (V_{ch}) for the 3000 K—typical RGB light source of Fig. 1.

$$O_c = 100\left(\frac{V_{\mathrm{ch}_{\mathrm{test}}}}{V_{\mathrm{ch}_{\mathrm{ref}}}}\right)_{\mathrm{CIELAB}}. \qquad (2)$$

In order to unravel the statistical correlation hidden into the variables CRI-R_a, Q_a, Q_g, O_c and V_{ch}, a statistical study was performed. This approach will allow us to find a minimal set of uncorrelated variables that optimally describe all the attributes of color quality.

Figure 3(a) shows that R_a and Q_a follow an almost identical trend as a function of the statistical percentiles (value of a variable below which a certain percent of observations fall). This is manifested through a nearly constant Q_a-R_a function on the right axis. On the contrary, O_c-R_a [see Fig. 3(b)] presents a nonlinear relationship, meaning that O_c and R_a provide information about different attributes of color quality.

Statistical Pearson correlations along with their level of significance of the 118-spectra are summarized in Table 1. The high similarity between CRI-R_a and Q_a observed in Fig. 3 is confirmed by a correlation coefficient of 0.950. Thus, these two indexes do not complement each other, even when the CQS-Q_a was designed with a clear motivation of mixing color fidelity and people's preference for chroma enhancement, by using more saturated test-color samples and not penalizing for increased chroma.

In Table 1, it is seen that the less-correlated pair of variables are R_a and O_c. This means that maximal

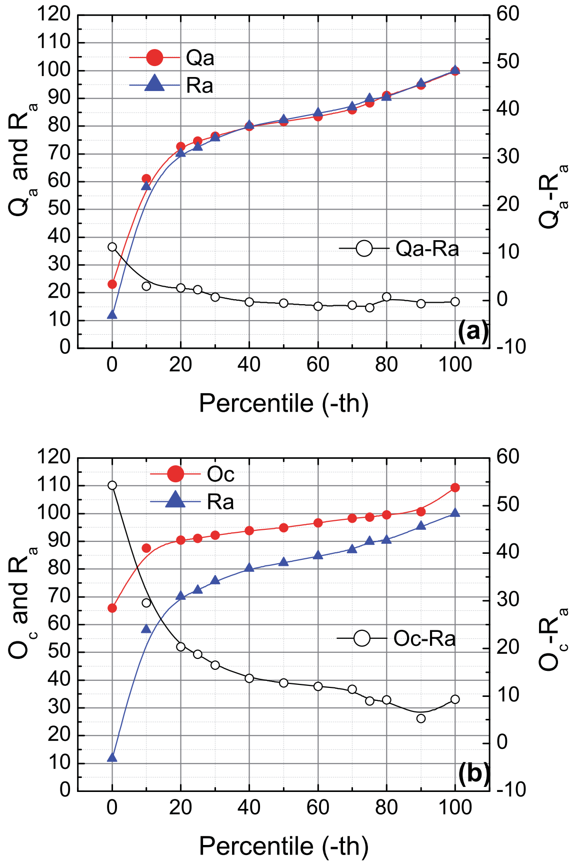

Fig. 3. (Color online) (a) Q_a, R_a (left axis) and Q_a-R_a (right axis) as a function of the statistical percentiles and (b) O_c, R_a (left axis) and O_c-R_a (right axis) as a function of the statistical percentiles.

Table 1. Pearson Coefficients of Correlation Between Different Pairs of Color-Related Indexes for the 118-Spectra Database[a]

	R_a	Q_a	Q_g	O_c	V_{ch}
R_a	1	0.950*	0.619*	0.577*	0.589*
Q_a		1	0.732*	0.606*	0.616*
Q_g			1	0.791*	0.784*
O_c				1	0.992*
V_{ch}					1

[a] Significance values (p-values) lower than 0.001 are indicated with an asterisk symbol.

information of color quality is obtained when both variables are used in the assessment of light sources. It is worth noting that these two decorrelated indicators precisely correspond to the fidelity and colorfulness dimensions, respectively, in agreement with the results obtained through psychophysical studies.

In summary, the application of Pearson correlation coefficients of different attributes of color quality over an extensive database consisting of 118 spectra that represent the vast majority of different lighting technologies currently available in the market confirms that a joint specification of a fidelity index (R_a) along with a colorfulness index (our proposed O_c) is required for a complete statistical specification of color quality. This statistical approach reinforces a series of psychophysical studies performed recently [2,4–8] that indicate that the colorfulness dimension of color quality is the best complement to indexes based on fidelity schemes (color differences from a reference source) such as CQS-Q_a or CIE-CRI-R_a.

From this work it becomes clear (both from psychophysical and statistical standpoints) that a meaningful indicator of color quality should be a weighted function of R_a and O_c. Although it could be proposed for correlation coefficients to be the weighting factors for the definition of an ultimate color quality index, psychophysical tests would be required to support such a statement, reinforcing the need for future field works to quantify the role played by both color dimensions.

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