Robust Chroma and Lightness Descriptors

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Abstract

New descriptors for lightness and chroma are presented that are based on properties of a wraparound Gaussian metameric to the given XYZ tristimulus coordinates. For the 1600 samples of the Munsell glossy set, both descriptors are found to correlate to Munsell value and chroma at least as well as the corresponding CIECAM02 descriptors when the Munsell samples are under the CIE C illuminant. However, when the illuminant is changed the new descriptors were found to be considerably more consistent under the second illuminant than those of CIECAM02.

Introduction

Object colour can be described in terms of three main dimensions, which are often specified as hue, chroma, and lightness [1]. In terms of hue, Mirzaei et al. [2][3] propose using the peak wavelength of a metameric Gaussian-like function (called a wraparound Gaussian) as a hue descriptor and show that it correlates as well as CIECAM02 hue does to Munsell hue [4], NCS hue [5], and the hue names in Moroney's color thesaurus [6][7][8]. The Gaussian-based hue descriptor is also shown to be significantly more stable than CIECAM02 when the illuminant differs from CIE Standard Illuminant C.

Given a CIE XYZ and the spectrum of the illuminant, the key idea of the hue descriptor is to determine the wraparound Gaussian reflectance function that is metameric (i.e., leads to the same XYZ) under the given illuminant and then base the hue on a property of that reflectance, namely the wavelength at which the Gaussian peaks.

This paper introduces Gaussian-based chroma and lightness descriptors and compares them to CIECAM02 in terms of (i) how well they each correlate with the chroma and value designators of the 1600 Munsell [4] papers, and (ii) how stable the respective descriptors are under a change in the illuminant.

Logvinenko's Wraparound Gaussians

The Gaussian-like representation used here originates from Logvinenko's illuminant-invariant object-color atlas [10]. In contrast to other popular color spaces such as CIELAB/CIECAM02, Logvinenko's atlas provides a coordinate system that is independent of the illuminant. The atlas is defined in terms of a special set of optimal spectral reflectance functions, no pair of which becomes metameric under any all-positive illuminant. In a subsequent paper [11], he suggests a Gaussian parameterization of his color atlas. This Gaussian parameterization involves reflectances defined in terms of a 3-parameter wraparound Gaussian function $g(\lambda;k,\sigma,\mu)$ defined as follows.

When $\mu \le (\lambda_{\max} + \mu_{\min})/2$ then

for $\lambda_{\min} \le \lambda \le \mu + \Lambda/2$

$$g(\lambda;k,\theta,\mu) = k\exp[-\theta(\lambda-\mu)^2] \qquad (1)$$

for $\mu+\Lambda/2 \le \lambda \le \lambda_{\max}$

$$g(\lambda;k,\theta,\mu) = k\exp[-\theta(\lambda-\mu-\Lambda)^2] \qquad (2)$$

When $\mu \ge (\lambda_{\max}+\mu_{\min})/2$ then

for $\lambda_{\min} \le \lambda \le \mu - \Lambda/2$

$$g(\lambda;k,\theta,\mu) = k\exp[-\theta(\lambda-\mu+\Lambda)^2] \qquad (3)$$

for $\mu-\Lambda/2 \le \lambda \le \lambda_{\max}$

$$g(\lambda;k,\theta,\mu) = k\exp[-\theta(\lambda-\mu)^2] \qquad (4)$$

In these equations, $\Lambda = \lambda_{\max} - \lambda_{\min}$, $\theta = 1/\sigma^2$, and λ_{max} and λ_{min} are the wavelength limits of the visible spectrum. For $0 \le k \le 1$, $\lambda_{\min} \le \mu \le \lambda_{\max}$ and positive θ, we have a Gaussian-like reflectance (i.e., it is in [0, 1] for all wavelengths) function. We will refer to the triple kσμ as KSM coordinates, where σ stands for standard deviation, μ for peak wavelength, and k for scaling. Figure 1 shows an example of a wraparound Gaussian metamer for the spectral reflectance of Munsell paper 5 YR 5/6 under D65. Based on these KSM coordinates, we define descriptors for lightness (called KSM lightness) and chroma (called KSM chroma) and compare them to CIECAM02 lightness and saturation. Our tests show two important properties of both KSM lightness and chroma. First, they correlate well with the value and chroma designators of Munsell papers. Second, KSM descriptors are much more stable under a change of illuminant than CIECAM02.

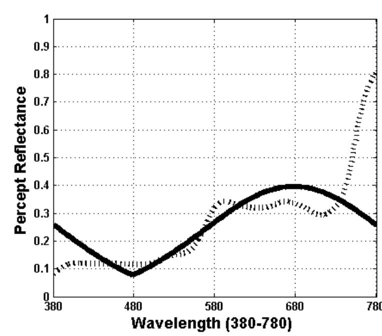

Figure 1. The spectral reflectance of Munsell 5 YR 5/6 (dotted black) and its metameric wraparound Gaussian (solid black) spectrum under D65. Result is for the CIE 1931 $\bar{x}\bar{y}\bar{z}$ 2-degree standard observer.

CIE Lightness

The CIE defines lightness in terms of brightness, where brightness is "…a visual perception according to which an area appears to exhibit more or less light." (p. 26 of [12]). Lightness is then defined as "…the brightness of an area judged relative to the brightness of a similarly illuminated reference white" (p. 26 of [12]).

KSM Lightness

Given the XYZ coordinates (CIE 1931 2-degree observer functions $\bar{x}, \bar{y}, \bar{z}$) for light reflected from an object illuminated by light of known spectrum, the parameters k, σ, and μ of the metameric wraparound Gaussian reflectance are determined. Given these KSM parameters, the KSM lightness is defined by:

$$L(k,\sigma,\mu) = 100 \times \int_{\lambda_{min}}^{\lambda_{max}} g_{k,\sigma,\mu}(\lambda)\,\bar{y}(\lambda)d\lambda \qquad (5)$$

Chroma and Saturation

Chroma is defined as "…the colourfulness of an area judged as a proportion of the brightness of a similarly illuminated reference white" (p. 27 of [12]); where colourfulness is defined as "…that attribute of a visual sensation according to which an area appears to exhibit more or less chromatic content." (p. 26 of [12]).

Saturation is defined as "…the colourfulness of an area judged in proportion to its brightness" (p. 27 of [12]). The distinction is between judging the chromatic content of the object with respect to the brightness of a reference white versus the object's own brightness. Both chroma and saturation are open-ended scales with a zero origin at neutral colors.

KSM Chroma

Generally, the chromatic content of a wraparound Gaussian will decrease with increasing σ since as σ increases the corresponding wraparound Gaussian reflectance function becomes broader and flatter. Therefore it is natural for KSM chroma to be inversely proportional to σ. However, simply using $1/\sigma$ is insufficient in that there is also some dependence on hue. Therefore, KSM Chroma, *C,* is defined as:

$$C(\sigma,\mu) = h/\sigma \qquad (6)$$

where h is defined to be $h = 2.4 + \left|\frac{\mu-\lambda_{min}}{\lambda_{max}-\lambda_{min}} \times 2\pi - t\right|$, $\lambda_{min} \le \mu \le \lambda_{max}$ and offset, t, is determined empirically as t=1.15π for the Munsell dataset. The region around 1.15π corresponds to a greenish yellow hue. As μ departs from t, h increases. Note that the offset of 2.4 is included to avoid zero chroma when we are at t.

Modeling Munsell Designators Under CIE C

To see how well the Munsell designators are modeled using the KSM lightness and chroma descriptors, we evaluate them on the set of reflectances of the 1600 papers from the Munsell glossy set. We synthesized the XYZ tristimulus values of all 1600 papers based on the Joensuu Color Group spectral measurements [4] under illuminant C using the CIE 1931 $\overline{xyz}$ 2-degree observer colour matching functions and then computed the corresponding KSM and CIECAM02 lightness descriptors. When calculating the CIECAM02 descriptors, we adopted the parameters suggested for the "average surround" condition and full adaptation.

In the following figures, the Munsell reflectances used are those of the papers of hue 5RR, 5YR, 5YY, 5GY, 5GG, 5BG, 5BB, 5PB, 5PP, and 5RP, chroma 2, 4, 6, 8, 10, and value 5, 6, 7, 8, and 8.5. Figure 2 plots a marker encoding the Munsell value for each of these Munsell papers at a location determined by the KSM/CIECAM02 lightness descriptor. It can be seen that lightness descriptors in both systems appear to correlate very well with the Munsell value designator. This is indicated by the fact that the colours of the same Munsell value align horizontally. Note that KSM lightness descriptors $L(k,\sigma,\mu)$, which are originally in [0, 1], have been scaled by 100 for easier comparison to CIECAM02.

One numerical measure of how well the lightness descriptors account for Munsell value is the correlation coefficient between the Munsell value designators and the lightness descriptors. Correlation coefficients for the two lightness descriptors are high: 0.991 (KSM) and 0.995 (CIECAM02). As a second quantitative measure, we trained a lightness classifier based on genetic algorithm optimization. The problem is defined as finding the lightness boundaries that optimally categorize the Munsell papers into 5 Munsell value groups (5, 6, 7, 8, 8.5) with the lowest misclassification rate. The misclassification rate then provides a measure of how well the given descriptor models Munsell value. As can be seen from Figure 2, there is no sample that is misclassified based on either its CIECAM02 lightness or KSM lightness.

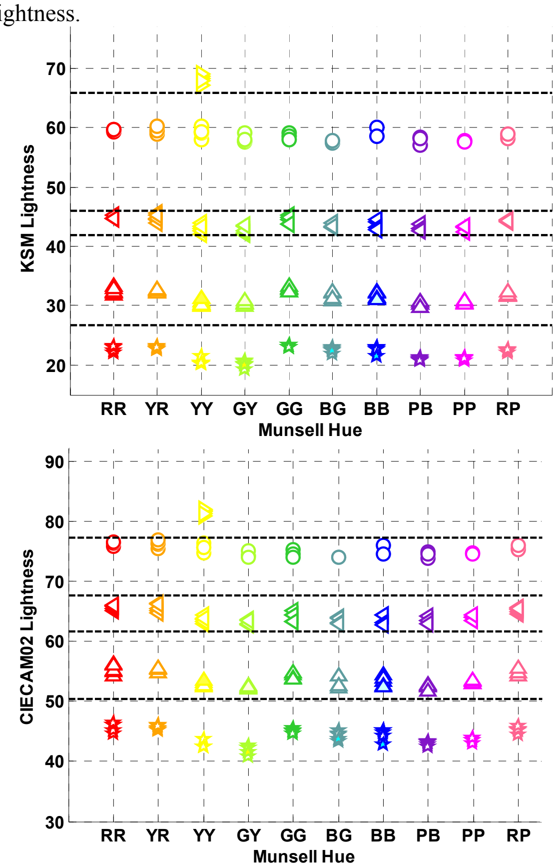

Figure 2. Lightness descriptor versus Munsell value for Munsell papers of Munsell hue 5RR, 5YR, 5YY, 5GY, 5GG, 5BG, 5BB, 5PB, 5PP, and 5RP; chroma 2, 4, 6, 8, 10; and value 5, 6, 7, 8, and 8.5. The marker shape represents the Munsell value: 5 (star), 6 (upward pointing), 7 (left pointing), 8 (circle), and 8.5 (right pointing). Top and bottom plots are of the KSM and CIECAM02 lightness descriptors, respectively. The horizontal alignment in the panels shows that papers of the same Munsell value but differing chroma and hue are all being assigned the same lightness descriptor. The horizontal dashed lines are the class boundaries as determined by genetic algorithm optimization.

A similar test was carried out on the chroma designators of Munsell papers. Figure 3 plots a marker encoding the Munsell chroma for each of the Munsell papers at a location determined by the KSM chroma (upper plot) or CIECAM02 saturation (lower plot) descriptor. The different marker shapes (i.e., upward-pointing triangles, left-pointing triangles, circles, right-pointing triangles, and stars) in the plots correspond to the Munsell chroma of 2, 4, 6, 8, and 10, respectively. The horizontal alignment of similar symbols indicates that KSM chroma and CIECAM02 saturation both correlate well with Munsell chroma.

We are using CIECAM02 saturation rather than CIECAM02 chroma because we found that it correlated better with Munsell chroma. Note that KSM chroma is scaled to match the Munsell chroma range. The correlation coefficient of Munsell chroma designators with respect to KSM chroma and CIECAM02 saturation are 0.96 and 0.94, respectively. In comparison, the correlation coefficient for CIECAM02 chroma was 0.86. The chroma misclassification rates for a chroma classifier trained using genetic algorithm optimization are 14.4% and 19.3% for KSM chroma and CIECAM02 saturation, respectively.

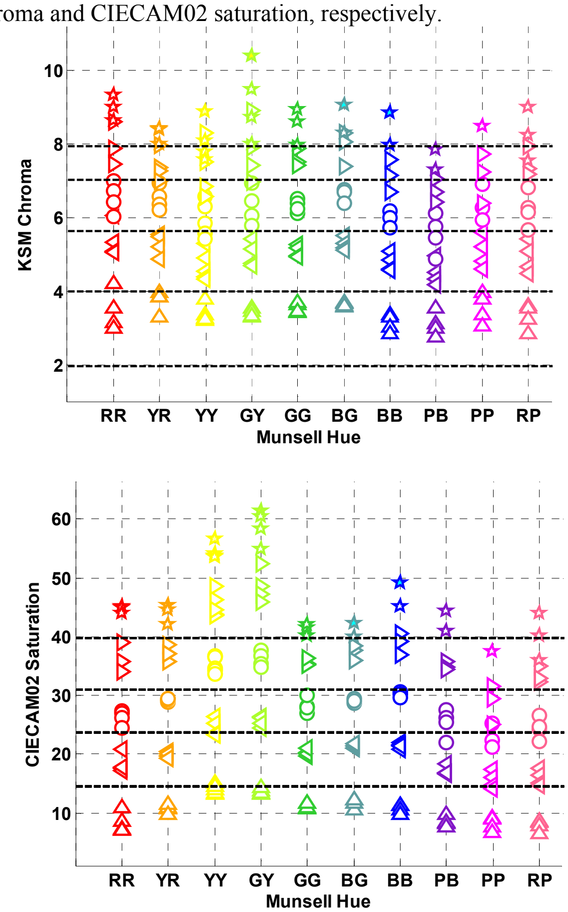

Figure 3. Chroma/saturation descriptor versus Munsell chroma for Munsell papers of Munsell hue 5RR, 5YR, 5YY, 5GY, 5GG, 5BG, 5BB, 5PB, 5PP, and 5RP; chroma 2, 4, 6, 8, 10; and value 5, 6, 7, 8, 8.5. The marker shape represents the Munsell chroma: 2 (upward pointing), 4 (left pointing), 6 (circle), and 8 (right pointing), 10 (star). The horizontal alignment in the panels shows that papers of the same Munsell chroma but differing hue and value are all being assigned the same chroma/saturation descriptor. The horizontal dashed lines are the chroma class boundaries as determined by genetic algorithm optimization.

Robustness to illuminant change

The tests above have shown that the proposed KSM lightness and chroma descriptors correlate well with the Munsell value and chroma designators. Mirzaei et al. [2][3] found that their Gaussian-based hue descriptor was more stable with respect to a change of illuminant than CIECAM02. This leads to the question as to whether the same will be true for KSM lightness and chroma. As they point out, however, any colour descriptor—whether CIECAM02, KSM or any other alternative—is limited by the existence of metamer mismatching since a given XYZ under one illuminant can become any of a multitude of possible XYZ within its metamer mismatch volume under the second illuminant; and as Logvinenko et al. [13] show this the theoretical metamer mismatch volume can be surprisingly large. However, an advantage of the KSM descriptors over CIECAM02 descriptors under a change of illuminant is that the KSM descriptors are guaranteed to lead to a physically plausible answer since they are based on the properties of a metameric reflectance. In contrast, CIECAM02 updates its descriptors to account for a change in illuminant using a von Kries diagonal transformation, for which there is no guarantee of a physically plausible answer.

To determine the relative stability of the KSM descriptors to those of CIECAM02 under a change in illuminant, we synthesize the XYZ tristimulus values of the 1600 Munsell reflectances under two illuminants (e.g., D65 and A) and then determine the corresponding descriptors. Figure 4 plots the lightness descriptor under A versus the lightness descriptor under D65 for KSM (upper) and CIECAM02 (lower). Figure 5 makes a similar comparison but in terms of chroma/saturation. From the figures it can be seen that, in each case, the CIECAM02 descriptors deviate from the diagonal more than their KSM counterparts. Table I provides a quantitative comparison based on the coefficient of variation of the root-mean-square error [14] and clearly shows that the KSM descriptors are more stable than the CIECAM02 descriptors.

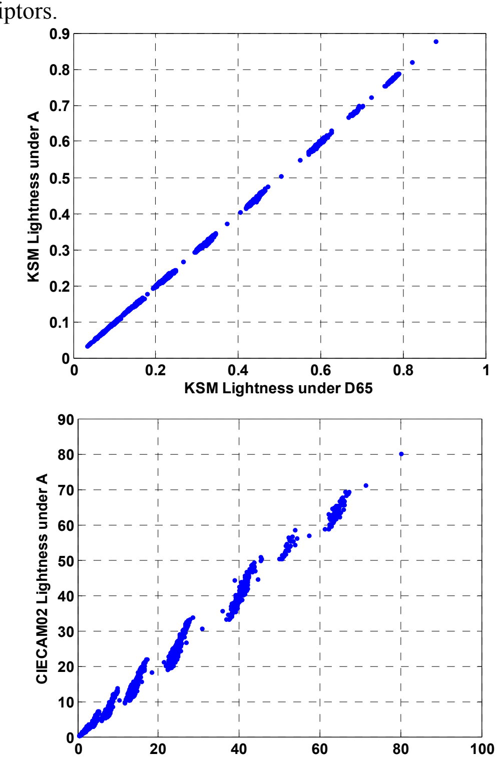

Figure 4. KSM (upper) and CIECAM02 (lower) lightness descriptors of the 1600 Munsell papers under illuminants D65 and A. A lightness descriptor that is completely invariant to the illumination will lead to points lying strictly on the diagonal.

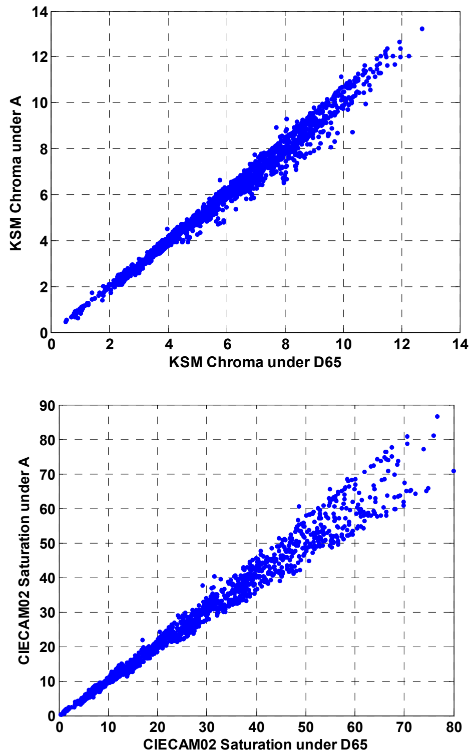

Figure 5. KSM chroma (upper) and CIECAM02 saturation (lower) descriptors of the 1600 Munsell papers under illuminants D65 and A. A descriptor that is completely invariant to the illumination will lead to points lying strictly on the diagonal.

Table I: Coefficient of variation of the RSME of the descriptors obtained for the 1600 Munsell papers under illuminant D65 versus illuminant A.

	Lightness	Chroma
CIEAM02	3.89	3.98
KSM	0.27	2.21

Conclusion

The proposed lightness and chroma descriptors were shown to correlate as well as CIECAM02 descriptors to those of the corresponding Munsell designators, but have the additional advantage that they are more consistent across illuminants. Used in conjunction with the earlier Gaussian-based hue descriptor [2] they provide a foundation for the specification of the hue, lightness and chroma dimensions of object colours under average viewing surround conditions.

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Author Biography

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