Gaussian Illuminants and Reflectances for Colour Signal Prediction

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Abstract

An alternative to the von Kries scaling underlying the chromatic adaptation transforms found in colour appearance models such as CIECAM02 is suggested for predicting what the colour signal (e.g., XYZ) reflected from a surface under a first illuminant is likely to become when lit instead by a second illuminant. The proposed method, G²M, employs metameric Gaussian-like functions to model the illuminant and reflectance spectra. The method's prediction is based on relighting the Gaussian-like reflectance spectrum with the second Gaussian-like illuminant. Tests show that the proposed G²M method significantly outperforms CIECAT02.

Introduction

The colour signal (i.e., cone response triple or CIE XYZ) observed reflected from an object's surface will generally change when the spectrum of the incident light is changed. This paper investigates the problem of predicting the new colour signal given as input the original colour signal along with the colour signal of the incident light as reflected by an ideal reflector. Many methods have been proposed for making such prediction of which von Kries scaling [1] is perhaps the most common. Often the scaling is performed in a sharpened [2] basis, as is done, for example, in the chromatic adaptation transforms of Bradford [3] and the CIECAT02 of CIECAM02 [4]. In a different vein, Fairchild [5] proposed a spectral adaptation method based on the ratio of smoothed spectra.

As an alternative to von Kries scaling, the Gaussian Metamer (GM) method [6] instead predicts the new colour signal by finding a wraparound Gaussian reflectance [7] that is metameric to the given colour signal, computationally relighting that reflectance and then computing the resulting colour signal. The mean prediction error for the GM method was reported to be roughly half that of either von Kries or Bradford. The Gaussian Metamer method, however, requires knowledge of the full spectrum of the incident illumination, not just its colour signal. To eliminate the need for the full illuminant spectrum, we propose replacing the true illuminant spectrum with a metameric Gaussian spectrum. Although the prediction error increases when using a metameric illuminant, it remains, nonetheless, less than two thirds of the CIECAT02 error. The details are presented below.

Although predicting the colour signal under an illuminant change is potentially related to chromatic adaptation, it is not the same as predicting the resulting colour appearance [8]. Neither is it the same as predicting what human subjects may see as corresponding colours on displays since then the 'corresponding colours' are the colours of lights, not object colours. One exception in this regard is Fairchild's [5] Spectral Adaptation method and data. The bulk of the Luo et al. LUTCHI dataset [9] is based on the matching of lights, with a relatively small portion performed using objects.

The existence of metamer mismatching also means there is no unique colour signal to predict. Since there are many reflectances that can lead to the same colour signal under the first light, the set of possible colour stimuli that results under the second light forms a volume in colour space, often referred to as the metamer mismatch volume. Any colour signal in the metamer mismatch volume is a possible 'correct' answer. Our goal is simply to find the colour signal that fits the experimental data best on average, with the potential error in any particular case limited only by the size of the associated metamer mismatch volume.

Gaussian Reflectance and Illuminant Spectra

Logvinenko [7] defines a set of Gaussian-like spectral reflectance functions defined in terms of their scaling, k_m, standard deviation, σ_m, and peak wavelength, μ_m. These Gaussian-like functions are not strictly Gaussians, but rather are defined on a finite wavelength interval and in some cases wraparound at the ends of the interval, hence the name "wraparound Gaussians". Although the equations defining them are piecewise and a bit complex, intuitively they simply describe a Gaussian centered at μ_m on the hue circle. Following Logvinenko, the reflectance functions are defined by Eqs. 1 to 4.

If $\mu_m \le (\lambda_{\max} + \mu_{\min})/2$:

For $\lambda_{\min} \le \lambda \le \mu_m + \Lambda/2$

$$g_m(\lambda; k_m, \theta_m, \mu_m) = k_m \exp[-\theta_m(\lambda - \mu_m)^2] \quad (1)$$

For $\mu_m + \Lambda/2 \le \lambda \le \lambda_{\max}$

$$g_m(\lambda; k_m, \theta_m, \mu_m) = k_m \exp[-\theta_m(\lambda - \mu_m - \Lambda_m)^2] \quad (2)$$

If $\mu_m \ge (\lambda_{\max} + \mu_{\min})/2$ we have two cases:

For $\lambda_{\min} \le \lambda \le \mu_m - \Lambda/2$

$$g_m(\lambda; k_m, \theta_m, \mu_m) = k_m \exp[-\theta_m(\lambda - \mu_m + \Lambda)^2] \quad (3)$$

For $\mu_m - \Lambda/2 \le \lambda \le \lambda_{\max}$

$$g_m(\lambda; k_m, \theta_m, \mu_m) = k_m \exp[-\theta_m(\lambda - \mu_m)^2] \quad (4)$$

where $\lambda_{\max}$ *and* $\lambda_{\min}$ are the ends of the visible spectrum, $\Lambda = \lambda_{\max} - \lambda_{\min}$ and $\theta_m = 1/\sigma_m^2$. For $0 \le k_m \le 1$,

$\lambda_{\min} \le \mu_m \le \lambda_{\max}$ and positive θ_m, we have a Gaussian-like reflectance function.

Now consider also the three-parameter set of illuminant functions of the same form:

If $\mu_l \le (\lambda_{\max} + \mu_{\min})/2$:

For $\lambda_{\min} \le \lambda \le \mu_l + \Lambda/2$

$$g_l(\lambda; k_l, \theta_l, \mu_l) = k_l \exp[-\theta_l(\lambda - \mu_l)^2] \quad (5)$$

For $\mu_l + \Lambda/2 \le \lambda \le \lambda_{\max}$

$$g_l(\lambda; k_l, \theta_l, \mu_l) = k_l \exp[-\theta_l(\lambda - \mu_l - \Lambda_l)^2] \quad (6)$$

If $\mu_l \ge (\lambda_{\max} + \mu_{\min})/2$ we have two cases:

For $\lambda_{\min} \le \lambda \le \mu_l - \Lambda/2$

$$g_l(\lambda; k_l, \theta_l, \mu_l) = k_l \exp[-\theta_l(\lambda - \mu_l + \Lambda)^2] \quad (7)$$

For $\mu_l - \Lambda/2 \le \lambda \le \lambda_{\max}$

$$g_l(\lambda; k_l, \theta_l, \mu_l) = k_l \exp[-\theta_l(\lambda - \mu_l)^2] \quad (8)$$

Note that for the spectral power distributions the restriction is on the scaling is simply $k_l >= 0$ since the intensity of the light is not limited. We will refer to triples (k_m, σ_m, μ_m) and (k_l, σ_l, μ_l) as the KSM coordinates of the reflectance and light, respectively.

Proposed Method

Given the colour signal specified in CIE XYZ (or cone LMS) coordinates of light reflected from a surface and the spectra of the first (F) and second (S) illuminants, the first step in the original GM method is to determine the KSM coordinates of the wraparound Gaussian reflectance using a fast interpolation method [10] that is metameric (i.e., of identical XYZ) to the given surface under F. This metameric reflectance spectrum is relit—in other words, multiplied by the full spectrum of S—and the colour signal under S is then calculated using the $CIE\,1931\,\bar{x}\bar{y}\bar{z}$ colour matching functions.

The proposed new method models the surface reflectance as well as both illuminants using wraparound Gaussian metamers and will be denoted G^{2}M. The first step in the G^{2}M method is to determine the KSM coordinates (k_F, σ_F, μ_F), again using the fast interpolation method, of the Gaussian illuminant spectrum that is metameric to F. The second step is to find the KSM coordinates (k_m, σ_m, μ_m) of the Gaussian reflectance that under Gaussian illuminant (k_F, σ_F, μ_F) has the same XYZ as the given surface under F. The third step is to find the Gaussian illuminant with coordinates (k_S, σ_S, μ_S) that is metameric to S. The fourth step is to relight the Gaussian reflectance (k_m, σ_m, μ_m) using the Gaussian illuminant (k_S, σ_S, μ_S) and determine its resulting XYZ colour signal.

Tests

We compare the prediction results using GM and G^{2}M to those of CIECAT02, which is a chromatic adaptation transform and the first step in the CIECAM02 colour appearance model [4]. The three methods' predictions are compared to the computed ground-truth values under the second illuminant (i.e., XYZ of the actual reflectance spectra multiplied by the spectrum of the second illuminant).

Munsell Papers under CIE Illuminants

In the first test we consider the set of 1600 Munsell papers [11] under CIE D50 as the first illuminant and CIE A and CIE D65 as two different second illuminants. The accuracy of each colour signal prediction is measured in terms of the CIEDE2000 colour difference measure. Table 1 lists the results where it can be seen that the GM and G^{2}M predictions are better than those of CIECAT02 using complete adaptation. Although the performance of G^{2}M is, as expected, slightly worse than that of GM, the difference is surprisingly small given that in G^{2}M the spectra of both illuminants are replaced with wraparound Gaussians.

Table 1: CIEDE2000 prediction errors of CIECAT02, GM and G^{2}M for the case of the 1600 Munsell papers with the illuminant changing from CIE D50 to CIE A and to CIE D65.

To	Method	Median	Mean	95th Percentile
A	GM	0.70	0.86	2.06
	G^{2}M	0.80	0.97	2.22
	CAT02	1.53	1.77	4.04
D65	GM	0.28	0.37	0.98
	G^{2}M	0.33	0.40	0.99
	CAT02	0.40	0.47	1.08

Although GM and G^{2}M make better predictions than CIECAT02, an additional advantage of these methods is that their predictions are guaranteed to be within the metamer set so long as the KSM coordinates have $k_m \le 1$ since that condition ensures that the resulting wraparound Gaussian is a reflectance function (i.e., strictly within the range 0 to 1). For a very few colour signals the KSM coordinates have $k_m > 1$. For any such case, we use a rectangular metamer function from Logvinenko's original object colour atlas [12] in place of a wraparound Gaussian. Of the 1600 colour signals of the Munsell papers under D50, GM found the KSM coordinates of only 44 of them had $k_m > 1$ and G^{2}M found only 43. For these few cases rectangular metamer functions were used in place of wraparound Gaussian functions. Since the rectangular reflectance atlas is complete, we are guaranteed that there will always be a rectangular reflectance function that is metameric to any given colour signal. As a result, all colour signal predictions are guaranteed to be feasible in that they lie within the metamer mismatch volume of the given colour signal.

Chromatic Illuminants and Varying Chroma/Value

As a further test of the proposed G^{2}M method of colour signal prediction, we consider the set of illuminants Logvinenko and Tokunaga used in their asymmetric colour matching experiment [13]. The spectra of these illuminants are shown in Fig. 1, where the colour of the curves indicates their corresponding spectra, except for the neutral, which is plotted in gray. Since the two reds, R1 and R2, are similar, we use only R1.

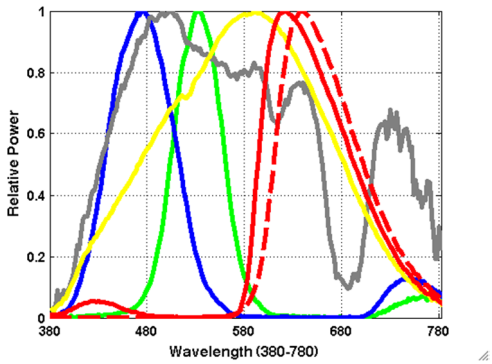

Fig. 1. *Spectral power distributions of the green (G), blue (B), neutral (N), yellow (Y), first red (R1) and second red (R2) illuminants used in Logvinenko and Tokunaga's experiments [13]. The plotted colours identify the associated spectrum along with grey indicating N. The solid red indicates R1 and the dashed red indicates R2.*

We considered 20 different hues from the Munsell Book of Color that sample the full hue circle. They are: 5 R, 10 R, 5 YR, 10 YR, 5 Y, 10 Y, 5 GY, 10 GY, 5 G, 10 G, 5 BG, 10 BG, 5 B, 10 B, 5 PB, 10 PB, 5 P, 10 P, 5 RP, and 10 RP. To evaluate the effect of Munsell chroma and value on the predictions, we test the three methods at these hues while varying the chroma over 2, 4, 6, and 8, and value over 5 and 7.

For a change of illuminant from G, B, Y, or R1 to N, Table 2 gives the median and average CIEDE2000 error in the predictions taken across the 20 Munsell hues at a given value and chroma. It can be seen that both GM and G^{2}M methods consistently outperform CIECAT02.

To assess the results visually, consider the example of G to N prediction. Fig. 2 plots the GM, G^{2}M, and CIECAT02 predictions in chromaticity space for the 20 hues at value 7, chroma 8. The average error over the 20 papers in this case is 8.82 CIEDE2000 for GM, 9.72 for G^{2}M, 15.54 for CIECAT02.

In terms of how the prediction error varies with chroma, Fig. 3 plots the median error for the same 20 hues at value 7, with the chroma varying over 2, 4, 6, and 8. The illuminant change is from G to N. The error tends to increase with increasing chroma for all three methods; however, the GM and G^{2}M errors are significantly less than those of CIECAT02 in all cases.

Conclusion

A new method of predicting the change in colour signal of the light reflected from a surface was presented and shown to make significantly more accurate predictions than CIECAT02 with full adaptation. The proposed G^{2}M method eliminates the requirement of the previous Gaussian Metamer (GM) method [6] that full spectral power distributions of the two illuminants be known. Although the tests show that the accuracy of G^{2}M is somewhat less than that of GM, it is still significantly more accurate than CIECAT02 as measured in terms of CIEDE2000 colour differences. G^{2}M shares with GM the fact that, unlike von-Kries-based prediction methods, all of its predictions are guaranteed to represent a physically realizable change in colour signal.

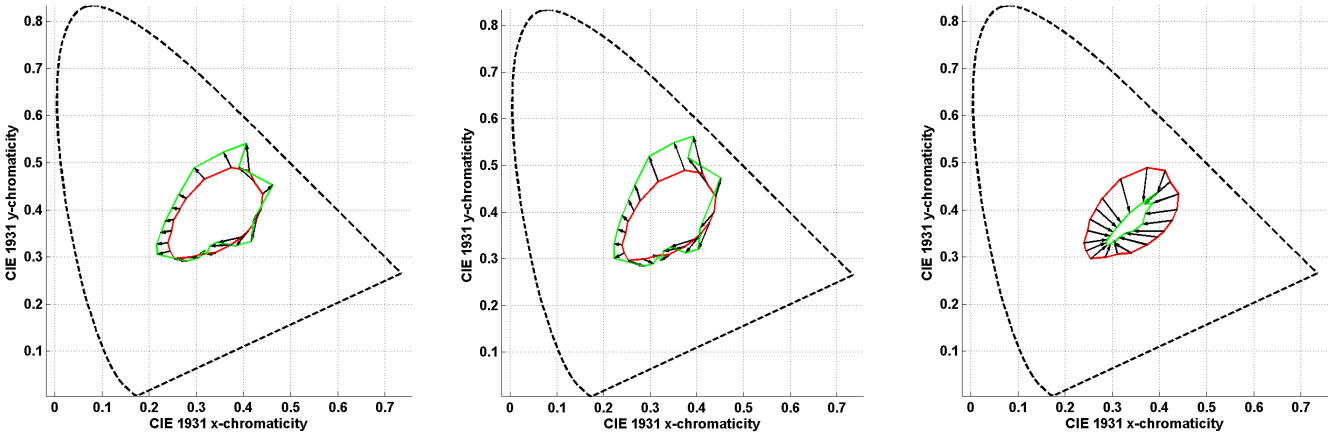

Fig. 2. *Colour signal prediction for the 20 Munsell papers (of chroma 8 and value 7) when the illuminant is changed from G (green) to N (neutral). Left GM, center G^{2}M and right CIECAT02. Plot is in CIE xy-chromaticity space. An arrow tail indicates the actual chromaticity of the paper under the neutral illuminant with the corresponding arrow head its predicted chromaticity. The red and green curves simply connect all the arrow tails and arrow heads for clarity. The red curves are the same in all 3 panels.*

Table 2: The median and average prediction error in CIEDE2000 for the change from each of the 5 different chromatic illuminants to N ('white'). Each row is for papers of the 20 Munsell hues at the specified value and chroma. The last row reports the mean of the values in the corresponding column.

First Illuminant	Munsell Attribute		Median CIEDE2000			Mean CIEDE2000		
	Value	Chroma	GM	G^2M	CAT02	GM	G^2M	CAT02
G	5	2	2.13	2.94	5.89	2.83	4.04	5.99
G	5	4	4.93	5.79	10.31	4.42	6.13	9.90
G	5	6	6.54	7.50	12.55	6.02	7.59	12.38
G	5	8	5.44	8.56	14.22	6.94	8.61	13.89
G	7	2	2.30	2.49	7.18	3.11	3.56	6.33
G	7	4	6.03	5.50	12.14	6.38	7.11	11.13
G	7	6	6.51	6.88	14.81	7.65	8.40	13.30
G	7	8	6.96	7.30	17.62	8.82	9.72	15.54
B	5	2	0.22	0.69	0.57	0.31	0.75	0.71
B	5	4	0.42	1.03	1.10	0.50	1.15	1.19
B	5	6	0.56	1.26	1.45	0.68	1.42	1.51
B	5	8	0.66	1.38	1.87	0.74	1.61	1.83
B	7	2	3.88	6.67	6.57	5.15	6.44	7.63
B	7	4	4.19	9.47	11.35	6.46	9.79	12.67
B	7	6	6.18	11.33	15.69	7.63	11.72	15.44
B	7	8	7.15	12.67	18.74	8.80	13.19	17.87
Y	5	2	2.13	2.94	5.89	2.83	4.04	5.99
Y	5	4	4.93	5.79	10.31	4.42	6.13	9.90
Y	5	6	6.54	7.50	12.55	6.02	7.59	12.38
Y	5	8	5.44	8.56	14.22	6.94	8.61	13.89
Y	7	2	2.30	2.49	7.18	3.11	3.56	6.33
Y	7	4	6.03	5.50	12.14	6.38	7.11	11.13
Y	7	6	6.51	6.88	14.81	7.65	8.40	13.30
Y	7	8	6.96	7.30	17.62	8.82	9.72	15.54
R1	5	2	0.22	0.69	0.57	0.31	0.75	0.71
R1	5	4	0.42	1.03	1.10	0.50	1.15	1.19
R1	5	6	0.56	1.26	1.45	0.68	1.42	1.51
R1	5	8	0.66	1.38	1.87	0.74	1.61	1.83
R1	7	2	3.88	6.67	6.57	5.15	6.44	7.63
R1	7	4	4.19	9.47	11.35	6.46	9.79	12.67
R1	7	6	6.18	11.33	15.69	7.63	11.72	15.44
R1	7	8	7.15	12.67	18.74	8.80	13.19	17.87
Mean	-	-	4.01	5.72	9.51	4.78	6.33	9.21

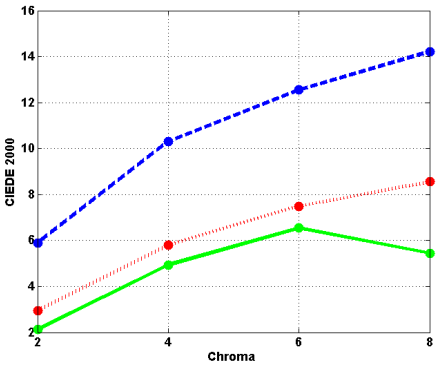

Fig. 3. *Different methods' median CIEDE2000 prediction error as a function of Munsell chroma (2, 4, 6, 8) at value 7 for a change of illuminant from G to N. The GM, G^2M, and CIECAT02 results are plotted in solid green, dotted red, and dashed blue, respectively.*

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