Incidence of Metamerism in Natural Scenes

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Abstract

Estimates of the incidence of metameric surfaces, defined as having different spectral reflectances but appearing the same under a given light, were obtained from 40 hyperspectral images of natural scenes. The degree of metamerism was specified with respect to a color-difference metric after allowing for full chromatic adaptation to the scene. Although the proportion of pairs of surfaces in an image that were metameric was very low, between about 10^{-4} and 10^{-5}, the relative proportion, i.e. of pairs indistinguishable under one of the daylights that were metameric was high, of the order of 10^{-1}, depending on the type of scene and criterion degree of metamerism. The proportion of metamers in scenes containing foliage was generally higher than in scenes containing man-made structures, and this difference increased as the degree of metamerism increased.

Introduction

Metamerism is the phenomenon of different spectral energy distributions producing identical responses in the eye, or, more generally, sensor system.[1] Metamers arise because the number of degrees of freedom in the sensor system, three for the cones in the human eye or a typical camera, is smaller than the number of degrees of freedom needed to specify different spectra.[2-4] The most important examples of metamers are provided by surfaces with different spectral reflectances that look the same when illuminated by a particular light.[1] In practice, such metamerism may be discounted providing that the surfaces continue to look the same when the spectrum of the illumination changes, for their visual identity is then an invariant and not an accident of viewing condition. Metamerism does, however, become a practical problem when the reflected lights become distinguishable with an illuminant change.

Although the degree of metamerism can be expressed in terms of a metric on the space of reflectances, a more relevant measure is one that quantifies the extent to which reflectances become visually distinguishable when the illuminant changes.[1] The difference in appearance may be expressed in terms of a color-difference metric, and this forms the basis for the CIE 1986 special metamerism index.

Are, then, metamers common in the natural world? There has been some speculation that metamers in natural scenes ought to be rare,[5-7] but although there is a large literature on metamerism,[1] particularly dealing with theoretical issues,[8-10] few data are available about the actual proption of metamers in the natural environment.[6] This is not altogether surprising, since the density of any particular spectral reflectance is generally unknown, and estimates need to be based on data with spatial resolution compatible with that of the eye (or other sensor). To address this problem, an analysis was made of spectral-reflectance data obtained with a hyperspectral imaging system. This system was used to record 40 distant and close-up images of a large ensemble of scenes drawn from the uncultivated and cultivated countryside of the Minho region of Portugal, which has a variety of vegetation and natural rock formations (some examples are shown in Fig. 1). The required estimates were obtained by calculating the proportion of pairs of surfaces in a scene in which color differences were subthreshold under one illuminant, a daylight of correlated color temperature 25000 K, but suprathreshold under another illuminant, a daylight of correlated color temperature 4000 K, these illuminants representing, respectively, the north sky and combinations of direct sun and sky.[1]

Such estimates of the proportion of metameric pairs depend of course on the choice of threshold color difference and the criterion degree of metamerism, as well as on other variables, including the nature of the scene, the spectra of the two illuminants, and the particular color-difference metric. Nevertheless, as shown here, it is still possible to make order-of-magnitude estimates of the incidence of natural metamers, and more precise comparisons of their variation across particular kinds of scenes. Contrary to what might be expected,[5,6] the incidence of metamers in scenes containing foliage is higher than in those containing man-made structures, and this difference increases as the criterion degree of metamerism increases.

Methods

The hyperspectral imaging system was based on a low-noise Peltier-cooled digital camera providing a spatial resolution of 1344 × 1024 pixels (Hamamatsu, model C4742-95-12ER, Hamamatsu Photonics K. K., Japan) with a fast tunable liquid-crystal filter (VariSpec, model VS-VIS2-10-HC-35-SQ, Cambridge Research & Instrumentation, Inc., MA) mounted in front of the lens, together with an infrared blocking filter. Focal length was typically set to 75 mm and aperture to f/16 or f/22 to achieve a large depth of focus. The line-spread function of the system was close to Gaussian with standard deviation approx. 1.3 pixels at 550 nm. The intensity response at each pixel, recorded with 12-bit precision, was linear over the entire dynamic range. The peak-transmission wavelength was varied in 10-nm steps over 400–720 nm. The bandwidth (FWHM) was 10 nm at 550 nm, decreasing to 7 nm at 400 nm and increasing to 16 nm at 720 nm. Before image acquisition, the exposure at each wavelength was determined by an automatic routine so that maximum pixel output was within 86–90% of the CCD saturation value.

Figure 1. A sample of the 40 scenes used in this study (adapted from Ref. 9).

Immediately after acquisition, the reflected spectrum from a small flat gray (Munsell N5 or N7) reference surface in the scene was recorded with a telespectroradiometer (SpectraColorimeter, PR-650, Photo Research Inc., Chatsworth, CA), the calibration of which was traceable to the National Physical Laboratory. Images were corrected for dark noise, spatial nonuniformities (mainly off-axis vignetting), stray light, and any wavelength-dependent variations in magnification or registration. Effective spectral reflectances at each pixel were estimated by normalizing the corrected signal against that obtained from the gray reference surface. The spectrum of the reflected light at each pixel could then be estimated from the product of its effective spectral reflectance and a given global illuminant spectrum (the effect of indirect illumination has been analyzed in a previous study[11]). Additional details of the methodology are given elsewhere.[12]

With the acceptance angle of the camera, the spatial resolution of the system closely matched that of the human eye. Since it is this correspondence that is critical to the analysis[6] rather than the absolute level of spatial resolution, each pixel was assumed to correspond to a single surface in the scene (that its reflectance might be the superposition of several distinct reflectances at some finer scale is immaterial). The proportion of surfaces with indistinguishable reflectances was very small and is tabulated in the following section.

Scenes were simulated under successive global daylight illuminants of correlated color temperatures first 25000 K and second 4000 K, each with luminance 100 cd m^{-2}. These illuminants were chosen in preference to the CIE standard fluorescent lamps because of their relevance to vision in natural scenes. In each scene, a sample of 2500 (or 5000) pixels was chosen at random, and the illuminant was fixed at 25000 K. (Samples were distributed uniformly to capture the properties of the scene as a whole rather than of any particular surface: estimates of the proportions of metameric pairs did not differ significantly across the two sizes of sample.) The spectrum of the reflected light at each pixel in the sample was then converted to tristimulus values. The effects of full chromatic adaptation to the sample were next calculated from a standardized model,[13] CMCCAT2000; that is, a fixed linear transformation M defined by CMCCAT2000 was applied which converted the original tristimulus values X, Y, Z to nominal R, G, B values; these were then scaled by a diagonal (von Kries) linear transformation representing full adaptation; and then the inverse transformation M^{-1} was applied to obtain the corresponding colors X_C, Y_C, Z_C. These X_C, Y_C, Z_C values were finally converted to CIELAB L^*, a^*, b^* values with respect to a reference white D_{65} of luminance 100 cd m^{-2}.

The distinguishability of spectra was specified in relation to a threshold quantity defined by the CIE 2000 color-difference formula[14] CIEDE2000. Thus color differences ΔE between the members of each pair of pixels in the sample were compared with a nominal threshold value ΔE^{thr}, whose value is given in the Results section. Additional calculations were made with other plausible values[15] of the chromatic-adaptation transformation M. With 2500 pixels in the sample, there were $N = 2500\times2499/2 = 3123750$ distinct pairs. The number N_1 of all pairs of pixels in N with color differences ΔE less than ΔE^{thr} was first determined. The illuminant was then changed from 25000 K to 4000 K and the number of pairs N_2 in N_1 determined whose color differences ΔE evaluated under the second illuminant exceeded a certain multiple $n = 1, \ldots, 4$, of ΔE^{thr}, thereby defining the criterion degree of metamerism.

The proportion of metameric pairs in the scene as a whole was estimated by N_2/N and, as a relative measure, by N_2/N_1. These proportions were averaged over 15 scenes classified as urban, containing predominantly man-made structures, and 25 scenes classified as rural, containing predominantly foliage.

Proportions are reported as logarithms to the base 10 because of the large variations in magnitude and the linearizing effect with criterion degree of metamerism n.

Results

Table 1 shows results for the adaptation model CMCCAT2000 and color-difference formula CIEDE2000 with nominal threshold value ΔE^{thr} of 0.5, which is approximately equal[16] to a CIELAB threshold value ΔE_{ab} of 1, typical for the present task.[4] The absolute proportion $p_{\text{abs}} = N_2/N$ of metameric pairs and the relative proportion $p_{\text{rel}} = N_2/N_1$ in $\log_{10}$ units are given as a function of the criterion degree of metamerism n for scenes classified as urban or rural. Standard deviations are population estimates based on the number of scenes shown in parentheses. The decline in the log proportion of metamers with n was linear under all conditions. Almost exactly the same proportions were obtained with the opposite illuminant shift, from 4000 K to 25000 K, and similar patterns of dependence on $n = 1, \ldots, 4$ were obtained with a sharp adaptation transform[15] and with larger values of the threshold ΔE^{thr}.

Discussion

It seems that the incidence of metameric pairs of surfaces in natural scenes is very low. From the present analysis of 40 hyperspectral images, between about 10^{-4} and 10^{-5} of all pairs of surfaces were indistinguishable under one illuminant and distinguishable under another, independent of whether the scene was classified as urban or rural. The proportion of metamers declined less rapidly with the criterion degree of metamerism for scenes containing foliage, and for sufficiently high criterion degrees of metamerism, it was always higher than for scenes containing man-made structures. The higher metamerism associated with foliage is probably due to the presence of the chlorophylls and carotenoids, which provide multiple reflectance peaks.

Knowledge of the low incidence of metameric pairs in natural scenes may, however, be less useful than it seems for an observer attempting to estimate the chances of error in a given task requiring a judgment of surface color. This is because there is an asymmetry in the conditional probabilities associated with distinguishable and indistinguishable pairs of surfaces under two illuminants. Thus, as Table 1 shows, the proportion of pairs whose color differences were subthreshold under the first (25000 K) illuminant is very low (column with $n = 0$), i.e. between 10^{-3} and 10^{-4}. This proportion sets an upper limit on the absolute proportion of metameric pairs, since they are, by definition, a subset of the proportion of subthreshold pairs under the first illuminant. Accordingly, an observer viewing a natural scene under a 25000 K illuminant can, in the absence of additional information, assume correctly that there is a very low probability of metamerism (this is also true for the opposite direction of illuminant change, with scenes first under a 4000 K illuminant). Moreover, presented with a pair of distinguishable surfaces from this scene, the observer can safely assume that the probability of the pair becoming indistinguishable under the second illuminant is also very low. In other words, two surfaces that appear different are almost certainly made of different materials.

Table 1: Logarithm of absolute and relative proportions of metameric pairs in natural scenes under daylight illuminants with correlated color temperatures 25000 K and 4000 K. Data are for urban scenes containing mainly buildings and rural scenes containing mainly foliage. The proportions tabulated for $n = 0$ are for pairs with subthreshold color differences $\Delta E < \Delta E^{\text{thr}}$ under the first illuminant; those for $n = 1, 2, 3, 4$ are, respectively, for pairs with subthreshold color differences $\Delta E < \Delta E^{\text{thr}}$ under the first illuminant and suprathreshold color differences under the second, i.e. $\Delta E > \Delta E^{\text{thr}}$, $\Delta E > 2\Delta E^{\text{thr}}$, $\Delta E > 3\Delta E^{\text{thr}}$, and $\Delta E > 4\Delta E^{\text{thr}}$. Means were taken over 2500 randomly sampled pairs in each scene. Standard deviations are population estimates based on the number of scenes shown in parentheses.

		Degree of metamerism, n				
		0	1	2	3	4
Urban (15)	Mean log p_{abs}	–3.62	–3.84	–4.41	–4.85	–5.21
	Std Dev	0.36	0.27	0.27	0.38	0.41
	Mean log p_{rel}		–0.23	–0.79	–1.24	–1.61
	Std Dev		0.14	0.46	0.63	0.69
Rural (25)	Mean log p_{abs}	–3.79	–3.92	–4.21	–4.48	–4.74
	Std Dev	0.49	0.39	0.36	0.36	0.42
	Mean log p_{rel}		–0.14	–0.42	–0.69	–0.96
	Std Dev		0.18	0.30	0.46	0.58

By contrast, presented with a pair of indistinguishable surfaces from a scene, the observer cannot, without additional information, then estimate the probability of the pair becoming distinguishable under the second illuminant. In fact, this conditional probability is high, with values ranging from about 0.06 to 0.8, depending on the type of scene and criterion degree of metamerism. In other words, two surfaces that appear the same may well not be made of the same material.

As has been noted elsewhere,[7] the significance of metamerism in natural scenes depends on the observer's task. But the effects of metamerism may also be indirect, and high levels of metamerism may signify a more general instability in the appearance of scenes, which, in turn, might affect the judgment of surface colors under changes in illuminant.[17]

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David Foster received his B.Sc. in Physics in 1966 and Ph.D. in 1970 from Imperial College London, and his D.Sc. in 1982 from London University. He was appointed lecturer at Imperial College in 1970 and has subsequently held professorships at Keele University, Aston University, UMIST, and Manchester University. His research work has concentrated on visual psychophysics. He is a Fellow of the Institute of Physics, the Institute of Mathematics and its Applications, and the Optical Society of America.