Observers discount effects of multiple chromatic light sources in estimating surface colour

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ABSTRACT

We tested whether observers discount the effect of changes in orientation in an achromatic setting task when the scene contains a blue diffuse and two yellow punctate sources, placed symmetrically over the line of sight of the observer. All observers discount, though not perfectly, the effects of the spatial and spectral variation in the illumination. We discuss the implications of our results for the dimensionality of an illuminant representation by spherical harmonics.

1. INTRODUCTION

When the spatial and spectral distribution of daylight illumination is non-uniform, then the spectral power distribution of light emitted by a Lambertian surface depends not only on its surface reflectance but also on its orientation in the scene. In a scene where the lighting model consists of a neutral punctate source and a neutral diffuse source, human observers partially but systematically discount the effect of changing orientation in judging the albedo of achromatic surfaces[1,2]. A similar geometric effect is found in the colour domain where observers, when making achromatic settings for a surface patch at different orientations, are able to systematically discount the relative contributions of a yellow punctate light source and a blue diffuse light source as patch orientation changes[3]. Observers also discount secondary illumination originating from other chromatic surfaces near the test patch[4].

To discount the effect of orientation on surface appearance, the visual system must estimate not just surface orientation within the scene, but also the orientation of the surface with respect to the non-diffuse components of the lighting model. In the first three studies just described, the experimenters demonstrated that the visual system effectively estimated the direction to the punctate light source by recovering accurate estimates of direction from the observers' judgements of lightness and colour[1-3]. In this study we investigate whether observers can discount the effect of changes in orientation in an achromatic setting task when the scene contains more than one punctate chromatic light source.

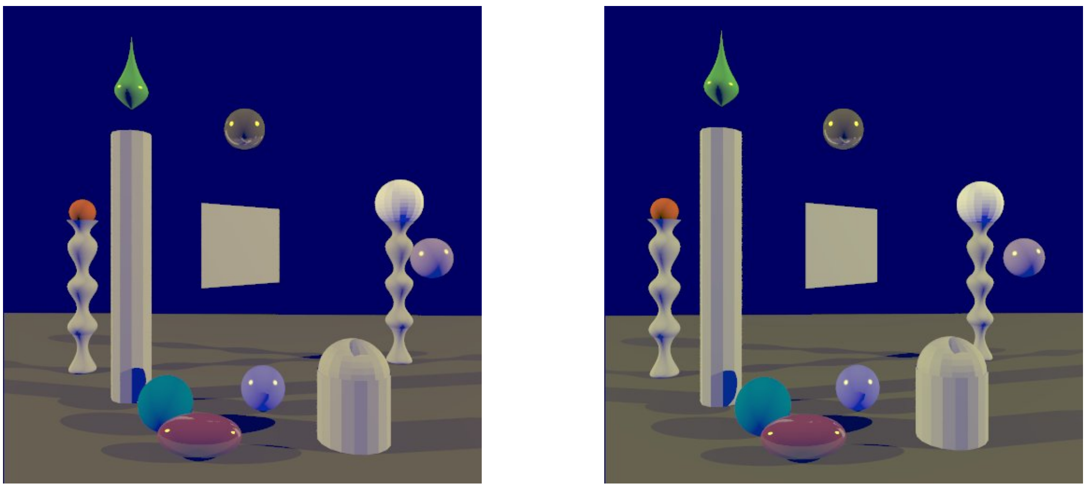

Figure 1: Sample stereo pair for cross fusion.

2. METHOD

The stimuli were computer-rendered three-dimensional scenes, composed of objects of various shapes and sizes and with a range of reflectance properties. Each scene contained a rectangular test patch at the centre (Figure 1). Observers viewed stimuli in a computer controlled stereoscope. Scenes were illuminated by a composition of a diffuse blue and two yellow punctate sources either 90° apart ($\psi_{P1} = 45, \psi_{P2} = -45$, where ψ_{Pi} is the angle between the observer's line of sight and the azimuth of the light source) or 160° apart ($\psi_{P1} = 80, \psi_{P2} = -80$). Figure 2 shows the same objects rendered under these two different lighting conditions. Note that the resulting shading (yellow-blue gradient) of matte objects under the former light condition is rather distinct from the shading under the latter light condition.

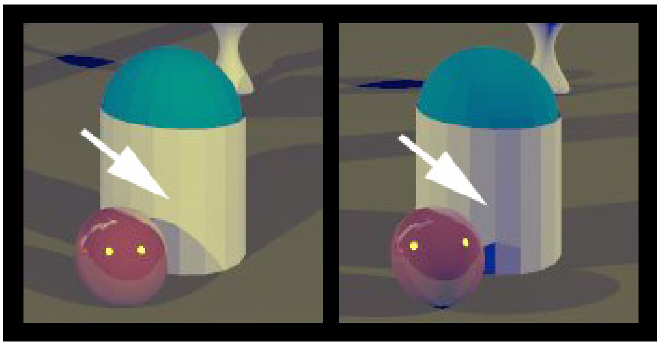

Figure 2: Excerpt from the stimulus.
Left: Shading at $\psi_{P1} = 45^\circ$, $\psi_{P2} = -45^\circ$
Right: shading at $\psi_{P1} = 80^\circ$, $\psi_{P2} = -80^\circ$.

The orientation of the test patch (ψ_T) was randomly varied between seven orientations ranging from – 65° to 65°. On each trial the task of the observer was to adjust the colour of the test patch until it was perceived to be achromatic (Instructions: "Make the rectangle look as if it is cut out from a grey piece of paper"). The colour of the test patch could be adjusted by using the computer keyboard, and it varied in the blue-yellow and red-green axis keeping the total luminance constant. Four naive observers repeated each orientation and light condition twenty times.

We measured the amount of relative blue, Λ^B, (blue/total luminance) in the observer's achromatic setting as a function of test patch orientation. If the observer mis-estimated aspects of the light such as the colour of diffuse or punctate component, or the position of the punctate source(s), however used these incorrect estimates consistently throughout the experiment to arrive at the achromatic point, then the resulting relative blue curve would deviate in a characteristic pattern from the ideal. We employ a generalization of an *equivalent lighting model (ELM)* developed in Boyaci et.al.[3]. The lighting parameters in this model are the relative blue chromaticity of the punctate source(s) π^B, and the diffuse source δ^B, the diffuse-punctate intensity ratio Δ, and the position of the punctate light source(s) ψ_{Pi}. (Actual values were: $\pi^B = 0$, $\delta^B = 1$, $\Delta = 0.24$, $\psi_{Pi} = \pm 80, \pm 45$) We used this model to predict the relative blue settings (Λ^B) at each test patch orientation for a Lambertian observer with ideal discounting:

$$\Lambda^B(\psi_T) = \frac{\pi^B\left[\cos(\psi_{P1} - \psi_T) + \cos(\psi_{P2} - \psi_T)\right] + \delta^B \Delta}{\cos(\psi_{P1} - \psi_T) + \cos(\psi_{P2} - \psi_T) + \Delta} .$$

If the scene were illuminated by only diffuse light, then the relative blue setting at each test patch orientation would be a constant:

$$\Lambda^B(\psi_T) = \delta^B .$$

3. RESULTS

We fit our model to observers' data by the method of maximum likelihood [6], assuming that the observers' settings are perturbed by Gaussian error with mean 0 and variance σ^2. If observers were not discounting the chromaticity of the light source when making achromatic settings at a given test patch orientation we would expect $\Lambda^B(\psi_T)$ to be a horizontal line (constant $\hat{\delta}^B$). We tested this hypothesis (H0, constrained model) versus the alternative that $\Lambda^B(\psi_T)$ varies as a function of test patch orientation (unconstrained model) by a nested hypothesis test[6] for both illumination conditions ($\psi_{Pi} = \pm 80, \pm 45$).

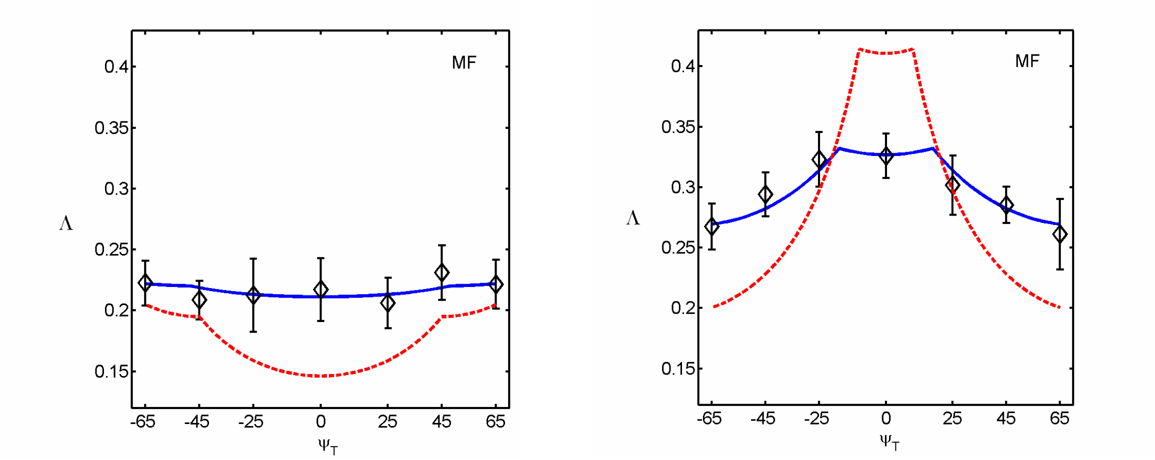

Figure 3: Results for one observer. Blue solid line: model fit, Red dashed line: model prediction. Relative blue settings are plotted as a function of test patch orientation $\Lambda^B(\psi_T)$.

Left: $\psi_{P1} = 45^\circ$, $\psi_{P2} = -45^\circ$, Right: $\psi_{P1} = 80^\circ$, $\psi_{P2} = -80^\circ$.

We obtain maximum likelihood estimates of the parameters for the constrained ($\hat{\delta}^B, \hat{\sigma}^2$) and the unconstrained lighting model ($\hat{\pi}^B, \hat{\delta}^B, \hat{\Delta}, \hat{\psi}_P, \hat{\sigma}^2$). If λ denotes the ratio of the maximum likelihood achieved in fitting the constrained and the unconstrained models, then -2log λ is approximately distributed as a χ^2_3 distribution under the null hypothesis[6]. For a test of size *p*, we reject the null hypothesis if and only if -2log λ is greater than the 1-*p* quantile of the χ^2_3 distribution. Results for the two light conditions for observer MF are shown in Figure 3, together with the predictions of the model. For the $\pm 80^\circ$ illumination condition we rejected the null hypothesis for all four observers, indicating that their relative blue setting for the test patch varied as a function of test patch orientation (BM: $p<.007$, BL: $p<.00001$, MF: $p<.00001$, SK: $p<.00001$). For scenes where the punctate sources were located at 45° and -45° we did not reject H0.

Following up on the 80° results, we furthermore tested the null hypothesis that observers' settings are in perfect agreement with the model predictions. In the constrained model (H0) we restricted the model parameters to their correct value ($\hat{\pi}^B = 0, \hat{\delta}^B = 1, \hat{\Delta} = 0.24, \hat{\psi}_P = \pm 80$) and only estimated σ^2. The unconstrained model was as before. We compared maximum likelihood estimates as described above, however -2log λ was here approximately distributed as a χ^2_4 distribution under the null hypothesis. We rejected the null hypothesis that, in the $\pm 80^\circ$ condition, observers perfectly discounted chromaticity of the illumination across test patch orientation (all observers $p<0.00001$). The results indicate that observers estimates of $\hat{\pi}^B, \hat{\delta}^B, \hat{\Delta}$, and $\hat{\psi}_P$ deviated from the veridical values (see Table 1).

In sum, all observers discounted, though not perfectly, the relative contribution of diffuse and punctate light sources across test patch orientations in the $\pm 80^\circ$ but not in the $\pm 45^\circ$ illumination condition. Maximum likelihood analysis of the data indicates that observers deviated in their estimates of the position of the punctate light source(s), they over-estimated the blue content of the punctate sources (π^B), underestimated the blue content of the diffuse source (δ^B) and overestimated the ratio of diffuse–punctate intensities (Δ).

Table 1: Estimates of the parameters of the ELM for all observers.

ID	$\hat{\psi}_P$	$\hat{\pi}^B$	$\hat{\delta}^B$	$\hat{\Delta}$
veridical:	80.0	0	1	0.24
BL	102.8	0.2126	0.3642	1.0000
BM	90.0	0.4303	0.4960	0.4467
MF	72.5	0.0493	0.5154	0.8872
SK	73.8	0.1329	0.5455	0.9327

4. CONCLUSIONS AND DISCUSSIONS

We conclude that the visual system effectively estimates the spatial and chromatic distribution of illumination in scenes in judging surface colour, even when the illumination consists of multiple punctate light sources together with a single diffuse source. Why do observers fail to discount illumination in the $\pm 45^\circ$ illumination condition? This is readily explained by looking at the model prediction (red dashed line) in Figure 3 and/or the shading pattern in Figure 2: The amount of blue in the test patch varies very little as a function of angle, the shading of the facets of the cylinder in Figure 2 illustrates this effect nicely (compare to the marked change in blue content in the $\pm 80^\circ$ condition). Given that observers' responses are noisy, we may simply not be able to detect an effect this small with the present method. It appears plausible that the characteristic chromatic shading of the neutral objects in the scene served as an important cue to the spatial and spectral distribution of the illumination. Observers, when interviewed after completing the experiment, were not aware of using any particular strategy when making their settings.

The representation problem. The spatial distribution of a lighting model can be represented by the weighted sums of *spherical harmonics* (SHs) basis functions. Analogous to the Fourier sine and cosine expansion, a function on a sphere can be expanded using the SHs[5]. Basri and Jacobs[5] have shown that one can capture most of the variations in the luminance of a matte Lambertian surface if one expands the lighting model with the first 9 SHs. Careful investigation suggest that an expansion with the first 4 SH can account for the effects of a lighting model which consists of a diffuse source and a single punctate source but not two. In order to represent more than one punctate source one needs to expand the lighting model using at least the first 9 SHs. The results in our experiment suggest that human visual system can use at least the first 9 SHs. A visual system using the 9 SHs is capable to perfectly compensate for the variations in luminance as long as a Lambertian surface is concerned.

References

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