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Time-lapse ratios of cone excitations in natural scenes

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ABSTRACT

The illumination in natural environments varies through the day. Stable inferences about surface color might be supported by spatial ratios of cone excitations from the reflected light, but their invariance has been quantified only for global changes in illuminant spectrum. The aim here was to test their invariance under natural changes in both illumination spectrum and geometry, especially in the distribution of shadows. Time-lapse hyperspectral radiance images were acquired from five outdoor vegetated and non-vegetated scenes. From each scene, 10,000 pairs of points were sampled randomly and ratios measured across time. Mean relative deviations in ratios were generally large, but when sampling was limited to short distances or moderate time intervals, they fell below the level for detecting violations in ratio invariance. When illumination changes with uneven geometry were excluded, they fell further, to levels obtained with global changes in illuminant spectrum alone. Within sampling constraints, ratios of cone excitations, and also of opponent-color combinations, provide an approximately invariant signal for stable surface-color inferences, despite spectral and geometric variations in scene illumination.
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1. Introduction

In natural environments, the light from the sun and sky varies continuously over the course of the day. As a result, the reflected light provides a constantly changing signal to the eye. As Larry Arend remarked,

> The retinal signal is jointly determined by some combination of distal optical variables, some of which (the ones we wish to recover) are intrinsic color properties of the surface and some of which are contingent, i.e., accidents of the transient optical environment in which the surface is being viewed.
> [Arend (2001), p. 392]

Yet despite this changing signal, our perception of natural scenes is stable. What, then, underpins this stability, in particular, the stability of perceived surface colors under different illuminations? As with geometrical shape perception under changes in object pose, taking ratios of signals can sometimes deliver an invariant property (e.g. Kent & Mardia, 2012; Maybank, 1995; Moons, Pauwels, Van Gool, & Oosterlinck, 1995). A retinally derived signal that offers an invariance to changes in illumination is the spatial ratio of cone excitations generated in response to light reflected from different surfaces (Foster & Nascimento, 1994). From computational simulations with natural scenes (Nascimento, Ferreira, & Foster, 2002), it is known that spatial ratios remain approximately invariant under changes in the illuminant.

This invariance property has long been assumed, explicitly or implicitly, in chromatic-adaptation models of the von Kries type (Brill, 2008; van Trigt, 2007; von Kries, 1902, 1905) and in the Retinex models due to Land (Funt, Ciurea, & McCann, 2004; Land, 1983; Land & McCann, 1971). Spatial ratios have also been used to explain judgments about surface color in displays of Munsell colored papers under different illuminants (Amano, Foster, & Nascimento, 2005), even when chromatic adaptation does not eliminate differences in color appearance (Reeves, Amano, & Foster, 2008). Moreover, in operationally oriented tasks, spatial ratios seem to be the kinds of signals preferred by observers for making discriminations between illuminant changes and simulated changes in surface reflectances (Nascimento & Foster, 1997).

Nonetheless the invariance of spatial ratios in both natural scenes and Munsell papers has been quantified only with simulated global changes in illumination spectrum (Nascimento, Ferreira, & Foster, 2002). This limitation is immaterial providing that interest is in spatially uniform illuminants (e.g. Foster, Amano, Nascimento, & Foster, 2006). But it does become relevant in the transient optical environment of the natural world where changes in the spectrum

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of the illumination are accompanied by changes in its geometry. Those changes may be global, due to movement of cloud and variations in atmospheric scatter, or local, due to changes in mutual illumination (Bloj, Kersten, & Hurlbert, 1999; Funt & Drew, 1993) and in shadows (Giles, 2001; Zhou, Huang, Troy, & Cadenasso, 2009), which may be attached, depending on the angle of incidence of the illumination and viewing direction, or unattached or cast, depending on other objects in the scene. Because of the general complexity of natural scenes (Arend, 2001; Endler, 1993), changes in mutual illumination and in the distribution of shadows probably represent the greatest challenge to the automatic extraction of surface-color attributes.

Most studies of the role of illumination geometry in perception have been concerned with object shape or surface perception (e.g. Bloj, Kersten, & Hurlbert, 1999; Castiello, 2001; Cavanagh & Leclerc, 1989; Elder, Trithart, Pintilie, & MacLean, 2004; Lee & Brainard, 2014; Leek, Davitt, & Cristino, 2015; Mamassian, Knill, & Kersten, 1998; Ripamonti et al., 2004; Schofield, Rock, & Georgeson, 2011; Tarr, Kersten, & Bülthoff, 1998; Wagemans, van Doorn, & Koenderink, 2010). But some studies have considered the distributional effects of shadows, for example, in matching and discrimination with regular geometrical arrays (e.g. Heckman, Muday, & Schirillo, 2005; Kingdom, Beauce, & Hunter, 2004); in detecting fruit in natural scenes (Lovell et al., 2005), and in relation to foraging behavior (Arnold & Chittka, 2012).

The effects of changing illumination geometry on reflected spectra can sometimes be unexpected. Fig. 1 shows sampled spectra and color images rendered from hyperspectral radiance images of a natural scene at different times of the day. The spectra at locations 1 and 2 in the foreground foliage are almost constant between 11:40 and 12:40 (graphs 1 and 2, left and center columns), yet appear to interchange as the direction of illumination modulates the detailed pattern of shadows between 12:40 and 16:37 (graphs 1 and 2, center and right columns). The spectrum at location 3 in the distant haze and woodland retains its profile but undergoes progressive compression as the amount of haze diminishes (graph 3, left, center, and right columns). By contrast, over the same period, the profile of the spectrum at location 4 from the midfield red roof remains almost constant (graph 4, left, center, and right columns).

The aim of this study was to test how well ratios of cone excitations sampled from natural scenes are preserved under natural changes in illumination, especially in the distribution of shadows, through the course of the day. Time-lapse sequences of hyperspectral radiance images were acquired from five outdoor vegetated and nonvegetated scenes. From each scene, 10,000 pairs of points were sampled randomly and ratios of cone excitations and of other postreceptoral combinations of cone excitations were measured across time. Estimates of the mean relative deviations in ratios were found to be generally large. But when sampling was limited to short distances or to moderate time intervals, they fell below the criterion level for detecting violations of ratio invariance. Additionally, when uneven changes in illumination geometry were excluded, for example, when sample points were first in direct sunlight and then partially in shade, they fell further, to levels obtained with simulated global changes in illumination spectrum. Within sampling constraints, ratios provide an approximately invariant signal for stable surface-color inferences.

Partial reports of these findings were presented at the Vision Sciences Society 15th Annual Meeting (VSS 2015) and at MODVIS 2015, St. Pete Beach, FL, USA, 2015. Preliminary accounts of time-lapse changes in cone-excitation ratios were included in unpublished reports from two Master's projects (Dörrer & Newton, 2007; Raath & Woodward, 2008).

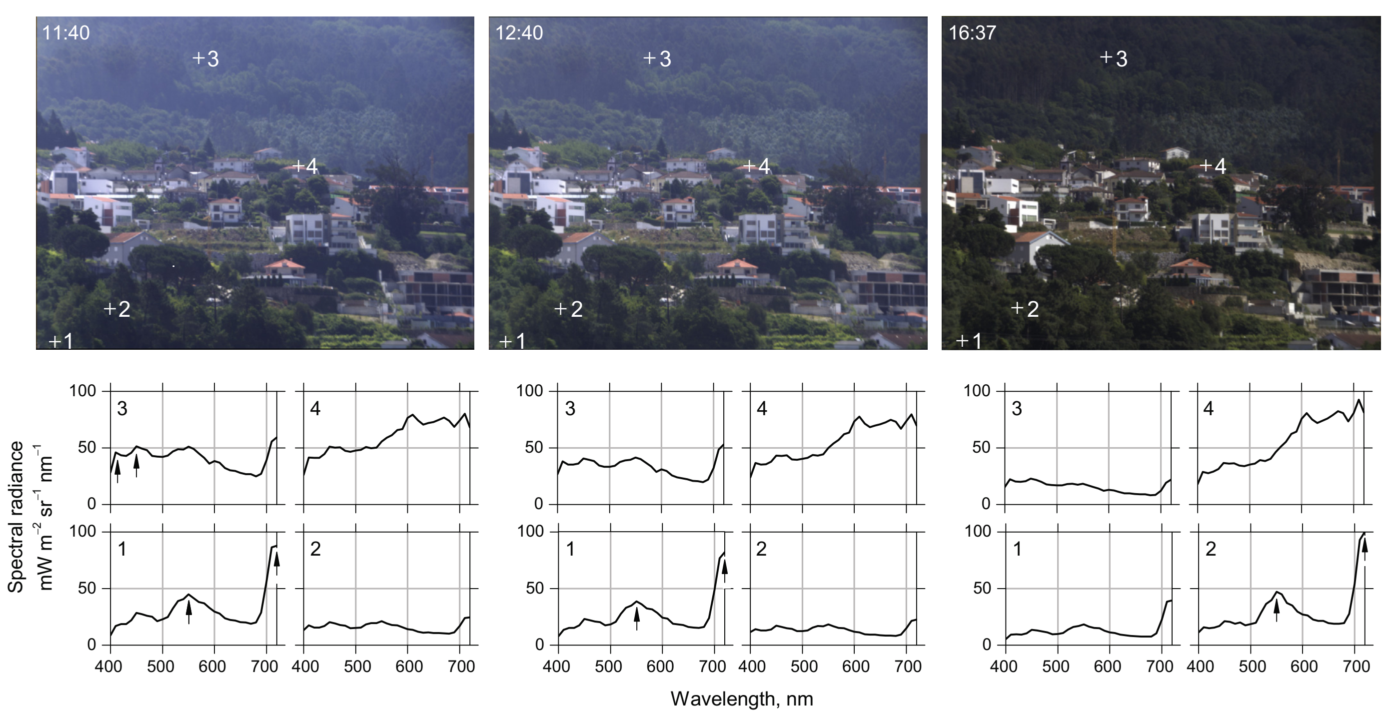

Fig. 1. Top row. Color images rendered from three hyperspectral radiance images of the parish of Nogueiró in the Minho region of Portugal. The images were acquired at 11:40, 12:40, and 16:37 on 9 June 2003. Bottom row. Plots of reflected radiance spectra at single-pixel locations marked by crosses in the images above. For the spectra at locations 1 and 2 in the foreground foliage, the maxima at 550 and 720 nm (arrowed, left, center, and right columns) are similar to those found in radiance estimates derived from laboratory spectral reflectance measurements (Carter & Knapp, 2001; Sims & Gamon, 2002). For the spectrum at location 3 in the distant woodland, the local maxima at 410 and 450 nm (arrowed, left column) were attributed to haze and are similar to those found in typical daylight spectra (Hernández-Andrés, Romero, & Nieves, 2001; Judd et al., 1964; see also Burton & Moorhead, 1987). Other aspects of the spectra are discussed in the text.

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