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Spatial distributions of local illumination color in natural scenes

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ABSTRACT

In natural complex environments, the elevation of the sun and the presence of occluding objects and mutual reflections cause variations in the spectral composition of the local illumination across time and location. Unlike the changes in time and their consequences for color appearance and constancy, the spatial variations of local illumination color in natural scenes have received relatively little attention. The aim of the present work was to characterize these spatial variations by spectral imaging. Hyperspectral radiance images were obtained from 30 rural and urban scenes in which neutral probe spheres were embedded. The spectra of the local illumination at 17 sample points on each sphere in each scene were extracted and a total of 1904 chromaticity coordinates and correlated color temperatures (CCTs) derived. Maximum differences in chromaticities over spheres and over scenes were similar. When data were pooled over scenes, CCTs ranged from 3000 K to 20,000 K, a variation of the same order of magnitude as that occurring over the day. Any mechanisms that underlie stable surface color perception in natural scenes need to accommodate these large spatial variations in local illumination color.

1. Introduction

The color and level of natural illumination, mainly light from the sun and sky, vary over time and with location in the scene being viewed. At any particular location, temporal changes can be slow, such as those arising from the elevation of the sun, producing a change from reddish at dawn (and dusk) to bluish at noon; or they can be fast as when a cloud occludes the sun. These spectral and colorimetric changes are well characterized and are considerable – expressed in terms of correlated color temperature (CCT) they are in the range 4000–40,000 K (Hernández-Andrés, Romero, Nieves, & Lee, 2001; Judd, MacAdam, & Wyszecki, 1964; Lee, 1994; Wyszecki & Stiles, 1982).

Despite these variations, visual sensitivity to global variations in the color of the illumination is generally low. Being able to compensate for global variations in illumination color is central to theories of stable surface color perception, i.e. color constancy, including Land's Retinex theory (Land & McCann, 1971; McCann, McKee, & Taylor, 1976) and other computational color-constancy algorithms (Gijsenij, Gevers, & van de Weijer, 2011; Hurlbert, 1986). Empirical laboratory studies with complex real three-dimensional scenes rendered with spatial color gradients have shown that sensitivity to smooth spatial variations in illumination color is also very low (de Almeida & Nascimento, 2009; Ruppertsberg, Bloj, & Hurlbert, 2008).

Natural environments, however, may contain more abrupt spatial variations of local illumination as a result of their complex spatial structures, which produce shading, mutual reflections, and occlusions (Chiao, Cronin, & Osorio, 2000; Endler, 1993). The spatial variations in local illumination intensity level have been well documented (Dror, Willsky, & Adelson, 2004; Morgenstern, Geisler, & Murray, 2014; Mury, Pont, & Koenderink, 2007, 2009), as has visual sensitivity to those variations (Lee & Brainard, 2011; McCann, Savoy, Hall, & Scarpett, 1974; Olkkonen & Brainard, 2011; Ruppertsberg et al., 2008).

Yet unlike the characterization of natural temporal changes in illumination color, the characterization of natural spatial variations in local illumination color and their consequences for color constancy have received relatively little attention (cf. Hubel, 2000). Chromatic spatial variations in natural scenes have been estimated indirectly from a computer analysis of color images (Gu, Huynh, & Robles-Kelly, 2014) and from empirical measurements with an RGB video camera to which a neutral sphere was attached and was visible in the field of view (Ciurea & Funt, 2003). Both of these approaches have provided useful but constrained data on local illumination. There are clearly significant methodological and experimental difficulties in obtaining more comprehensive data

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on local illumination color by making successive spectroradiometric measurements from within the scenes themselves.

The aim of the present work was to characterize the spatial variations in illumination color in natural scenes by spectral imaging. Small neutral probe spheres were embedded in the scenes, which were then imaged with a hyperspectral camera. From the reflected radiance images, the spectrum of the local illumination could be estimated simultaneously at each location (or surface direction) on each sphere in each scene and then characterized in terms of its chromaticity and CCT. The chosen scenes were 30 close-up and distant views of rural and urban environments. It was found that the spatial variations in local illumination color within these scenes were unexpectedly large and of the same order of magnitude as variations across the day.

2. Methods

2.1. Hyperspectral system

Hyperspectral radiance images of natural outdoor scenes were acquired with an in-house hyperspectral imaging system. It has been described previously (Foster, Amano, Nascimento, & Foster, 2006), but, in brief, the system consisted of a low-noise Peltier-cooled digital camera (Hamamatsu, model C4742-95-12ER, Hamamatsu Photonics K. K., Japan) and 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. The images were acquired over a wavelength range from 400 to 720 nm in 10 nm steps with an effective image size of 1344×1024 pixels. The focal length of the camera lens was typically 75 mm and the field of view was approximately $6.9^\circ \times 5.3^\circ$. Images were corrected at each wavelength for dark noise, stray light, and spatial non-uniformities. These corrected images were then registered over wavelength by uniform scaling and translation to compensate for small differences in optical image size with wavelength, i.e. chromatic differences of magnification, and any small differences in optical image position (Ekpenyong, 2013). Spectral radiances were calibrated with reference to the spectrum of the light reflected from an embedded surface covered in matt gray emulsion paint (VeriVide Ltd, Leicester, UK) to produce the surface reflectance of Munsell N5 or N7. This reference surface was always present in each scene and its reflected spectrum was measured with a telespectroradiometer (SpectraColorimeter, PR-650, PhotoResearch Inc., Chatsworth, CA) at the time of image acquisition. Depending on the scene the reference surface was either a small flat surface or one of the neutral probe spheres embedded in the scene. The hyperspectral radiance data at each pixel were corrected so that at the reference surface the recorded spectrum coincided with that measured with the telespectroradiometer. A more detailed description of the hyperspectral system and its calibration is given elsewhere (Ekpenyong, 2013; Foster et al., 2006).

The spectral accuracy of the hyperspectral system in recovering spectral reflectance factors of colored samples was established previously to be within 2% (Foster et al., 2006; Nascimento, Ferreira, & Foster, 2002) and the recovery of spectral radiance was therefore also within 2%. In separate measurements, errors in peak transmittance wavelength of the tunable filter were found to be less than 1 nm over 400–660 nm and less than 2 nm over 670–720 nm. Errors in peak spectral radiance recorded by the whole system at 436 and 546 nm were found to be less than 1 nm at the center and edges of the imaging field.

2.2. Scenes and illumination sampling

Hyperspectral radiance data from 30 natural scenes in the Minho region of Portugal were acquired during late spring and summer of 2002 and 2003. The sky in most of the scenes was clear but in five it was overcast with cloud. Each acquisition lasted a few minutes and took place within the period 11:00–18:00. There were 17 images of rural scenes, containing mainly trees, flowers and other vegetation, and 13 of urban scenes containing some type of man-made construction. Both close-up and distant views were included. The aperture of the camera was deliberately stopped down to provide a large depth of focus and particular care was taken to ensure that the spheres in the scenes were in focus. The line-spread function of the system estimated from the set of natural images was almost Gaussian with a standard deviation of 1.3 pixels at 550 nm (Foster et al., 2006). Fig. 1 shows color renditions of the scenes; no region of the images including the embedded spheres was significantly out of focus.

Where possible, the probe spheres embedded in each scene were distributed over the field of view. The spheres were made of glass or plastic material and were covered in Munsell N5 or N7 matt gray emulsion paint, and, depending on the scene, their diameters varied from 16 mm to 80 mm. The physical size of the spheres was not adjusted for constant image size because of their variable distance from the camera. The number of spheres in each scene varied from one to seven.

The global illumination in 24 of the scenes was measured at or close to the time of image acquisition by recording the spectrum reflected from a barium sulfate plug placed horizontally and located where only direct illumination was incident. In five of the scenes it was recorded from the top of one of the spheres in the scene. In one scene no direct illumination could be recorded.

These images of scenes with multiple embedded spheres were acquired solely for analyzing spatial variations in local illumination. Data from these images have not been reported previously and the images should be distinguished from similar images without multiple spheres used in previous studies for other purposes (Foster et al., 2006; Linhares, Pinto, & Nascimento, 2008).

2.3. Local illumination estimates

Estimates of the local illumination color were derived as follows. For each sphere in each scene, radiance spectra were extracted from the hyperspectral image at 17 sample points distributed uniformly over the image of the sphere. Each point corresponded to one image pixel. One point was located at the center of the image of the sphere and the others were distributed evenly along vertical, horizontal, and the two 45° oblique axes, with spacing one-sixth of the sphere diameter. Any sphere in the camera view that was partially occluded by other objects (e.g. leaves, trees) was excluded from the analysis. In total there were 112 spheres yielding a total of 1904 local illumination sample points.

The radiance spectra at each sample point represented an estimate of the local illumination incident on a planar surface element tangent to the sphere at that point, scaled by the reflecting properties of the Munsell paint. More precisely, let $L_i(\theta_i, \phi_i; x, y; \lambda)$ be the spectral radiance at wavelength λ incident at the point (x, y) in the direction (θ_i, ϕ_i) with respect to the surface normal (θ_{xy}, ϕ_{xy}); let $L_r(\theta_r, \phi_r; x, y; \lambda)$ be the corresponding spectral radiance reflected in the direction (θ_r, ϕ_r) defined by the viewing geometry; and let $f(\theta_i, \phi_i; \theta_r, \phi_r; x, y; \lambda)$ be the spectral bidirectional reflectance distribution function (Nicodemus, Richmond, Hsia, Ginsberg, & Limperis, 1997). Then