DETECTING ILLUMINATION CHANGES IN THREE-DIMENSIONAL SCENES

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Abstract

Craven & Foster (1992) found that observers could readily distinguish illuminant chromaticity changes from surface color changes in Mondrian scenes. Changes in illuminant did not affect the photoreceptor excitation ratios across edges; they concluded that the visual system detected surface changes as ratio constancy violations. In 3D scenes, with multiple illuminants and matte surfaces at many orientations, changes in the positions or chromaticities of light sources need not leave edge ratios invariant. We examine how well observers can distinguish changes in the direction of a collimated light source in rendered 3D scenes viewed binocularly. Observers were asked to distinguish illumination changes from matched changes in achromatic surface colors. We find that, in 3D scenes with non-homogeneous illumination, observers can discriminate very small changes (at 2-4 degrees, d' exceeds 1) in the spatial distribution of light from matched surface changes despite the lack of ratio constancy between adjacent surfaces.

Light arriving at the retina from a matte surface depends on several factors. Most environments we encounter have markedly complex light fields with multiple luminous sources and numerous objects that cast shadows or act as secondary light sources. Whenever the light field is inhomogeneous, the light reflected by matte surfaces varies with the orientation and location of the surface. There is now evidence that the visual system partially discounts each of these factors (see Boyaci et al, 2006 for a review; Bloj et al, 2004; Ikeda et al, 1998).

In 2D scenes illuminated homogeneously, the effect of changes in the illumination is simple: only chromaticity or intensity can change, and the effect of a change is to scale the excitations of the three photoreceptor classes. If $\left[\rho_L^x, \rho_M^x, \rho_S^x\right]$ are the excitations at retinal location x in the long-, middle- and short-wavelength classes (LMS) of photoreceptors, then the effect of a change of illumination is an approximate scaling of photoreceptor excitations within each class (Maloney, 1999). The excitations $\left[\rho_L^x, \rho_M^x, \rho_S^x\right]$ are replaced by excitations $\left[\kappa_L \rho_L^x, \kappa_M \rho_M^x, \kappa_S \rho_S^x\right]$. If the change is a change in intensity, the scaling factors are identical for all three photoreceptor classes: $\kappa_L = \kappa_M = \kappa_S$. If the change is a change in chromaticity of illumination, then each class of photoreceptors may be scaled by a separate scaling factor.

Such transformations of photoreceptor intensities do not affect the cone excitation ratios within each photoreceptor class across edges between pairs of surfaces (see figure **1A**). Foster and colleagues have shown that observers are remarkably sensitive to such changes in the illumination of 2D scenes (Craven & Foster, 1992; Nascimento & Foster, 2000). Their observers discriminated ratio constant light changes from image matched surface changes, in which ratios across edges change. Foster and colleagues suggest that observers rely on the constancy (or lack thereof) of cone excitation ratios to perform such discriminations (Foster & Nascimento, 1994; Amano & Foster, 2004). They conclude that observers are remarkably good at detecting light-induced changes in patterns of retinal excitation and discriminating them from other transformations.

In 3D scenes with multiple light sources, excitation ratios at edges between pairs of surfaces can vary greatly with changes in illumination. Ratio constancy rarely holds, even when albedo or reflectance remain unchanged. For example, imagine a simple 3D scene consisting of pyramids with grey, matte surface facets, illuminated by a neutral punctate light source that is far from the surfaces. Changes in the location of the punctate light transform the light falling on the retinas in complex ways. A simple illustration is shown in **figure 1B**, in which changing the position of a punctate source dramatically increases the ratio between the amounts of light reflected by the two surfaces in view.

It is an open question how sensitive observers are to the full class of 3D light transformations. The research we report is the first attempt to do so. In the current research, we address this question by asking observers to discriminate light transformation induced changes from image matched changes in the albedos of 3D objects. These objects are rendered under a light field composed of a combination of a punctate source and a diffuse source. Light changes induced by a change in the punctate source's position are matched for global image statistics with light changes induced by albedo changes. Furthermore, we designed stimuli (scenes) so that ratio changes in our scenes are non-predictive of transformation type because images for both stimulus types are rendered in yoked pairs such that ratios between adjacent surfaces are identical for each member of a yoked pair.

One possible outcome of this experiment is that observers cannot readily discriminate changes in illumination from matched changes induced by changes in surfaces. If so, then the remarkable performance found by Foster and colleagues is specific to two-dimensional, homogeneously illuminated scenes, and it is plausible that observers are in fact using ratio constancy in discriminating light and surface changes. Alternatively, they may do well at the current task, suggesting that the human visual system can discriminate changes in lighting (here light source direction) from surface changes even when edge ratios are not useful cues.

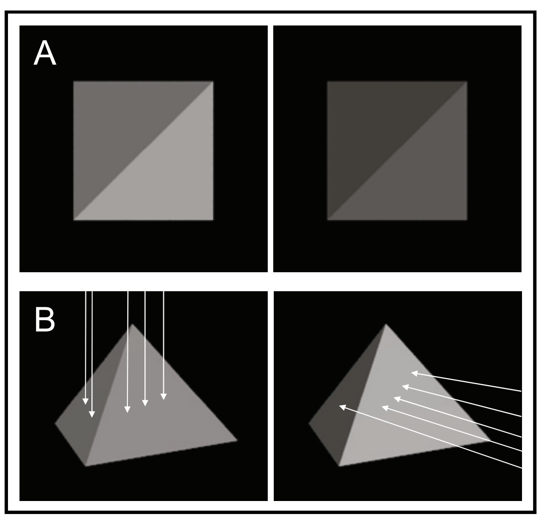

Figure 1. A: Rendering of a 2D scene with two surfaces of different albedos. Homogeneous illuminant intensity is decreased in the right frame, and ratio remains unchanged. **B:** Rendering of a pyramid with facets of different albedos. When a punctate source changes position (direction indicated by the white lines), the ratio between the intensities of the two facets changes dramatically.

Method

Task

Observers stereoscopically viewed rendered 3D scenes that underwent one of two possible changes with equal probability: 1) the reflectance properties of surfaces in the scene changed, or 2) a punctate light source changed position. Each scene consisted of two 1-second frames displayed with immediate replacement. Observers then reported change type, and if they reported a light change, they also reported light movement direction.

Stimuli

We rendered stereo pairs of scenes containing 4-sided pyramids with randomized heights and facet albedos under a combination of a collimated light source and a diffuse light source. Pyramids appeared in an invisible 9 × 9 grid subtending 11.5 dva. The only cue to the spatial distribution of the illumination was shading. Scenes lacked cast shadows and illumination gradients. See **figure 2** for an illlustration.

Stimuli for the two conditions were generated in yoked pairs. A new set of random pyramid heights and facet albedos was chosen for each yoked pair. The landscape determined by these constraints was then rendered twice: first with the collimated light source perpendicular to the center of the ground plane, and second after a rotation of the collimated light source ±2, ±4, ±6, or ±8 degrees from perpendicular. The axes of movement direction were roughly right-left and up-down. The resulting images comprised the two frames of a light transformation trial. The light signals produced under both punctate source positions were then permuted according to the same permutation matrix both before and after the light source rotation to create a reflectance change trial. The resulting images appear to be a set of pyramids whose albedos change randomly: some get darker, some lighter. The changes are inconsistent with the movement of a single collimated light source. Under this procedure, trial types are matched for magnitude of space average of color signals, variance of color signals, and in magnitude of ratio changes between adjacent facets.

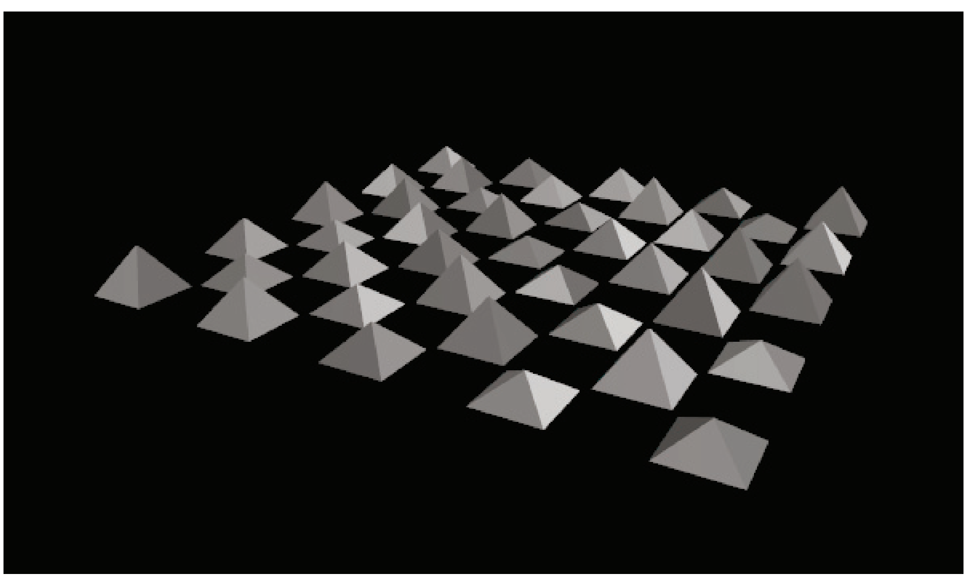

Figure 2. Oblique view of an example stimulus scene. Observer viewpoint was perpandicular to the ground plane and centered over the grid. Stimuli were viewed on a stereoscope.

Procedure

Observers viewed stimuli in a stereoscope. Stimuli were blocked by change magnitude (dictated by the amount of angular movement of the puncate source), and blocks were presented in order of ascending difficulty. Each block contained 240 trials, divided equally between imaged matched light and surface changes, with light movement directions occuring with equal probability. Observer responses were coded to estimate the discriminability of light versus surface changes at each level of change magnitude separately.

Results and Discussion

Discriminability of Light versus Surface Changes

Discrimination performance was quantified separately for each observer at each magnitude level by d' from signal detection theory (Green & Swets, 1966). We defined the hit rate, p_H, to be the probability of a "light" response when a light transformation occurred, and the false alarm rate, p_F, to be the probability of a "light" response when a surface transformation occurred. If z is the inverse of the cumulative unit normal distribution, then $d' = z(p_H) - z(p_F)$. A zero value of d' indicates chance performance, and d' increases with increased discrimination performance. Ninety-five percent confidence intervals for each d' estimate were obtained by a bootstrap method (Efron & Tibshirani, 1993) whereby each observer's performance in the corresponding condition was simulated 10,000 times and the 5th and 95th percentiles were calculated. Separate d' estimates and 95% confidence intervals are plotted for each observer in **figure 3**.

For all observers, performance increased significantly at the 0.05 level from the slightest transformation, defined as the magnitude of a 2˚ punctate source rotation, to the largest transformation, defined by the magnitude of an 8˚ punctate source rotation. Two of the four observers performed significantly above chance at the lowest magnitude with d' estimates of 0.88 and 0.36.

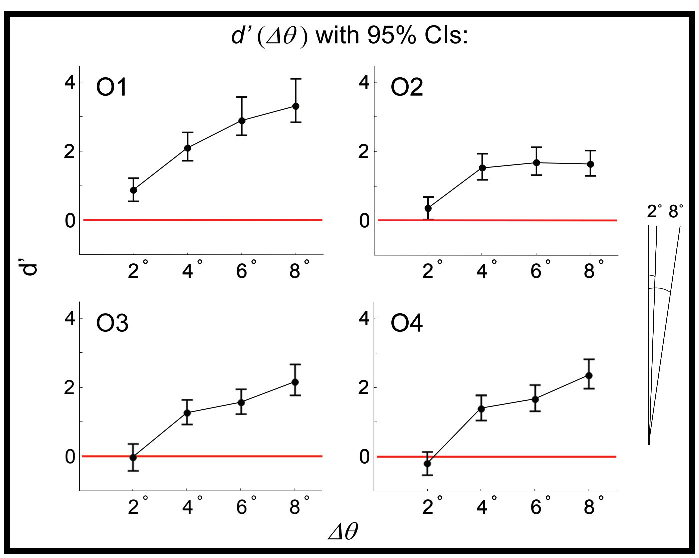

Figure 3. Discriminability of light versus surface changes plotted for each observer separately. $\Delta\theta$ is the amount of angular change of the punctate source and defines the magnitude of the image statistic changes for each block.

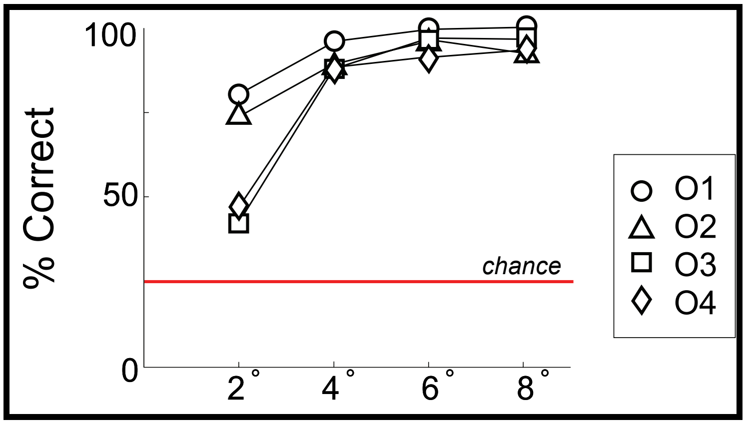

Figure 4. Discriminability of light movement direction with separate lines for each observer. Because there were 4 possible punctate source movement directions, chance performance is 25% correct.

Discriminability of Light Source Movement Direction

Observers were asked to report the perceived motion of the light source whenever they reported that the transformation was light induced. We calculated the percentage of correct direction reports out of the trials on which observers reported perceiving a light transformation. These percentages were calculated at each level of transformation magnitude for each observer separately. Because there were four possible movement directions, chance performance was 25% correct.

All observers were above chance at reporting movement direction when they perceived that the light had moved. The two observers who were at chance to discriminate light from surface transformations at the lowest change magnitude could still report the movement direction above chance when they correctly perceived that the light source had moved: 47% and 42% correct. Across observers, the mean percent correct at the 2˚ change level was 60.8%, at the 4˚ change level 90.3%, at the 6˚ change level 95.7%, and at the 8˚ change level 95.5%. Individual percent corrects are plotted as a function of angular movement in **figure 4**. These data demonstrate that when observers perceived changes in the light source position, they were able to report the direction of the change well above chance.

General Conclusion

In 3D scenes with inhomogeneous illumination, observers can discriminate very small changes in the spatial distribution of the light field from matched surface changes despite the lack of ratio constancy between adjacent surfaces.

Acknowledgements

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