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Detecting changes of spatial cone-excitation ratios in dichoptic viewing

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Abstract

Spatial ratios of cone excitations produced by light reflected by different surfaces in a scene may provide the cue for discriminating changes in illuminant from changes in surface reflectances. To test whether these ratios can be computed across the two eyes, observers were presented with simulations on a computer-controlled monitor of pairs of juxtaposed or separated Munsell surfaces undergoing an illuminant change with a small change in cone-excitation ratios or a change with constant cone-excitation ratios. Surfaces were viewed either binocularly or dichoptically. Observers reliably discriminated the two changes in both viewing conditions, although less well dichoptically. Cone-excitation ratios, which may in principle be computed retinally, may also be computed cortically. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

When the illuminant on a scene changes, the spatial ratios of cone excitations produced by light reflected from different surfaces remain almost exactly constant (Foster & Nascimento, 1994; Nascimento, Ferreira, & Foster, 1999). In contrast, if a surface-reflectance change takes place, then, in general, these ratios are not constant, and may undergo large changes. [1] The constancy or otherwise of cone-excitation ratios may provide the cue that enables observers to discriminate rapidly and effortlessly illuminant changes from material changes in a scene (Craven & Foster, 1992; Foster, Craven, & Sale, 1992). Cone-excitation ratios offer a compelling signal. If observers compare image sequences containing illuminant changes that fail to preserve cone-excitation ratios with image sequences corrected for these failures, they systematically interpret the corrected images as containing the illuminant change, even when the particular image sequence corresponds to a very rare event in the natural world (Nascimento & Foster, 1997).

Where in the visual pathway might spatial cone-excitation ratios be computed? In principle, the computation could take place in the retina where all the necessary signals are available (Cornelissen & Brenner, 1995; Rüttiger, Braun, Gegenfurtner, Petersen, Schönle, & Sharpe, 1999; Walsh, 1999; Moutoussis & Zeki, 2000). But could comparisons take place centrally, across the two eyes? The issue is complicated, and mechanisms operating at various levels in the visual system are known to contribute to colour appearance and colour constancy (Webster & Mollon, 1994; Zeki & Marini, 1998; Hurlbert, 1999; Rüttiger, Braun, Gegenfurtner, Petersen, Schönle, & Sharpe, 1999; Moutoussis & Zeki, 2000; Shevell & Wei, 2000). For example, in

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[1] The invariance of spatial cone-excitation ratios is a physical matter, which can be addressed quantitatively by sampling environmental spectral reflectances and illuminants. It should not be confused with von Kries' coefficient rule (von Kries, 1905), used to describe the effects of light adaptation on colour appearance by a scaling of receptor responses (Wright, 1934). See discussion in Foster, Nascimento, Craven, Linnell, Cornelissen, and Brenner (1997).

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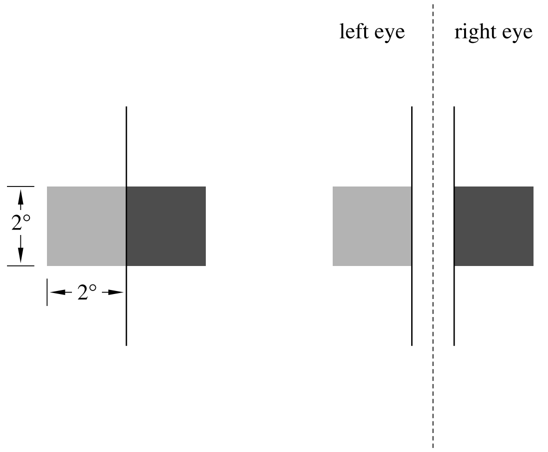
one study (Hurlbert, Bramwell, Heywood, & Cowey, 1998), normal observers and a cerebral achromatopsic were able to compare cone-excitation ratios between patches presented to one eye with those presented to the other eye, a result which might be explained by cone-excitation ratios being first computed across the eyes and then compared.

To address this question here, the detectability of changes in cone-excitation ratios was measured for juxtaposed and separated stimuli presented binocularly and dichoptically. It was found that changes in ratios could indeed be detected dichoptically, suggesting that comparisons may be made at a central site.


(a) binocular juxtaposed (b) dichoptic juxtaposed

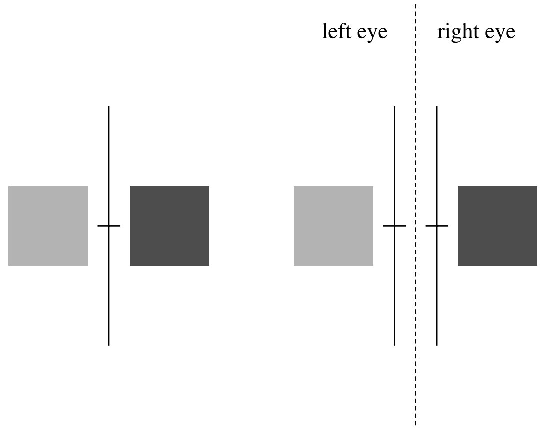

(c) binocular separated (d) dichoptic separated

Fig. 1. Spatial configuration of stimuli for (a) binocular and (b) dichoptic viewing of juxtaposed surfaces and for (c) binocular and (d) dichoptic viewing of separated surfaces. The background was dark. In dichoptic viewing, a black septum was aligned with the centre of the screen so that one surface was seen by one eye and the other surface by the other eye. Thin white vertical lines (shown black in the figure) were fused by the observer to aid alignment in dichoptic viewing.

2. Methods

2.1. Apparatus

An RGB colour-graphics system (VSG 2/3, Cambridge Research Systems, UK) controlled by a laboratory computer was used to generate the images, which were displayed on a 17-in. colour monitor (FlexScan T562-T, Eizo, Japan). Chromatic resolution was nominally 12 bits per gun and screen resolution was 1024 × 768 pixels with a frame rate of 100 Hz. The system was calibrated with a spectroradiometer (SpectraColorimeter PR-650, Photo Research, CA, USA), whose calibration was, in turn, traceable to the UK National Physical Laboratory. Errors in the displayed CIE (x, y, Y) coordinates of a white test patch were < 0.005 in (x, y) and $< 5\%$ in Y.

2.2. Stimuli

Stimuli were pairs of uniform coloured patches simulating natural Lambertian surfaces illuminated by natural, spatially uniform light sources; or they were modifications of these simulations to achieve the required levels of cone excitations, as explained later. Subsequent references to surfaces and illuminants should be taken to refer to the corresponding simulations. The luminances of the patches were drawn from the range 1.5–20 cd m^{-2}, with mean value 4 cd m^{-2}. Stimuli appeared in a dark field of luminance less than 0.1 cd m^{-2} and were viewed in a darkened room.

The surfaces were Munsell surfaces drawn at random from the Munsell Book of Color (Munsell Color Corporation, 1976). For efficient computation, their spectral reflectances were generated from the set of eight characteristic vectors obtained from a principal components analysis by Parkkinen, Hallikainen, and Jaaskelainen (1989). The set of reflectance functions spanned by this set of characteristic vectors includes many reflectance functions from natural surfaces including flowers, flower clusters, leaves, and berries (see, for example, Jaaskelainen, Parkkinen, & Toyooka (1990)). The light sources were drawn from a continuum of Planckian radiators having temperatures in the range 2000–100,000 K and constant integrated spectral power. These sources were preferred to daylights because they offered a larger range of colour temperatures.

In the first experiment the two surfaces, which were square and subtended 2° visual angle, were seen juxtaposed. Two viewing conditions were used: in one, the surfaces were viewed binocularly (Fig. 1a) and, in the other, the surfaces were viewed dichoptically, one surface seen by one eye and the other surface by the other eye (Fig. 1b). In dichoptic viewing, a black septum was aligned with the centre of the screen and the positions of the surfaces were adjusted so that each was seen by the ipsilateral eye and not the contralateral eye; two thin white vertical lines (shown in black in Fig. 1, width 1 pixel, subtending 0.9 min arc visual angle) on the inside edges of the surfaces were fused by the observer as an aid to the side-by-side alignment of the surfaces. In the second experiment the gap sizes between the two surfaces was varied (Fig. 1c and d). Observers fixated the centrally located fixation cross. Viewing distance was 1 m.

2.3. Procedure

A temporal forced-choice procedure was used (Foster, Amano, & Nascimento, 2001). Each trial was divided into two 2-s intervals separated by 1 s. In each interval, two images, each lasting 1 s, were presented in succession to represent illuminant changes with zero or non-zero deviations in cone-excitation ratios. Combinations of surfaces and illuminants were repeatedly sampled until the required relative deviation was obtained. The corresponding image sequence with zero deviations was produced by correcting the ratios in the non-zero-deviation sequence. (How the deviations were quantified is described in Section 2.4; for further details on the sampling and correcting procedures, see Nascimento & Foster (1997)).

Observers were instructed to choose the interval containing the change that appeared more like an illuminant change. Subjects were not given feedback on their performance. In each session, which lasted for one hour, observers were tested in the binocular condition only or in the dichoptic condition only. The ordering of the viewing conditions was balanced over sessions. In the second experiment all gap sizes were tested in the same session for a given viewing condition. The ordering of gap sizes was balanced over sessions.

2.4. Stimulus parameterization: relative deviation

Stimuli were parameterized by the extent to which ratios of cone-excitations deviated from constancy. For each image sequence, three ratios of cone excitations can be defined, one for each cone class. Let r_1, r_2, and r_3 be the ratios for short-, medium-, and long-wavelength-sensitive cones, respectively. Let $\boldsymbol{r} = (r_1, r_2, r_3)$ be the three-dimensional vector consisting of these ratios for the first image and $\boldsymbol{r}' = (r'_1, r'_2, r'_3)$ be the corresponding vector for the second image. A convenient summary measure of the difference between the two is given by the *relative deviation*, that is, the quotient $|\boldsymbol{r} - \boldsymbol{r}'|/\min\{|\boldsymbol{r}|, |\boldsymbol{r}'|\}$, where the vertical bars signify the length of the vector; thus, $|\boldsymbol{r}| = (r_1^2 + r_2^2 + r_3^2)^{1/2}$. Values of the relative deviation ranged from zero to 0.275 and were quantized into bins of width 0.05. Cone excitations were calculated from a set of spectral sensitivities defined for light incident at the cornea and were based on transformations of D.B. Judd's modification of the colour-matching functions for the CIE 1931 Standard Colorimetric Observer (Smith & Pokorny, 1972, 1975, see Wyszecki & Stiles, 1982).

2.5. Observers

Three observers, PA, PG, and AS, participated in the first experiment and three other observers, JL, PP, and FS, participated in the second experiment. Each had normal colour vision, as assessed with the Farnsworth–Munsell 100-Hue test and Ishihara plates, and normal Snellen acuity. Each was unaware of the purpose of the experiment.

3. Results and comment

3.1. Juxtaposed surfaces

Performance was measured as a function of the relative deviation in spatial cone-excitation ratios. Fig. 2 shows for each observer per cent 'illuminant-change' responses to the intervals of zero-relative-deviation sequences as a function of relative deviation in spatial cone-excitation ratios in the other interval. Each data point was based on at least 180 trials. Data are shown for dichoptic viewing (filled symbols) and binocular viewing (open symbols). The continuous and dotted lines are best fitting functions of the relative deviation.

The task can clearly be performed dichoptically. Discrimination performance increased as relative deviation increased for both binocular and dichoptic viewing, but was generally poorer with dichoptic viewing, at most by about 10 percentage points, a statistically significant effect ($P \leq 0.02$). The level of performance with binocular viewing was similar to that reported previously for simple stimuli consisting of pairs of surfaces (Nascimento & Foster, 1997).

The particular pattern of discrimination performance shown in Fig. 2 raises two questions. First, if spatial cone-excitation ratios can be computed across the two eyes, why is performance better with binocular viewing than with dichoptic viewing? Second, is the deviation in performance from a smoothly increasing function at small relative deviations in cone-excitation ratios (Fig. 2, observers PG and AS) an indication of an experimental artefact?

3.2. Separated surfaces

It might be hypothesized that binocular viewing is better because of a contribution from a monocular computation of spatial cone-excitation ratios, which would be absent in dichoptic viewing. Conversely, dichoptic viewing might be poorer because of fluctuations

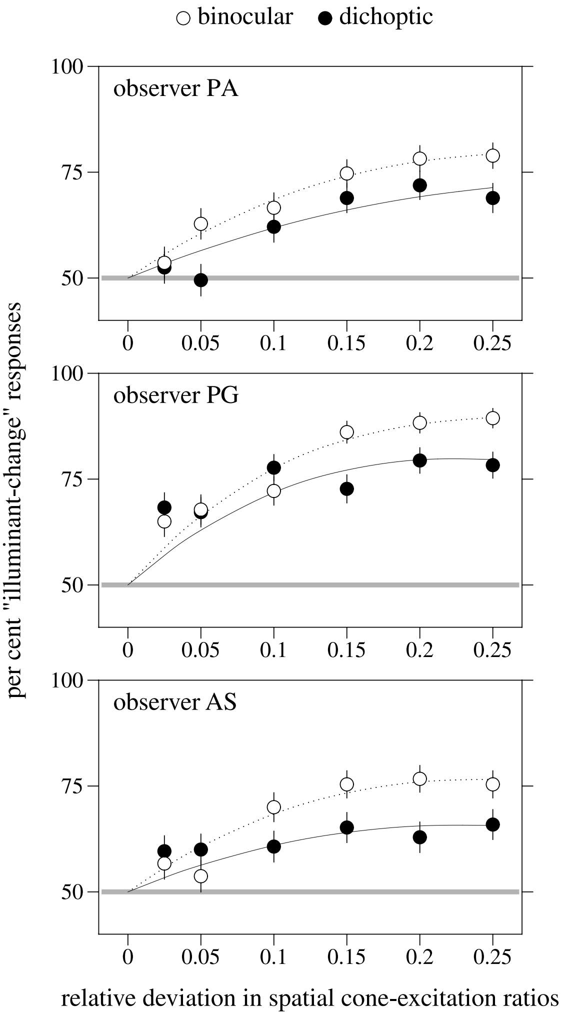


Fig. 2. Per cent 'illuminant-change' responses to zero-relative-deviation image sequences as a function of relative deviation in spatial cone-excitation ratios. Data are shown for both dichoptic (filled symbols) and binocular (open symbols) viewing. Each data point was based on at least 180 trials. The continuous and dotted curves are each best-fitting inverse cumulative Gaussian transforms of a quadratic function of the relative deviation.

in vergence producing rivalry. It seemed plausible that both factors would vary with the spacing between the two surfaces. Thus, a monocular contribution might be limited by the extent of horizontal interactions in the retina or between monocularly driven cortical cells, and vergence fluctuations in dichoptic viewing might have less impact with non-contiguous surfaces. To test this hypothesis, discrimination performance was measured with dichoptic and binocular viewing as the size of the gap between the surfaces was varied. As the difference in observed performance in the two viewing conditions was not large, it was anticipated that it might be difficult to disconfound the two effects, but, because they act in opposite directions, the difference in their variations with gap size might be detectable. Moreover, for sufficiently large gap sizes, both effects should disappear.

To test for a possible artefact underlying the elevated performance with small relative deviations in cone-excitation ratios, the experiment was performed with both large and very small relative deviations in cone-excitation ratios. For the latter, performance should fall close to chance levels. To test for an effect of reduced information in dichoptic viewing, performance was also measured monocularly.

Fig. 3 shows for each observer per cent 'illuminant-change' responses to zero-relative-deviation image sequences as a function of gap size between the two surfaces. Relative deviations in spatial cone-excitation ratios were either in the range 0.225–0.275 (left column) or 0–0.025 (right column). Results are shown for dichoptic viewing (filled symbols) and binocular viewing (open symbols). Results for monocular viewing were not reliably different from those for binocular viewing ($P > 0.5$) and are omitted. Each data point was based on at least 144 trials. The continuous and dotted lines are best fitting functions.

There was a reliable effect of gap size for relative deviations in spatial cone-excitation ratios of 0.225–0.275. Thus, the slopes of the fitted lines were different with binocular and dichoptic viewing, and the effect was significant (observer JL, $P < 0.01$; FS, $P = 0.03$) or close to significant (observer PP, $P = 0.06$). For gap sizes of 2.5°–3.0°, performance for binocular and dichoptic viewing converged to identical levels, for all observers. Nevertheless, the slopes of the individual fitted lines were only occasionally significantly different from zero, and differed from observer to observer. From these data, therefore, it is not possible to disconfound the separate contributions of a monocular computation of cone-excitation ratios and vergence fluctuations.

With regard to the control on possible artefacts with small relative deviations in cone-excitation ratios (right column of Fig. 3), performance was, as expected, very close to chance levels, and the differences in slopes of the fitted lines were not significant for any observer ($P > 0.1$). Why some observers should perform better than expected at small relative deviations (Fig. 2, observers PG and AS) remains unclear.

4. Discussion

The principal implication of the present work is that observers can discriminate between illuminant changes and surface-reflectance changes by making comparisons of signals across the two eyes. As the first experiment showed, the discriminability of image sequences with zero and non-zero relative deviations in cone-excitation ratios increased monotonically with the size of the non-zero relative deviation. Given that the comparison between the surfaces must have taken place at or beyond a locus where the signals from the two eyes are combined, this result suggests that cone-excitation ratios may be computed at a central cortical level.

The level of discrimination performance with dichoptic viewing and small gap sizes was, however, generally lower than with binocular viewing. The effect seemed not to be attributable to reduced stimulus information, as monocular and binocular viewing produced similar levels of performance. As the gap between the surfaces increased, the detectability of changes in cone-excitation ratios for dichoptic and for binocular viewing converged towards each other, which may be explained either by a degradation in the monocular computation of ratios over increasing distances or by a diminution in the effects of fluctuations of vergence as dichoptically viewed surfaces become more widely separated.

Although it might be assumed that the detection of changes in cone-excitation ratios—by monocular or binocular mechanisms—involves the direct computation of those ratios, it is possible that post-receptorally the computation is based on changes in ratios of opponent and of non-opponent combinations of cone excitations (Nascimento & Foster, 1994; Hurlbert et al., 1998, footnotes 1 and 2); for these ratios of combinations are also almost invariant under illuminant changes (Zaidi & Shapiro, 1993; Finlayson, Drew, & Funt, 1994;

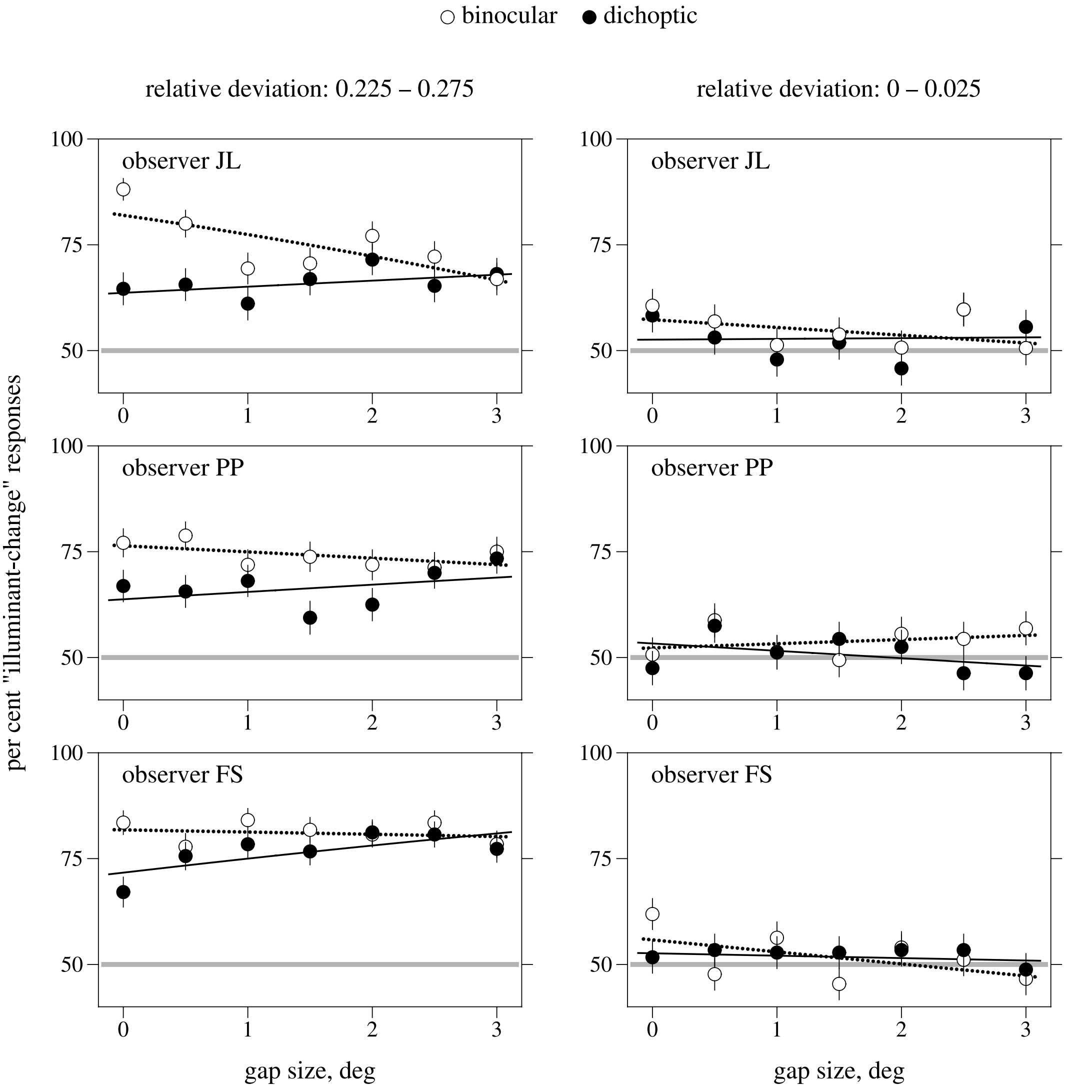


Fig. 3. Per cent ‘illuminant-change’ responses to zero-relative-deviation image sequences as a function of the size of the gap between the two surfaces. Left column shows data for relative deviations in spatial cone-excitation ratios in the range 0.225–0.275 and right column for relative deviations in the range 0–0.025. Data are shown for both dichoptic (filled symbols) and binocular (open symbols) viewing. Each data point was based on at least 144 trials. The continuous and dotted curves are each best-fitting inverse cumulative Gaussian transforms of a linear function of the gap size. For relative deviations in spatial cone-excitation ratios of 0.225–0.275, the differences in the slopes of the fitted lines with binocular and dichoptic viewing was either significant or close to significant. For relative deviations of 0–0.025, the differences in the slopes were not significantly different from zero.

Nascimento & Foster, 1994; Zaidi, Sephar, & DeBonet, 1997; Bäuml, 1999; Nascimento & Foster, 2000). Whether it is ratios of cone excitations or ratios of combinations of cone excitations that are computed remains to be established.

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