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Sensitivity to Spatial Phase at Equiluminance

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We have measured sensitivity for discriminating the spatial phase of multi-harmonic and two-harmonic patterns modulated either in luminance or in chromaticity (red–green). The multi-harmonic patterns were either highpass squarewaves, lines or ramps. For all patterns, contrast thresholds for discriminating 0 from 180 deg phase were similar to those for discriminating −90 from 90 deg, for luminance or chromatic modulation (or both). For all types of multi-harmonic patterns, the ratio of contrast thresholds for the phase discrimination to that for pattern detection was the same for luminance and chromatic modulation, and for combinations of both. Similarly, phase thresholds, the minimum detectable differences in phase (about a mean 0 deg), were the same for chromatic and luminance patterns, provided that contrast was scaled to equate detection thresholds of the patterns. Similar results were observed for simple three-harmonic patterns ($f+2f+3f$), and for ($f+2f$) two-harmonic patterns. Strangely, however, two-harmonic patterns of $f+3f$ (first two terms of square-wave) of moderate to high spatial frequency did show a two-fold advantage for luminance over colour, as Troscianko and Harris (1988) have previously reported (*Vision Research*, *28*, 1041–1049), possibly because the two harmonics have a greater separation in frequency. However, for most classes of patterns, sensitivity for spatial phase is as good for chromatic as for luminance modulation, suggesting that similar sorts of mechanisms operate under these two conditions.

Phase Colour Edges Lines Equiluminance

INTRODUCTION

Many lines of evidence have suggested that vision is degraded at *equiluminance*. For example, several studies have suggested that for patterns modulated in wavelength but not in luminance, motion discrimination is poor (Ramachandran & Gregory, 1978; Cavanagh *et al.*, 1984; Cavanagh & Anstis, 1991; Mullen & Boulton, 1992), borders appear less distinct (Boynton, 1978), stereo acuity is severely degraded (Julesz, 1971; Lu & Fender, 1972; De Weert & Sadza, 1983), vernier acuity thresholds are more than doubled (Morgan & Aiba, 1985), and orientation discrimination is impaired (Webste *et al.*, 1990). However, at least some of the poorer performance at equiluminance can be explained by the lower cone contrast. After equating for cone contrast, sensitivity for chromatic modulation is 5–9 times better than for luminance modulation (Chaparro *et al.*, 1993). Even sensitivity for motion, thought to be particularly compromised at equiluminance, can be as good or better at equiluminance than for luminance patterns, provided it is expressed in terms of cone contrast (Derrington & Henning, 1993; Gegenfurtner & Hawken, 1995). Similarly, under most conditions vernier acuity is not impaired at equiluminance (Krauskopf & Farell, 1991), nor is orientation discrimination (Würger & Morgan, 1995).

In this study we pursue further the issue of spatial discrimination at equiluminance by investigating another aspect of spatial vision, discrimination of spatial phase. That phase is important for vision is clearly demonstrated by the fact that it is the Fourier phase spectrum, not the amplitude spectrum, that determines the appearance of images (Oppenheim & Lim, 1981; Piotrowski & Campbell, 1982; Tadmor & Tolhurst, 1992). Spatial phase also plays a key role in several models of feature detection, such as the local energy model of Morrone and Burr (1988), where it serves both for feature location and feature identification.

Phase sensitivity has been studied extensively for luminance-contrast, using a variety of stimuli ranging from simple two-harmonic patterns (Nachmias & Weber, 1975; Burr, 1980; Field & Nachmias, 1984; Klein & Tyler, 1986) to multi-harmonic patterns that approximate more closely natural scenes (Burr *et al.*, 1989). Provided that stimuli are "M-scaled" (size increases with eccentricity), sensitivity for phase discrimination does not vary

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with retinal eccentricity (Morrone *et al.*, 1989; but see also Rentschler & Treutwein, 1985; Bennett & Banks, 1991; Stephenson *et al.*, 1991).

Several studies have suggested that phase discrimination may be mediated by two or more classes of quasi-linear mechanisms with different phase spectra (e.g. Field & Nachmias, 1984; Burr *et al.*, 1989). Most psychophysical evidence suggests two types of detectors, of even and odd symmetry, with flat phase spectra of 0 and 90 deg, respectively (e.g. Burr *et al.*, 1989). The psychophysics is reinforced by electrophysiological measurements. Visual evoked potentials (VEPs) have been recorded from humans in response to stimuli that change spatial phase periodically (Burr *et al.*, 1992; Girard & Morrone, 1995), indicating the existence of units with different phase spectra. The data from animal neurophysiology show that the receptive fields of simple cells vary considerably in symmetry, from even- to odd-symmetric, encompassing the whole range in between (e.g. Field & Tolhurst, 1986; Hamilton, Albrecht & Geisler, 1989; DeAngelis, Ohzawa & Freeman, 1991).

Although spatial phase has been well studied for luminance-modulated patterns, few studies have investigated phase sensitivity for chromatically modulated patterns. Troscianko and Harris (1988) measured phase sensitivity with two-harmonic patterns and reported reduced phase sensitivity at equiluminance (after scaling contrast to equate sensitivity). However, since it has been previously shown that the two-harmonic condition does not always generalise to more natural images (Morrone *et al.*, 1989) we have measured phase sensitivity to *multi-harmonic* patterns. Our results show that for multi-harmonic patterns, phase sensitivity at equiluminance is very similar to that for luminance-modulated patterns, provided that the patterns are equated in contrast for differences in sensitivity. We also replicated Troscianko and Harris's results under our conditions, but showed that the advantage for luminance modulation was only for two-harmonic stimuli of $(f + 3f)$ of moderate to high spatial frequency content (fundamental greater than 1 c/deg). These results have been presented in abstract form (Martini *et al.*, 1993; Girard *et al.*, 1993).

METHODS

Stimuli

For most experiments the stimulus was a one-dimensional pattern given by:

$$S(y) = L_0 + \frac{2A}{\pi}\sum_{k=1}^{T/2}\frac{1}{k}\cos\left(\frac{2\pi k}{T} - \phi\right).G(k), \quad (1)$$

where L_0 is the mean luminance, A amplitude, T the period (in pixels) and ϕ the phase at the origin. $G(k)$ is a lowpass filter that smoothly attenuates higher harmonics to avoid ringing and minimise possible artefacts introduced by chromatic aberrations:

$$G(k) = exp(-k^2/2\sigma^2), \quad (2)$$

where σ is the cut-off frequency constant, usually 10 times the frequency of the fundamental (unless otherwise stated). When $\phi = \pm\pi/2$ (± 90), equation (1) is the Fourier expansion of a sawtooth waveform. $\phi = 0$ or 180 deg changes the appearance of the pattern to a series of lines of the same polarity, while intermediate phases produce a combination of lines and edges (see examples in Fig. 1). Peak-to-peak contrast varies with phase, but RMS contrast does not. We therefore define contrast as RMS contrast, the square root of variance divided by L_0.

A squarewave pattern can be obtained from equation (1) by summing only the odd harmonics. Applying a highpass filter to such waveform, to attenuate smoothly the first and third harmonics, produces a Cornsweet-like stimulus identical to that of Burr *et al.* (1989), used for some measurements in experiment I. In this case, $G(k)$ becomes:

$$G(k) = exp(-k^2/2\sigma_h^2) - exp(-k^2/2\sigma_l^2) \quad (3)$$

where $\sigma_h = 128$ and $\sigma_l = 4$ times the frequency of the fundamental. The maximum power of this stimulus is in the seventh harmonic: Fig. 3 of Burr *et al.* (1989) shows the power spectrum.

Equiluminant gratings were produced by summing red and green waveforms [defined by equation (1)] in antiphase. The chromaticity of the pattern was varied by changing its *colour ratio*, the percentage of the red in the mixture, while maintaining a fixed total contrast and mean luminance (see Mullen, 1985). The contrast of both red and green guns remain unchanged with colour-ratio. For the later experiments, the 'luminance-modulated' gratings (yellow–black) were made by summing the red and green gratings in the same phase.

Stimuli were horizontal gratings generated by a computer-controlled Digital Signal Processor (VSG2/2 graphics card: Cambridge Research Systems), displayed on the face of a Barco Calibrator colour monitor (CIE co-ordinates: red: $x = 0.618$, $y = 0.351$; green: $x = 0.286$, $y = 0.601$) at a frame rate of 120 Hz, 512 lines per frame and 14 bits per colour per pixel. They were viewed binocularly with natural pupils through a yellow filter (Kodak Wratten L16) that heavily attenuated wavelengths below 520 nm. Viewed through the filter the CIE co-ordinates for the red were: $x = 0.647$, $y = 0.351$; and for the green: $x = 0.392$, $y = 0.606$, and the mean luminance was 14 cd/m^2. At equiluminance (zero contrast), the CIE co-ordinates were $x = 0.551$, $y = 0.447$. The luminances of the red and green guns were calibrated by photometry (Minolta Chromameter CS100), suitably linearised and equated in amplitude so red and green had the same luminance. At maximum contrast, the medium wavelength cones modulate at 37% and the long wavelength cones at 13%. Viewing distance was 1.1 m

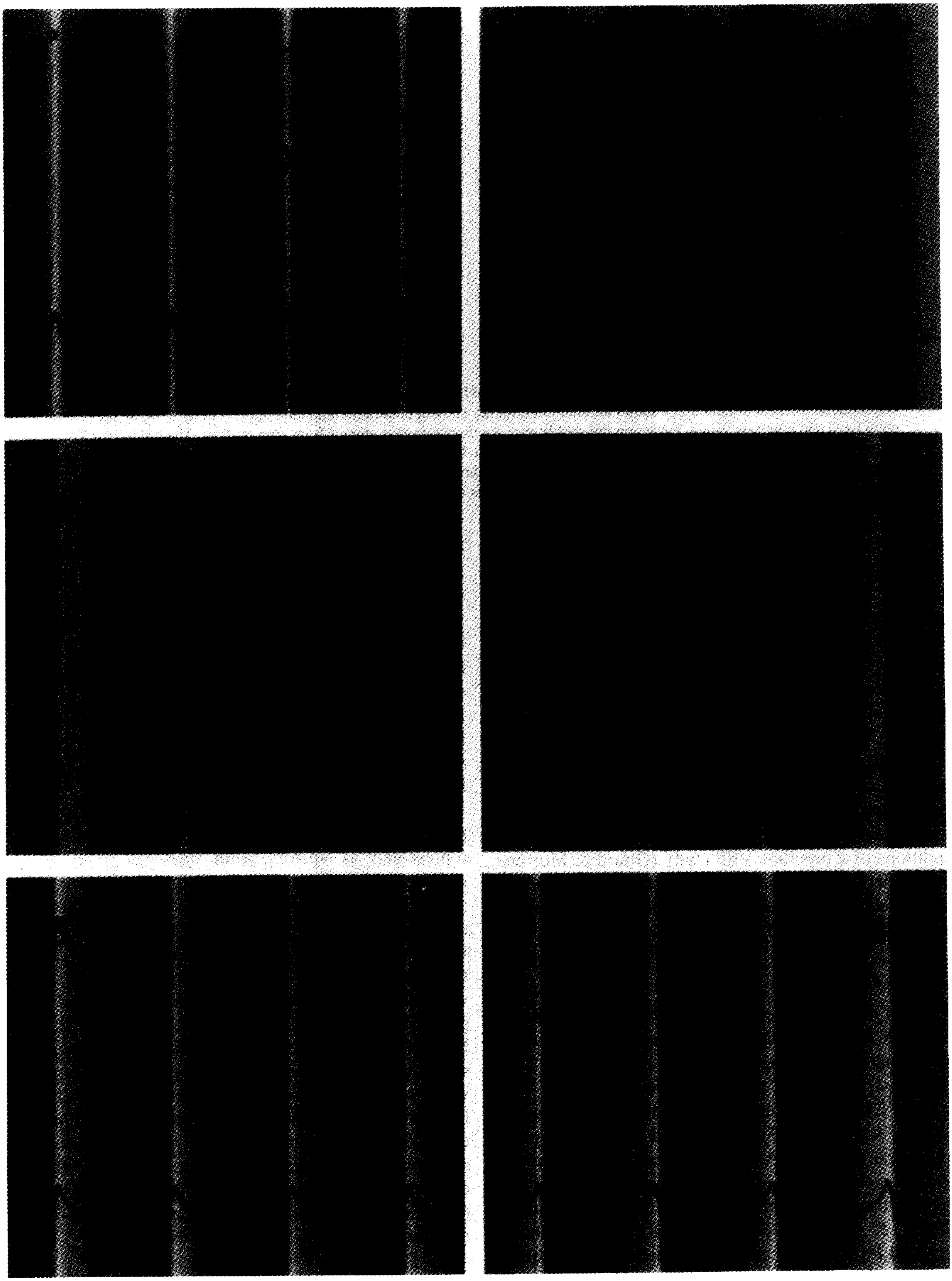

FIGURE 1. Black and white examples of some of the stimuli used in this study, defined by equation (1). For $\phi = 0$ or 180 deg, the stimuli appear like lines. For $\phi = \pm 90$ deg, the stimuli are saw-tooth waveforms. Intermediate phases define a mixture of the two stimuli. For experiment I the task of the subjects was to discriminate the stimulus pairs 0–180 deg or ±90 deg, as the contrast was reduced to threshold. For experiment II, subjects discriminated stimulus pairs of constant contrast, while the phase homed in on threshold (always around a mean of 0, like the pairs in the bottom row).

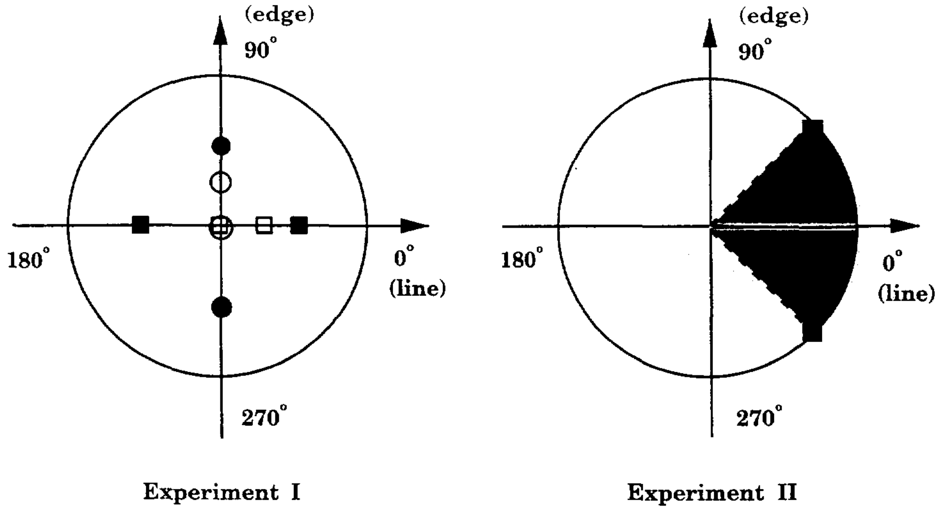

FIGURE 2. Polar representation of stimuli for experiments I and II. The open symbols refer to detection tasks, closed symbols to discrimination. The left-hand figure shows the conditions for the 180 deg phase discrimination of experiment I, where the phases were fixed and contrasts varied. Detection thresholds were for discriminating stimuli from zero contrast. The right-hand figure shows phase discrimination for fixed contrasts. Phase varied from trial to trial, while contrast (distance from the origin) remained constant. The shaded area represents the phase thresholds plotted in Figs 5 and 6. Examples of the stimuli corresponding to the filled circles and squares are given in Fig. 1.

for most experiments, but was varied to maintain a constant number of cycles of waveform when the spatial frequency of the fundamental was changed. At 1.1 m the stimulus subtended 10 deg of visual field.

The patterns were generally stationary during presentation, and were displayed in a random position from trial to trial to impede the subject from using local contrast cues. For the ramp and line patterns, the maximum random displacement was equal to 1 period; for the high pass squarewave, the maximum displacement was 0.25 periods. For some experiments, the stimulus was "jittered" randomly from frame to frame, to disadvantage chromatic mechanisms, and to emulate conditions of a previous VEP study (Girard & Morrone, 1995). Here the spatial location of the grating was changed abruptly and continually at random within each trial at a frequency of 16 Hz.

Procedure

Two of the authors served as subjects (P.G. and P.M.), both with normal or corrected-to-normal spatial vision and normal colour vision.

Contrast and phase thresholds were collected by a temporal 2AFC procedure guided by the Quest algorithm (Watson & Pelli, 1983), that placed contrast or phase values near threshold. After a minimum of five estimates for each measurement, data were pooled and fitted to a Weibull function by means of the Simplex algorithm (Nelder & Mead, 1964) to obtain the estimate of threshold level at 82% correct responses. Before collection of data, subjects were given extensive training with all patterns and configurations, until a reasonably steady performance was achieved.

Subjects were required to discriminate between two stimuli presented at successive temporal intervals (each marked by a tone) by pressing the appropriate response button. Stimulus duration was always 250 msec, with abrupt onset and offset. In the detection paradigm they were asked to discriminate a low intensity waveform from a blank field. In the phase reversal paradigm the discrimination was between a pattern and its contrast reversed version (discrimination of 180 deg phase difference), illustrated by the first two rows of Fig. 1. In the phase discrimination task (experiment II) subjects had to select the stimulus of positive phase from two stimuli with phases symmetrical about 0 deg (the left-hand pattern in the last row of Fig. 1).

The design of the experiments is best illustrated by the polar representation of Fig. 2. Here the stimuli are represented as vectors, with phase ϕ given by the argument and contrast by the norm. The open symbols of the left-hand diagram illustrate the detection task of experiment I. The filled symbols of the same diagram illustrate the contrast reversal (180 deg phase discrimination) paradigm. In both these conditions, contrast strength varied from trial to trial to home in on threshold. In the phase discrimination paradigm of experiment II (right-hand diagram) contrast was fixed at a suprathreshold value, while phase varied from trial to trial about a mean value of 0 deg to home in on an estimate of phase threshold (angle indicated by shading). Varying phase does not affect total contrast, but varies the amount of sine and cosine contrast in the mix. In this paradigm the only cue for discrimination is the reversal of the sine (edge) component, since the cosine (line) component is not varied in the two intervals of each trial.

RESULTS

Experiment I: Detection and phase reversal discrimination

This experiment compared thresholds for discriminat-

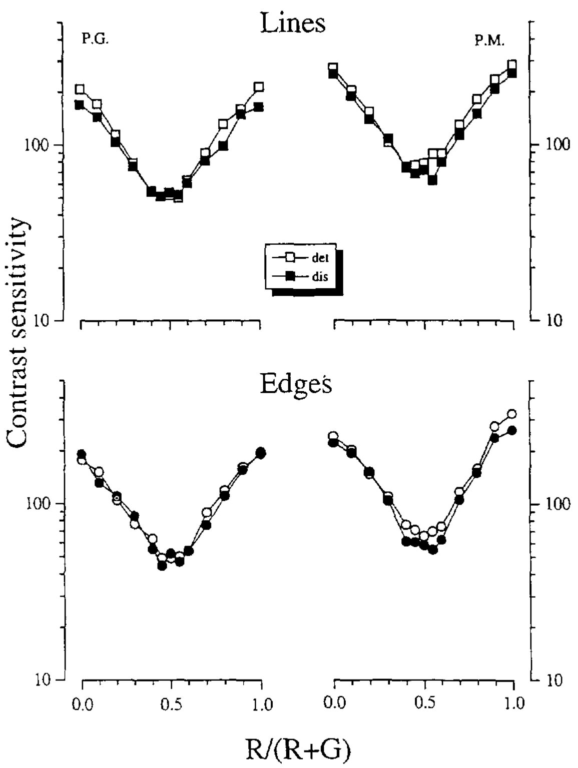

FIGURE 3. The sensitivity for contrast detection (○,□) and 180 deg phase-discrimination (●,■) of a single cycle of a highpass squarewave as a function of colour ratio, for subjects P.G. and P.M. The spatial frequency of the fundamental was 0.25 c/deg, and the attenuation such that the most power was at the 7th harmonic, 1.75 c/deg. Discrimination was based on the apparent brightness, or hue, or both (depending on colour ratio) of its central band for the ±90 deg phase discrimination (edges), or on the polarity of luminance or colour of the lines for the 0–180 deg discrimination (see figure in Burr *et al.*, 1989).

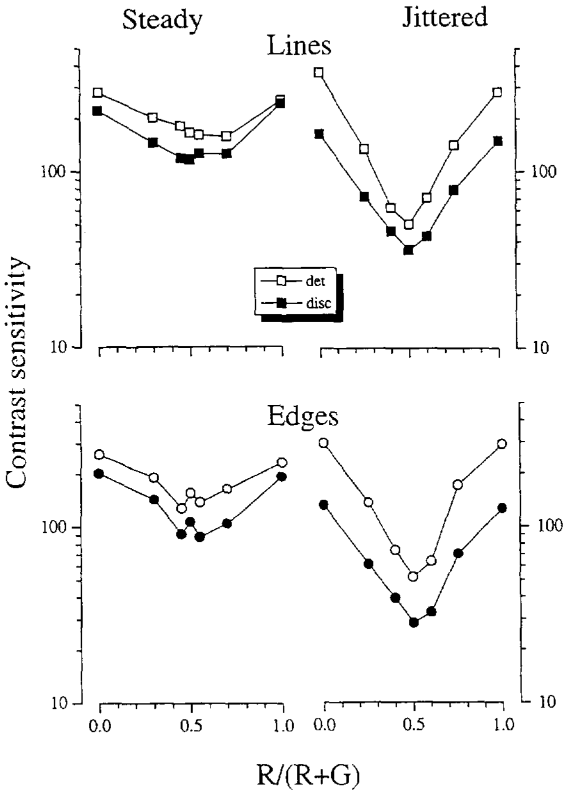

FIGURE 4. The sensitivity for contrast detection (○,□) and 180 deg phase discrimination (●,■) of a lowpass ramp waveform ($sf = 0.7$ c/deg, $\sigma = 7$ c/deg) as function of colour ratio, for subject P.G. The stimuli were either stationary (steady) or randomly displaced each frame (jittered). Again the phase discrimination was either 0–180 deg (lines) or ±90 deg (edges).

ing phase shifts of 180 deg with simple detection thresholds, over the range of colour ratios.

Thresholds were measured first with a single cycle of a highpass squarewave, similar to that used by Burr *et al.* (1989: see their Fig. 2). Only one cycle of the grating was shown on the monitor, so that subjects could base their discrimination on the apparent brightness, or hue, or both of its central band. Spatial frequency of the fundamental was 0.25 c/deg, with maximum power at the seventh harmonic, 1.75 c/deg. Contrast sensitivity for both detection (open symbols) and phase reversal discrimination (filled symbols) are plotted as a function of colour ratio in Fig. 3. All curves have a U-shape, reflecting the lower sensitivity for colour ratios around 0.5, the equiluminant point of the subject (measured by standard flicker-photometry). However, at all colour ratios, thresholds for 180 deg phase discrimination are virtually identical to those for detection.

Thresholds were also measured with blurred ramp patterns, either stationary within each trial (Fig. 4, left), or caused to jitter randomly from frame to frame (Fig. 4, right). These curves also have a U shape, deeper for the jittered condition, reflecting the poorer sensitivity for chromatic patterns at high temporal modulation. For both the steady and jittered conditions, discrimination thresholds were higher than detection thresholds, probably because detection can be achieved with only the first harmonic, while discrimination requires the higher harmonics. However, the difference between detection and discrimination was constant on the logarithmic scale, suggesting that detection and 180 deg phase-discrimination differ only by a scaling factor over the entire range of colour ratios.

These results suggest that once contrast has been equated for detectability, phase discrimination is as good for chromatically modulated as for luminance-modulated patterns. The patterns needed to be about 1.5 times detection threshold for phase discrimination for the steady ramp stimuli (Fig. 4, left), about twice the detection threshold for the jittered ramp stimuli (Fig. 4, right), and for the highpass "squarewave", phase discrimination was possible at detection threshold (Fig. 3). This suggests a similarity of performance for colour and luminance mechanisms.

Experiment II: Phase sensitivity to multi-harmonic patterns

In this experiment subjects were asked to discriminate differences in phase of patterns presented at a fixed contrast level. Phase varied between trials, but RMS contrast remained unchanged (see Methods and Figs 1

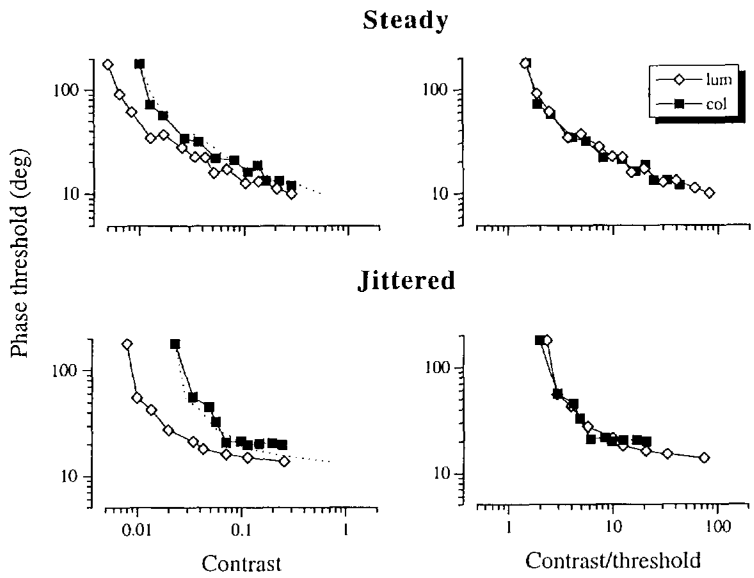

FIGURE 5. Thresholds for luminance (◇) and colour (■) phase discrimination in experiment II, for subject P.G. Red and green ramp waveforms were added in phase for luminance and in antiphase for chromatic patterns, both at a colour ratio of 0.5. Stimuli varied symmetrically about a mean phase of 0 deg, so that discrimination could only be based on the polarity of the edge component (see Fig. 2 and the Methods section). On the left, phase thresholds [2 ϕ in equation (1)] are plotted as a function of contrast, for steady and jittered stimuli. The dotted line corresponds to the luminance curve shifted along the abscissa by a scaling factor equal to the logarithmic difference in contrast sensitivity for colour and luminance stimuli. On the right, contrast is expressed in threshold units (i.e., normalised by dividing for the contrast detection threshold).

and 2). In this experiment we did not span the range of colour-ratios, but used only the ratio 0.5, the value that produced minimal sensitivity for both subjects in experiment I (also the V_λ equiluminant point).

For the luminance-modulated condition the colour ratio was also 0.5, but with the red and green components summed in-phase to produce a yellow–black modulation. For this study only the ramp stimulus was used; the high-pass squarewave was not included, because of the possibility of chromatic aberrations generated by higher frequency components.

Phase thresholds are shown in Fig. 5 as a function of stimulus contrast, for both steady and jittered patterns (top and bottom rows, respectively). Phase sensitivity increases progressively with contrast (Fig. 5, left) for both luminance and colour, in the steady and jittered paradigm. For any fixed contrast level, thresholds for luminance are always lower than those for colour. However, when the difference in contrast sensitivity is taken into account, the thresholds are very similar. The dotted line represents luminance thresholds scaled to equate contrast sensitivity (by the value given in experiment I). This curve follows closely the colour function, for both the steady and jittered conditions. This result is also shown in the curves on the right, where contrast has been normalised to "threshold units", by dividing it for the detection threshold value. There the colour and luminance functions appear indistinguishable.

Experiment III: Lowpass filtering

One potential problem with equiluminant patterns is the possibility of chromatic aberrations that may introduce a luminance artefact, giving the possibility of a non-chromatic cue for discrimination. Chromatic aberrations depend strongly on spatial frequency, and can usually be neglected for all practical purposes below 4 c/deg (Le Grand, 1956; Flitcroft, 1989). In any event, their effects should vary with the spatial frequency content of the patterns, and hence vary with image blur. We therefore repeated the measurements of experiment II, with a sawtooth grating blurred by a Gaussian filter [equation (2)] with progressively lower cut-offs.

Figure 6 shows the dependence on lowpass cut-off frequency [σ in equation (2)] for the yellow–black pattern and the equiluminant red–green pattern, with contrast

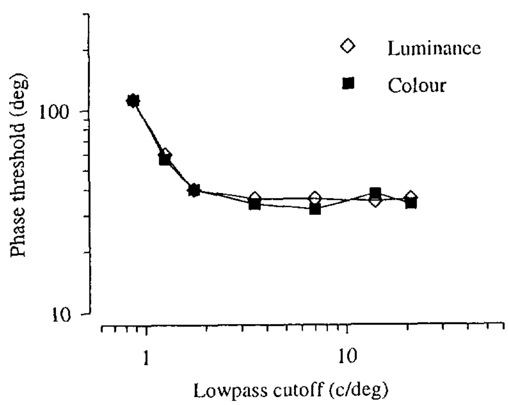

FIGURE 6. Thresholds for luminance (◇) and colour (■) phase discrimination in experiment III, for subject P.M. Stimuli were stationary lowpass ramp waveforms ($sf = 0.7$ c/deg) presented at a contrast four times detection threshold. Phase thresholds are plotted as function of cut-off frequency [σ in equation (2)]. Note that colour and luminance thresholds are equally affected by blur over the entire range.

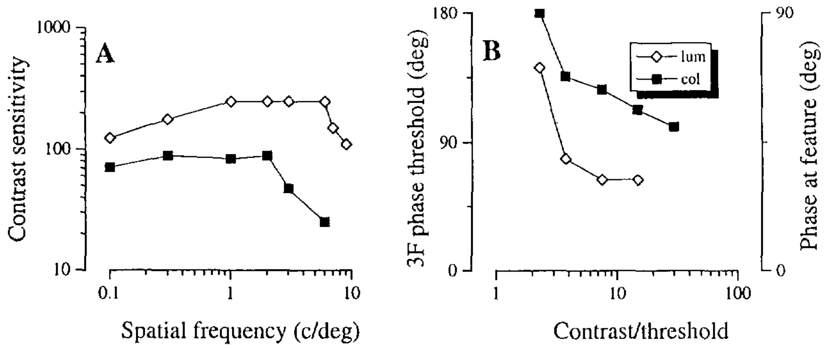

FIGURE 7. (A) Contrast sensitivity (Michaelson contrast) to luminance (◇) and chromatic (■) sinusoidal gratings for subject P.M. as a function of spatial frequency. Viewing distance was varied to maintain a fixed number of cycles ($n = 9$) on the screen. Stimulus duration was 250 msec with abrupt onset and offset. (B) Thresholds for phase discrimination of two-harmonic waveforms in experiment IV, plotted as function of suprathreshold contrast level for subject P.M. Stimuli were $f + 3f$ patterns with $F = 1$ c/deg [equation (1) with $k = 1,3$], where the phase [ϕ in equation (1)] was always 0 deg for the fundamental, but was varied in the interval 0–180 deg for the third harmonic. Threshold was taken as the smallest phase difference between f and $3f$ that could be discriminated from a peaks-add pattern. The left-hand ordinate expresses this threshold as the phase of the third harmonic, at the point where that of the first is 0 deg. The right-hand ordinate shows the threshold expressed as the phase of both harmonics at the point of maximal phase congruence, for comparison with data from the previous experiments. Both harmonics were presented at a constant multiple of detection thresholds [derived from the graph (A)], plotted on the abscissa.

fixed at four times detection threshold. Phase sensitivity decreased with cut-off frequency, but at the same rate for colour and luminance. There was no selective deterioration (nor improvement) of the equiluminant condition compared with luminance, suggesting that chromatic aberrations were either absent in the conditions used here, or that they did not interfere with the discrimination task.

Experiment IV: Phase sensitivity to patterns of two and three harmonics

The results so far are difficult to reconcile with the findings of Troscianko and Harris (1988), who reported sensitivity for phase discrimination of chromatic patterns to be twice as poor as that for luminance patterns. We therefore examined phase discrimination using their same paradigm, with a two-component stimulus comprising a fundamental (of 1 c/deg) and the third harmonic. Subjects were asked to discriminate between a pattern in which both harmonics had a 0 phase (peaks-add configuration) and another in which the fundamental was kept fixed at the origin and the third was shifted in phase by a variable amount. For comparison with Troscianko and Harris' results, phase thresholds are expressed as the phase of the third harmonic at the point where the first harmonic has phase zero (left-hand ordinate). But for compatibility with previous data of this paper, the thresholds are also expressed as the phase of both harmonics at the point of phase congruence [ϕ of equation (1)] on the right-hand ordinate.

We first replicated the experiment of Troscianko and Harris using their exact conditions, where both harmonics were scaled in amplitude to equate sensitivity. This required that contrast sensitivity for colour and luminance modulation was first measured separately, reported in Fig. 7(A). Luminance sensitivity was relatively constant over the range 1–3 c/deg, while colour sensitivity decreased by a factor of two from 1 to 3 c/deg. The compound waveforms were then constructed separately for the luminance and colour conditions, with the harmonics scaled so both were at threshold. The contrast of both harmonics in the compound were then varied together, and reported in Fig. 7B in threshold-units (multiples of detection threshold). Phase sensitivity varied with contrast in a similar way to that reported by Troscianko and Harris. There was a constant advantage for luminance patterns over the whole range, by a factor of about two.

One major difference between the present configuration and that of the previous experiments is the amplitude relations of the harmonics. We therefore repeated the measurements using the same paradigm but varying the amplitude relations between the harmonics, while keeping the contrast fixed at 7.5 times the detection threshold of the *compound* (measured independently for each condition). The results for two different spatial frequencies are shown in Fig. 8(A) and (B). In both cases, phase discrimination depended to some extent on the relative amplitude relationship of the two harmonics. What is interesting, however, is that the difference between colour and luminance remained more or less constant at the higher frequency [Fig. 8(A)], confirming the previous result of Fig. 7, but virtually vanished at the lower frequency [Fig. 8(B)]. Measuring phase thresholds as a function of spatial frequency (with an amplitude ratio appropriate for both colour and luminance), shows that the two thresholds are very similar at the lowest frequencies, but tend to diverge in the higher range [Fig. 8(C)].

The same kind of measurements were repeated with a pattern comprising three harmonics, $(f + 2f + 3f)$ with fundamental frequency 1 c/deg. The phase of the first and second harmonics was held constant at 0 deg at the origin, while the phase of the third was systematically shifted to obtain an estimate of threshold. Results are

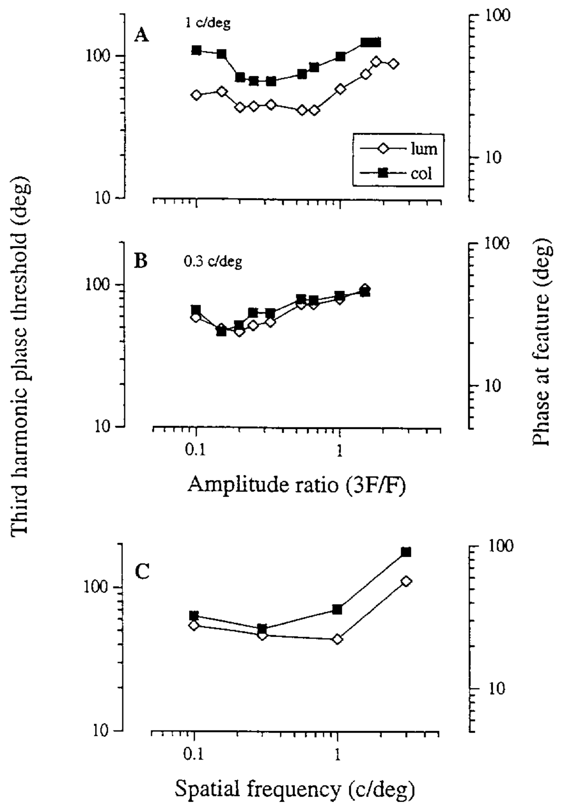

FIGURE 8. Thresholds for phase discrimination of luminance (◇) and colour (■) for two-harmonic waveforms in experiment IV, for subject P.M: **(A)** and **(B)** thresholds are plotted as function of the amplitude ratio of the harmonic components ($3f/f$); fundamental frequency was 1 and 0.3 c/deg, respectively, contrast 7.5 times the detection threshold of the compound; and **(C)** amplitude ratio ($3f/f$) was fixed at 0.2 and thresholds plotted for a number of different fundamental frequencies. Contrast was 7.5 times the detection threshold of the compound.

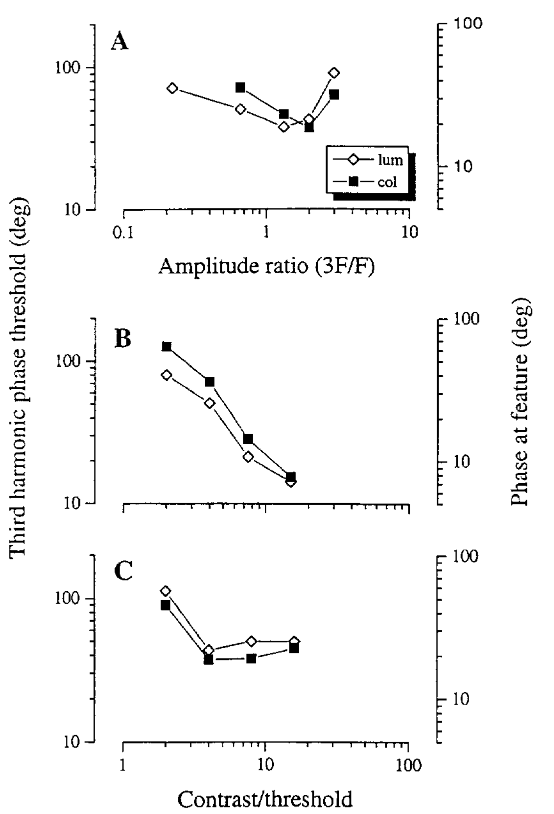

FIGURE 9. Thresholds for phase discrimination of luminance (◇) and chromatic (■) three-harmonic waveforms ($f + 2f + 3f$), for subject P.M. The phase of the fundamental and second harmonic was always constant at 0 deg at the origin. The amplitude of $2F$ is always the same as that of F; **(A)** thresholds are plotted as function of the amplitude ratio ($3f/f$) of the fundamental to the third harmonic, where $F = 1$ c/deg and contrast four times detection threshold of the compound; **(B)** and **(C)** thresholds are shown for a number of different contrasts (expressed in detection threshold units) at an amplitude ratio of 0.66 and 2, for **(B)** and **(C)**, respectively. With the higher amplitude ratio, thresholds were consistently lower for the chromatic condition.

shown in Fig. 9 at a contrast four times the detection threshold of the compound. Again phase sensitivity varies slightly with amplitude ratio [Fig. 9(A)], but the curves are different for colour and luminance. While discrimination for luminance patterns is relatively better when the third harmonic is of low contrast, colour phase discrimination improves with contrast to equal and even surpass luminance discrimination at high contrasts. Figures 9(B) and (C) explore the effect of contrast for this stimulus, at two $3f/f$ amplitude ratios (0.67 and 2, respectively). The results are consistent at all contrasts, with a slight advantage for luminance patterns at the lower amplitude ratio, and for colour at the higher amplitude ratio.

Finally, we measured phase discrimination thresholds for another two-harmonic pattern, $f + 2f$, the first two terms of a sawtooth waveform. We first established that phase thresholds were best for both colour and luminance when the amplitude of the second harmonic was half that of the first (results not shown). We then measured phase discrimination for both luminance and chromatic stimuli as a function of fundamental spatial frequency up to 3 c/deg. The results are reported in Fig. 10. Over the range of spatial frequencies measured, there was no appreciable difference in phase discrimination of luminance and chromatic patterns, except perhaps at the very highest spatial frequency where the second harmonic is 6 c/deg, quite high for an equiluminant grating.

DISCUSSION

The results of the experiments reported here strongly suggest that phase discrimination is as good for chromatic as for luminance patterns, provided they are scaled in contrast to equate for detection sensitivity. For the highpass filtered patterns, sensitivity for the 180 deg phase discriminations was the same as that for detection, at all colour-ratios. For the ramp patterns, phase discrimination thresholds were higher than detection thresholds (probably because the fundamental aided detection but not discrimination), but the ratio of discrimination to detection thresholds was the same at all colour-ratios, with no selective deficit for phase discrimination at equiluminance. Even when the patterns were caused to jitter rapidly, disadvantaging colour mechanisms, the discrimination–detection ratio was constant with colour-ratio. Similarly, thresholds for

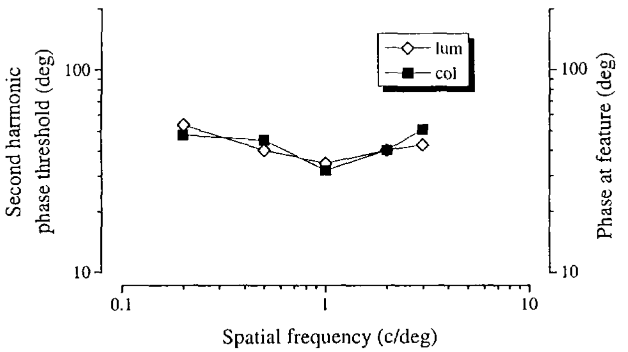

FIGURE 10. Thresholds for phase discrimination of luminance (◇) and colour (■) for two-harmonic waveforms ($f + 2f$) for subject P.M., as a function of spatial frequency. Amplitude ratio ($2f/f$) was fixed at 0.5 and contrast was 7.5 times the detection threshold of the compound.

detecting small differences in phase were identical for luminance-modulated and colour-modulated patterns, after equating for detection threshold. Furthermore, for all the patterns used in this study, discrimination thresholds did not change with the average phase: contrast thresholds for discriminating 90 from −90 deg phase were as fine as those for discriminating 0 from 180 deg, for all colour-ratios. It is unlikely that the results were influenced by chromatic aberrations, as they were not selectively affected by image blur.

Our results would seem to be at odds with those of Troscianko and Harris, who reported poor chromatic phase discrimination for a two-harmonic ($f + 3f$) stimulus. We have replicated Troscianko and Harris' results, and shown them to be valid for the particular stimuli they used. However, even for that class of stimuli ($f + 3f$), phase discrimination was poorer for colour only for moderately high spatial frequencies. At low spatial frequencies discrimination thresholds for the two conditions were quite similar. When the second harmonic was added to the mix, phase discrimination for chromatic patterns was as good as for luminance patterns. Indeed, even with only the first and second harmonics ($f + 2f$), the luminance and colour thresholds were virtually identical at all spatial frequencies. Only for $f + 3f$ combinations of moderate to high spatial frequency was there an advantage for luminance patterns.

It is not at all clear why there should be an advantage for luminance patterns with these particular stimuli. Possibly the factor-of-three separation between harmonics is sufficiently great so as to excite different units of different spatial frequency selectivity. The finest chromatically opposed units are probably tuned to spatial frequencies much lower than the finest luminance-selective units, so there is less of a range of frequency-selective units available to participate in the discrimination. However, there are insufficient data available in the present study to pursue this idea further. It is also interesting that this result is reminiscent of that of Morrone *et al.* (1989), who showed luminance phase discrimination to be as good for peripheral as for central viewing (after scaling for cortical magnification), except for the particular conditions of two-harmonic patterns at relatively high spatial frequency [those used by Bennett and Banks (1991) and by Rentschler and Treutwein (1985)]. It was suggested there that the peculiarly poor phase discrimination for two-harmonic patterns in the periphery may be related more to crowding like phenomena than phase discrimination *per se*, and is perhaps caused by cortical under-sampling.

While the Fourier phase spectrum is a convenient description of the image, it is unlikely that the human visual system decodes phase by performing a Fourier analysis, or any similar technique. One plausible strategy is that phase is detected by comparison of the output of two or more classes of quasi-linear detectors with different phase spectra (see Burr *et al.*, 1989). The underlying assumption of this reasoning is that phase of a stimulus is not evaluated globally with respect to an arbitrary origin, but only at the *salient features*, given by peaks of local energy (Morrone & Burr, 1988). At these points the *arrival phases* of individual harmonics are most similar, and may be used to identify the feature (edge, line or both).

The phase spectra of detectors determine the shape of the receptive fields: even-symmetric receptive fields correspond to 0 or 180 deg phase preference, odd-symmetric fields to ±90 deg. Discrimination of the polarity of lines requires detectors with even-symmetric receptive fields (or at least fields that are not exactly odd-symmetric) and discrimination of edge polarity requires odd-symmetric (or asymmetric) receptive fields. As sensitivity for phase discrimination did not vary with average phase for any of the patterns, both luminance and chromatic pathways should comprise detectors with both even- and odd-symmetric fields. The fact that the thresholds for chromatic phase discrimination were as fine as those for luminance suggests that the receptive fields of the chromatic pathway are similar in shape to those of the luminance pathway.

A quasi-linear operator with an odd-symmetric receptive field will necessarily have a band-pass tuning function. Thus, the present results also imply the existence of chromatically tuned mechanisms with band-pass tuning characteristics. This is consistent with the recent findings of Losada and Mullen (1994), who have demonstrated band-pass masking functions at equiluminance. However, it is at odds with the common assumption that chromatic mechanisms have low-pass tuning characteristics, that have often been invoked to explain decreased performance at equiluminance (e.g., Morgan & Aiba, 1985).

The present result is very consistent with our recent visual evoked potential (VEP) studies (Girard & Morrone, 1995). This study demonstrated strong and reliable VEPs in response to alternating the polarity of edges, defined either by changes in luminance or chromaticity (with suitable precautions that the potentials did not arise from changes in local luminance). The potentials to chromatically defined edges were weaker than those to chromatically defined lines, suggesting that there may be fewer detectors with asymmetric receptive fields. However, extrapolation of the potentials to zero voltage predicted similar thresholds for lines and edges, consistent with this study.

Phase-selective mechanisms probably play an important role in feature detection, a possibility made most explicit in the model of Morrone and Burr (1988). The fact that chromatic mechanisms are equally sensitive to spatial phase suggests there may exist similar mechanisms in human vision for detecting and identifying chromatic features in natural images.

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