RESPONSES OF MACAQUE GANGLION CELLS TO THE RELATIVE PHASE OF HETEROCHROMATICALLY MODULATED LIGHTS

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SUMMARY

1. We measured the response of macaque ganglion cells to sinusoidally modulated red and green lights as the relative phase, $\theta$, of the lights was varied.

2. At low frequencies, red–green ganglion cells of the parvocellular (PC-) pathway with opponent inputs from middle-wavelength sensitive (M-) and long-wavelength sensitive (L-) cones were minimally sensitive to luminance modulation ($\theta = 0$ deg) and maximally sensitive to chromatic modulation ($\theta = 180$ deg). With increasing frequency, the phase, $\theta$, of minimal amplitude gradually changed, in opposite directions for cells with M- and L-cone centres.

3. At high frequencies (at and above 20 Hz), phasic cells of the magnocellular (MC-) pathway were maximally responsive when $\theta \approx 0$ deg and minimally responsive when $\theta \approx 180$ deg, as expected from an achromatic mechanism. At lower frequencies, the phase of minimal response shifted, for both on- and off-centre cells, to values of $\theta$ intermediate between 0 and 180 deg. This phase asymmetry was absent if the centre alone was stimulated with a small field.

4. For PC-pathway cells, it was possible to provide an account of response phase as a function of $\theta$, using a model involving three parameters; phases of the L- and M-cone mechanisms and a L/M cone weighting term. For red–green cells, the phase parameters were monotonically related to temporal frequency and revealed a centre–surround phase difference. The phase difference was linear with a slope of 1–3 deg Hz$^{-1}$. If this represents a latency difference, it would be 3–8 ms. Otherwise, temporal properties of the M- and L-cones appeared similar if not identical. By addition of a scaling term, the model could be extended to give an adequate account of the amplitude of responses.

5. We were able to activate selectively the surrounds of cells with short-wavelength (S-) cone input to their centres, and so were able to assess L/M cone weighting to the surround. M- and L-cone inputs added linearly for most cells. On

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average, the weighting corresponded to the Judd modification of the luminosity function although there was considerable inter-cell variability.

6. To account for results from MC-pathway cells, it was necessary to postulate a cone-opponent, chromatic input to their surrounds. We developed a receptive field model with linear summation of M- and L-cones to centre and surround, and with an additional M,L-cone opponent input to the surround. It proved possible to account for response phase and amplitude of both on- and off-centre cells. For both, the proposed cone-opponent input to the surround must consist of a (+M−L) mechanism.

7. The dependence of minimum response of MC-pathway cells on $\theta$ closely resembles psychophysical results obtained using the same protocol, in which psychophysical modulation sensitivity was measured as a function of $\theta$. The results provide strong corollary evidence linking the MC-pathway to psychophysical performance in heterochromatic flicker photometry.

INTRODUCTION

In heterochromatic flicker photometry, a pair of lights in sinusoidal counterphase modulation often show residual flicker after adjustment to equiluminance, i.e. after the sensation of flicker has been minimized by adjusting the relative radiance of the lights. De Lange (1958) observed that this residual flicker sensation could be cancelled by adjusting the relative physical phase of the two component lights, and he ascribed the phenomenon to a latency difference between the cones. The results of this study and subsequent confirmatory work by Walraven & Leebeek (1964) and Vos & Walraven (1966), all performed at low photopic levels, were later attributed to a difference between rod and cone latencies (von Grunau, 1977; van der Berg & Spekreijse, 1977). However Cushman & Levinson (1983), working at high photopic luminance levels, observed residual flicker and were able to show it could be cancelled by a small phase adjustment.

In a different psychophysical procedure, modulation thresholds were measured at photopic luminance levels as a function of the relative physical phase of red and green component lights (Lindsay, Pokorny & Smith, 1986). As relative phase was varied, modulation thresholds traced out a U-shaped function. The physical phase at which modulation threshold is maximal corresponds to the phase at which subjects see little or no residual flicker. Phase shifts measured with this technique are revealed by a translation of the U-shaped function along the physical phase axis, which we will term a phase asymmetry. At low frequencies, modulation sensitivity is highest to chromatic modulation (with the lights modulated in counterphase, i.e. with a phase difference near 180 deg), while at high frequencies, modulation sensitivity is highest to achromatic modulation (with the lights in phase, i.e. with a phase difference near 0 deg). The function relating the phase of least sensitivity to temporal frequency rises rapidly from near 0 deg at 1 Hz, crosses 180 deg near 20 Hz and reaches 190 deg at higher frequencies. In further studies (Swanson, Pokorny & Smith, 1987a, 1988), these phase asymmetries were shown to be little affected by moderate chromatic adaptation (Swanson et al. 1988). It could be shown that they were not determined by latency differences between the cones; evaluation of de Lange's (1958) model using theoretical photopigment sensitivities would have
required unrealistic latency differences of 20–60 ms. The source of these phase asymmetries must thus be sought in post-receptoral processing.

Within the retino-geniculate pathway of man and other old-world primates, one afferent system consists of tonically responding, cone-opponent retinal ganglion cells which project to the parvocellular layers of the lateral geniculate nucleus (PC-pathway). The other consists of phasic ganglion cells which project to the magnocellular layers of the nucleus (MC-pathway; Wiesel & Hubel, 1966; de Monasterio & Gouras, 1975; Dreher, Fukuda & Rodieck, 1976; Creutzfeldt, Lee & Elepfandt, 1979; Perry, Oehler & Cowey, 1984). There is good evidence that the MC-pathway forms the physiological substrate of heterochromatic flicker photometry (Lee, Martin & Valberg, 1988). We therefore sought the physiological basis of phase asymmetries in the ganglion cells of the PC- and MC-pathways.

We measured responses of ganglion cells of the PC- and MC-pathways of the macaque on changing the relative phase of two equiluminant lights. We show that such a stimulus protocol provides a direct and powerful means of investigating the temporal characteristics of the opponent cone inputs to PC-pathway cells. We develop a model which can account for the phase and amplitude of these cells’ responses to time-varying stimuli, and thereby provide a quantitative characterization of their cone inputs. An elaboration of the model can account for the behaviour of the phasic, MC-pathway to our phase-varying stimulus. We show that the phase asymmetries found psychophysically are closely reproduced in the responses of cells of the MC-pathway.

**METHODS**

*Preparation.* We recorded ganglion cell activity from the retinae of macaques (*Macaca fascicularis*). After an initial intramuscular injection of ketamine, anaesthesia was maintained with halothane or isofluorane in a 70%–30% N2O4 mixture, using levels of 1–2% during surgery, and 0.2–1% during recording. Local anaesthetic was applied at the points of surgical intervention. The EEG (electroencephalogram) and ECG (electrocardiogram) were monitored continuously as a control for anaesthetic depth. Muscular relaxation was maintained by intravenous infusion of gallamine triethiodide (5 mg kg−1 h−1) together with a. 3 ml h−1 of dextrose Ringer solution. The end-tidal Pco2 was kept near 4% by adjusting the rate and depth of ventilation, and body temperature was maintained near 37.5 °C. A contact lens was used to focus the eye on a back-projection tangent screen 57 cm from the animal. This screen was used for mapping receptive fields and for projecting stimuli for cell classification. The position of the fovea and the optic disc were determined with the aid of a fundus camera. We checked the clarity of the optic media frequently, and terminated recording from the eye when the smaller retinal vessels could no longer be recognized. On completion of recording from both eyes, the animal was killed with an overdose of barbiturate. The details of recording technique and cell classification are given elsewhere (Lee, Martin & Valberg, 1989a). Briefly, after extracellular activity of a ganglion cell was isolated, we used flashed spots to classify the cell type. In the case of PC-pathway, tonic cells, responses to lights of different, equiluminous colours and to achromatic increments and decrements were recorded as an aid to cell classification. The set of tests used to identify ganglion cells had previously been used to distinguish between cells of the parvo- and magnocellular layers of the geniculate nucleus (e.g. Lee, Valberg, Tigwell & Tryti, 1987), and we are confident of our ability to distinguish between ganglion cells of the PC- and MC-pathways. We recorded from ganglion cells from parafoveal retina with retinal eccentricities of 2–10 deg.

*Equipment and calibration.* The apparatus used light-emitting diodes (LEDs), in a two-channel Maxwellian view system of very similar design to that used in psychophysical studies (Swanson, Ueno, Smith & Pokorny, 1987b), with the addition of a back-projection light on the optic axis for alignment. The LEDs had dominant wavelengths of 554 and 638 nm, with half-widths at half-height of 18 and 23 nm respectively, giving colourimetric purities of over 97%. The aerial image
of each LED had a diameter of about 3 mm in the plane of the pupil. The LED driver board used frequency modulation of a constant-amplitude pulse train. Using a photoelectric photometer, we could demonstrate a high degree of linearity over more than a 3 log unit range. Temporal sine-wave stimulus waveforms were generated by a computer (up to 19-52 Hz, 128 values per cycle, then 64 values per cycle) through 12 bit digital-to-analogue converters. We used temporal frequencies between 1-22 and 39-04 Hz. The time-averaged retinal illuminance was 2000 trolands (td) for a human observer, and all values cited are in human trolands. In view of the smaller size of the monkey eye, one would expect retinal illuminance in the macaque to be about 1-7 times that in man (Virsu & Lee, 1983). We used a circular stimulus of 4-7 deg diameter. Some data were obtained at a retinal illuminance of 200 td, with 0-6 deg and 20 deg fields, and with illuminated surrounds. The LEDs were adjusted to equal luminance using heterochromatic flicker photometry of one of the authors whose luminosity function resembled closely that of the 2 deg Judd (1951) observer. We confirmed this calibration by placing the front lens of a Photo Research Scanning Radiometer in the plane of the pupil, and comparing the luminances of the LEDs at this setting. The time-averaged chromaticity of the field was 595 nm. The macaque luminosity function has not been determined with precision, though available evidence suggests it is similar to that of man (DeValois, Morgan, Polson, Mead & Hull, 1974), consistent with the resemblance between the L- and M-cone pigment spectra of the two species (Bowmaker, Dartnall & Mollon, 1980; Baylor, Nunn & Schnapf, 1987).

The major experimental variable was the relative phase of the two LEDs. The phase of the green LED, relative to that of the red LED, was varied in 22-5 deg steps. For PC-pathway ganglion cells, pilot experiments indicated little response phase variation with contrast. We therefore fixed diode modulation at 50%, a level which yielded vigorous responses. For the majority of MC-pathway cells, the modulation of each diode was set at 20%; in early experiments some data were also collected at 5%, 10% and 50% modulation. For modulation depths lower than 20%, MC-pathway response amplitudes were too low for analysis at many values of \( \theta \). However, a progressive phase advance with increasing modulation depth occurred at 10 and 20 Hz. The choice of 20% modulation was a compromise offering good response amplitude.

Procedure. After isolation of a ganglion cell’s activity, its receptive field location was plotted on the tangent screen, and the Maxwellian-view stimulator adjusted to be centred on the pupil. The stimulator was then rotated about the pupil until its optic axis was approximately in line with the receptive field. Precise alignment of the stimulus on the receptive field centre was achieved by use of a small flickering spot (0-6 deg, 10 Hz) whose position in the object plane of the optical system was adjusted to give a maximal response from the cell. The computer which controlled the stimulus also averaged and stored cell responses. At each temporal frequency, for each of the sixteen values of physical phase about 6 s of data were collected in an interleaved manner. Thus, the number of modulation cycles over which data were averaged ranged from 8 cycles at 1-22 Hz up to 256 cycles at 39-04 Hz. Cell responses were stored with a resolution of 64 or 32 bins per cycle (the latter at frequencies above 19-52 Hz). The data were subject to Fourier analysis, and in this paper we report only the amplitude and phase of the first harmonic response.

RESULTS

Responses of PC-pathway cells

The most common PC-pathway cells are those which receive input from the L- and M-cones. We classified these cells as ‘red–on’ (i.e. presumed L-cone on-centre) if they gave a centre response to increments at long-wavelengths and ‘green–on’ (i.e. presumed M-cone on-centre) if they gave an excitatory centre response to shorter wavelengths. Such cells gave an on-response to achromatic increments (Creutzfeldt et al. 1979). In a parallel manner, cells were classified as ‘red–off’ (i.e. presumed L-cone off-centre) or ‘green–off’. Such cells were silenced by achromatic increments and gave a weak response to decrements. Measurement of responses to replacement of an achromatic field by a series of equiluminous coloured stimuli provided confirmation of such classification (Lee et al. 1987; Valberg, Lee & Tryti, 1987). This terminology is consistent with that used in the literature (e.g. Wiesel & Hubel, 1966). However,
it may be noted that all responses were sustained and that, in particular, the weak response of off-centre cells to the appropriate decrement does not parallel the vigorous off-responses characteristic of off-centre cells of the MC-pathway. Further, the difference between a ‘red–off’ and a ‘green–off’ may be obscured by the variation in cone weighting among different individual cells. However we show later that the frequency dependence of cell behaviour to our phase-varying stimulus confirmed the adequacy of our classification.

Our sample of these ‘red–green’ cells included eleven cells with M-cone centres (10 green–on, 1 green–off) and fourteen cells with L-cone centres (11 red–on, 3 red–off). This was a representative subsample of a more extensive population, other properties of which are described elsewhere (e.g. Lee, Pokorny, Smith, Martin & Valberg, 1990).

Response as a function of relative phase

Figure 1 shows response histograms of a red–on cell at three different frequencies as the relative phase, $\theta$, of the green light was varied, as sketched at left. Responses at sixteen values of $\theta$ were measured, of which eight are shown for two cycles of modulation. At low frequency, a vigorous response is present to chromatic modulation ($\theta = 180$ deg) with a response minimum to luminance modulation ($\theta = 0$ deg). At higher frequencies, a response to luminance modulation appears and

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**Fig. 1.** Response of a ‘red–on’ cell to two cycles of modulation at eight different relative phases ($\theta$) at three frequencies. Stimulus composition at left. About 6 s of activity was averaged for each histogram, with 64 bins per cycle. Histograms are displayed with 32 bins per cycle. A frequency-dependent change in $\theta$ at which the response minimum occurs can be seen. The asterisks indicate the histograms with minimum amplitude.
Fig. 2. First-harmonic amplitude and response phase plots for a ‘red-on’ cell, as a function of $\theta$. The format follows that of Fig. 1. ●, the first harmonic amplitude and phase components obtained from Fourier transform of the response histograms. Response phase is the sine relative to the zero transition of the red diode. Note that between the two rows there is a shift in the phase axis. The continuous lines are obtained from a linear vector model described in the text. Note that the amplitude minimum is usually associated with a rapid change in phase.

the response minimum shifts to positive values of $\theta$, to about 90 deg at 19.5 Hz and almost 180 deg at 53 Hz. For most cells, responses at this frequency were weak and we did not include them in the analysis; we show 53 Hz data for this cell to illustrate the major shift in the response minimum. The response minima are indicated by asterisks in Fig. 1.
Figure 2 shows the first-harmonic Fourier amplitude and phase of response of the red–on cell of Fig. 1 plotted as a function of $\theta$. Data are represented by symbols, the continuous lines passing near the points are the results of a model to be described later. Each pair of panels shows a different frequency. Response phases are expressed as the sine phase relative to the zero transition of the red light. At low frequencies, the maximal amplitude occurs at a physical phase near 180 deg (chromatic modulation) and the minimal amplitude near 0 deg (luminance modulation), consistent with the strong opponency of the cell. Amplitude minima are associated with a rapid transition of response phase. As frequency is increased, the minimum
moves to positive values of $\theta$. For ‘red–off’ cells, a similar pattern was seen. The amplitude of response as a function of $\theta$ was similar for ‘red–on’ and red–off’ cells, but their phase of response was 180 deg apart for all values of physical phase.

Figure 3 shows data for a ‘green–on’ cell. Response amplitude at low frequencies shows the same pattern as the ‘red–on’ cell; the minimum amplitude occurs near 0 deg and the maximum near 180 deg. However, the amplitude minimum moved from near 0 deg into the negative portion of the physical phase axis as frequency was increased. The one ‘green–off’ cell showed a similar pattern for response amplitude but a 180 deg difference in response phase. Results shown in Figs 2 and 3 were typical.
of all red–green cells studied, except for some variability in response amplitude and phase pattern.

We also recorded from fifteen ‘blue–on’ cells, with excitatory S-cone input. Cells were classified as ‘blue–on’ if, in a successive contrast protocol (Lee et al. 1987; Valberg et al. 1987), they gave a strong response to short wavelength stimuli, with a neutral point near 500 nm. The LEDs at 554 and 638 nm are not an effective stimulus for the S-cone. We thus consider these cells to give a pure surround response to our stimulus. Figure 4 shows amplitude and phase data for such a cell. The maximum amplitude was to luminance modulation (0 deg) with a minimum near 180 deg. Increase in frequency did not reveal a consistent variation in the value of $\theta$ associated with the minima and maxima of the amplitude data.

To estimate quantitatively the phase of least response, we determined the axis of symmetry of the amplitude data as a function of physical phase (Swanson et al. 1987a). This calculation uses all amplitude values to locate this minimum and assumes only that some form of symmetry exists, independent of the exact amplitude–contrast transfer function. Mean values of phase of minimum amplitude thus calculated are shown for the different cell types together with 95% confidence bounds in Fig. 5. The expected phase of least amplitude for red–green cells is 0 deg (luminance modulation) and, as already demonstrated in Figs 2 and 3, such cells showed minimum amplitude at phases near 0 deg at low frequencies. However, the phase of minimum amplitude moved with increasing frequency towards 180 deg for red–on and red–off centre cells and towards $-180$ deg for green–on or green–off
centre cells. This behaviour thus differentiates ‘red-off’ and ‘green-on’ cells, both of which receive +M−L-cone input; all cells with presumed L-cone centre input showed a minimum that shifted toward a positive value of $\theta$, while cells with presumed M-cone centre input showed a minimum that shifted towards a negative

\[
\begin{array}{c|c|c|c}
\theta \\
(deg) & \text{Waveform} & 2.44 \text{ Hz} & 9.76 \text{ Hz} & 39.04 \text{ Hz} \\
\hline
0 & \includegraphics[width=\textwidth]{waveform0.png} & \includegraphics[width=\textwidth]{histogram0_2.44.png} & \includegraphics[width=\textwidth]{histogram0_9.76.png} & \includegraphics[width=\textwidth]{histogram0_39.04.png} \\
45 & \includegraphics[width=\textwidth]{waveform45.png} & \includegraphics[width=\textwidth]{histogram45_2.44.png} & \includegraphics[width=\textwidth]{histogram45_9.76.png} & \includegraphics[width=\textwidth]{histogram45_39.04.png} \\
90 & \includegraphics[width=\textwidth]{waveform90.png} & \includegraphics[width=\textwidth]{histogram90_2.44.png} & \includegraphics[width=\textwidth]{histogram90_9.76.png} & \includegraphics[width=\textwidth]{histogram90_39.04.png} \\
135 & \includegraphics[width=\textwidth]{waveform135.png} & \includegraphics[width=\textwidth]{histogram135_2.44.png} & \includegraphics[width=\textwidth]{histogram135_9.76.png} & \includegraphics[width=\textwidth]{histogram135_39.04.png} \\
\pm 180 & \includegraphics[width=\textwidth]{waveform180.png} & \includegraphics[width=\textwidth]{histogram180_2.44.png} & \includegraphics[width=\textwidth]{histogram180_9.76.png} & \includegraphics[width=\textwidth]{histogram180_39.04.png} \\
-135 & \includegraphics[width=\textwidth]{waveform-135.png} & \includegraphics[width=\textwidth]{histogram-135_2.44.png} & \includegraphics[width=\textwidth]{histogram-135_9.76.png} & \includegraphics[width=\textwidth]{histogram-135_39.04.png} \\
-90 & \includegraphics[width=\textwidth]{waveform-90.png} & \includegraphics[width=\textwidth]{histogram-90_2.44.png} & \includegraphics[width=\textwidth]{histogram-90_9.76.png} & \includegraphics[width=\textwidth]{histogram-90_39.04.png} \\
-45 & \includegraphics[width=\textwidth]{waveform-45.png} & \includegraphics[width=\textwidth]{histogram-45_2.44.png} & \includegraphics[width=\textwidth]{histogram-45_9.76.png} & \includegraphics[width=\textwidth]{histogram-45_39.04.png} \\
\end{array}
\]

Fig. 6. Response histograms of a phasic on-centre cell to two cycles of modulation at eight different phases ($\theta$) at three frequencies. The stimulus composition is sketched at left. About 6 s of activity was averaged for each histogram, with 64 bins per cycle. Histograms displayed with 32 bins per cycle. Note different amplitude calibration for 2.44 Hz relative to other two frequencies. The value of $\theta$ for minimal response is 180 deg at high frequency, but displaced to positive values of $\theta$ at lower frequencies. The asterisks indicate the histograms in which the first-harmonic is minimal.

value of $\theta$. The expected phase of least amplitude for a blue–on cell is 180 deg (counterphase diode modulation), if the surround sums input from M- and L-cones (in any proportion). All blue–on cells had a minimum amplitude near 180 deg, with only random perturbations as a function of frequency.

The data are consistent with the interpretation that there is minimal or no difference in latency between the L- and M-cones and that the frequency-dependent phase shift of red–green chromatic cells is due to a centre–surround phase difference between the L- and M-cones feeding the centre and surround of a given ganglion cell.

**Responses of MC-pathway cells**

Cells were classified as phasic on- or off-centre according to their responses to flashed achromatic and chromatic spots of light and to responses to low luminance contrast. The cells recorded were members of a larger sample reported elsewhere (e.g. Lee et al. 1990). Our sample included thirteen on- and eighteen off-centre cells.
Fig. 7. Amplitude and phase plots of the first harmonic for a phasic on-centre cell as a function of $\theta$, specified relative to the red LED which is defined as having a phase of 0 deg.

- The first harmonic amplitude and phase components obtained from Fourier transform of the stimulus histograms. For clarity, at different frequencies the phase axis has been shifted. The phase of minimum amplitude is displaced from 180 deg at low frequencies.

The continuous line is obtained from a linear vector model described in the text.

Response as a function of relative phase

Figure 6 shows response histograms of a phasic on-centre neurone at three different frequencies as the physical phase, $\theta$, of the two lights was varied, as in Fig. 1. At
2.44 Hz, a response minimum can be seen between 45 and 90 deg. At 9.8 Hz, a first-harmonic minimum near 135 deg can be seen. At 39 Hz, the minimal response is near 180 deg (chromatic modulation). The histograms with the minimum response are indicated by asterisks. A significant response at twice the modulation frequency may be seen in some histograms.

![Graphs showing amplitude and phase plots for different frequencies](image)

Fig. 8. Amplitude and phase plots for a phasic off-centre cell. The format follows that of Fig. 2. The phase of minimum amplitude is displaced from 180 deg at low frequencies, in the same direction as for the on-centre cell.

Amplitude and phase of the first-harmonic response component were retrieved by Fourier analysis, and are plotted as a function of $\theta$ for a phasic on- and a phasic off-centre cell in Figs 7 and 8. The relationships between response amplitude and $\theta$ were similar for on- and off-centre cells, but the relationships between response phase and
\( \theta \) differed considerably, as might be expected. The data are given by the symbols; the continuous lines passing near the points are the results from a model to be described later. Each pair of panels shows data for a different frequency. At high frequency, the maximal amplitude occurs at a physical phase near 0 deg (luminance modulation) and the minimal amplitude near 180 deg (chromatic modulation). At lower frequencies, however, a minimum occurs in the positive \( \theta \) region. This occurs for both the on-centre and the off-centre cell.

These physical phase asymmetries of amplitude response minima were a general feature of both on- and off-centre neurones’ behaviour. To examine this finding more closely, we again determined the axis of symmetry of the amplitude data (Swanson et al. 1987a). The physical phase of least amplitude is plotted for twelve on-centre cells and seventeen off-centre cells in Fig. 9.

The expected physical phase of least amplitude for an achromatic cell should be 180 deg, or counterphase chromatic stimulation. However, on- and off-centre cells showed a physical phase of least amplitude near 90 deg at the lowest frequency of 1.22 Hz, increasing to near 180 deg at intermediate frequencies of 9.76–19.52 Hz. The majority of cells showed a phase of least amplitude greater than 180 deg at the highest frequency of 39.04 Hz. There was some variability among the cells in the amount of phase asymmetry at low frequencies, as can be assessed from the 95% confidence limits associated with the points in Fig. 9. Additionally, two cells (one on-centre and one off-centre of 10 and 8 deg eccentricity) showed stimulus phase minima displaced into the negative \( \theta \) region. In both cases, other tests revealed rod activity even at the 2000 td illuminance. Rod activity is unmistakable in this protocol, since the rod response follows the phase of the green LED. Data for these cells were not included in the average data. At 2000 td, these were the only MC-pathway cells studied showing rod activity. No rod activity was apparent in any of the PC-pathway cells tested.

The phase asymmetries shown in Fig. 9 appeared to be correlated with surround
rather than centre activation. Use of small spot stimuli (0-6 deg) diminished or abolished the changes shown in Fig. 9. A comparison of large-field and small-field data is shown in Fig. 10 for a phasic-on cell at 2000 td, in a format similar to that of Figs 7 and 8. The large-field data are shown by circles, and resemble those in Fig.

![Amplitude and phase plots for a phasic on-centre cell as a function of θ, with the format as in Fig. 2. Data are shown both for a 4.7 deg field (●, continuous line) and for a 0.6 deg field centred in a white surround (■, dashed line). The phase asymmetry is absent with the small field.](image)

7. Data for a 0.6 deg stimulus centred in a ca 20 td white surround are shown as squares. The small-field amplitude data showed no phase asymmetries, the physical phase of minimum sensitivity ranging from 175 to 182.5 deg without dependence on
temporal frequency. The small-field data showed higher amplitudes for the pure luminance, in-phase condition \((\theta = 0 \text{ deg})\) than the large-field data at low temporal frequencies. The 0.6 deg response phase data were linearly related to \(\theta\), except for the abrupt transition at the minimum near 180 deg, with the same slope at all frequencies, and only a vertical displacement as frequency was increased. In addition, response phase values for \(\theta = 0 \text{ deg}\), the in-phase condition, showed a phase retardation of about 45 deg compared with the 4.7 deg data at 1.22 Hz. These details are all consistent with the hypothesis that the 0.6 deg data represent primarily the centre response of the cell.

**Analysis of cell responses**

We have fitted the data to a linear model of the retinal ganglion cell. The first step in implementing the model was to calculate the response of the L- and M-cones to the stimulus.

**The L- and M-cone response**

Human and macaque L- and M-cones absorb light from both the red and green diodes. The amplitude of their expected modulations will depend on \(\theta\). Both cones will show the greatest modulation amplitude when \(\theta\) is zero, the pure luminance stimulus. We calculated the theoretical cone response by using human cone fundamentals (Smith & Pokorny, 1975). We assumed the cone response to be linearly related to absorption. For each diode, each cone response was normalized to the cone’s wavelength of maximum sensitivity and to its contribution to the luminosity function at that wavelength. The individual relative M- and L-cone responses to the red and green LEDs are plotted in the polar sketch of Fig. 11A for a \(\theta\) of 90 deg. The M- and L-cone amplitudes to the red LED are shown on the horizontal axis; those for the green LED at \(\theta\). By vector combination of the L-cone responses to the green \((S_{Lg})\) and red \((S_{LR})\) lights, we obtained the L-cone amplitude and phase as a function of \(\theta\):

\[
L_{\text{amp}} = (S_{Lg}^2 + S_{LR}^2 + 2S_{Lg}S_{LR}\cos \theta)^{0.5},
\]

\[
L_{\text{phase}} = \arctan [S_{Lg} \sin \theta / (S_{LR} + S_{Lg} \cos \theta)].
\]

A parallel calculation may be made for the M-cone amplitude and phase. \(L_{\text{amp}}\) and \(L_{\text{phase}}\) are of course functions of \(\theta\), as shown in Fig. 11B. As expected, the amplitude for either cone alone is greatest for \(\theta = 0 \text{ deg}\), and is smaller to the counterphase stimulus. The phase of response of each cone is displaced toward the physical phase of the light to which the cone is most sensitive. Thus the phase of the L-cone is displaced toward the phase of the red light and that of the M-cone closely follows the phase of the green light. The cones are modulated in phase when \(\theta\) is 0 deg and out of phase when \(\theta\) is 180 deg. In terms of Michelson contrast, 100% chromatic modulation with the lights used corresponded to 68% contrast in the M-cone and 20% cone contrast in the L-cone. Given these expressions for the L- and M-cone amplitudes, we can now combine the cone amplitudes by vector addition to derive a predicted cell response.
The response of a PC-pathway ganglion cell

For red–green cells, we considered two models. In the first, we assumed that centre and surround receive inputs from different cone types (e.g. L-cone centre, M-cone surround). In the second, we assumed that the centre receives input from a single

cone type (L or M) and the surround from a sum of L- and M-cones, as recently suggested by Lennie, Haake & Williams (1991).

Model 1. We assumed that for red–on and red–off cells, the centre receives input from the L-cone and the surround receives input from the M-cone. Conversely, for green–on and green–off cells, we assumed that the centre receives input from the M-cone and the surround receives input from the L-cone. The response of a ganglion cell

Fig. 11. A, a sketch to show vector summation of cone signals for a $\theta$ of 90 deg. B, theoretical amplitude and phase plots for the L- and M-cones. Cone sensitivities were derived from cone fundamentals normalized to their contributions to the luminosity function, and to their $\lambda_{max}$. In this normalization, the L-cone shows much higher amplitude than the M-cone to pure luminance modulation (0 deg). The L-cone absorbs almost equally from both red and green LEDs, so its amplitude is heavily dependent on $\theta$. The M-cone absorbs relatively less light from the red LED, so its amplitude is less dependent on $\theta$. The phase of the M-cone follows closely the phase of the green LED while the phase of the L-cone lies closer to the red LED. The cones are modulated in phase at 0 deg and out of phase at 180 deg. The value of $\theta$ in A, 90 deg, is arrowed.
was predicted by summing the L- and M-cone amplitude vectors. We weighted the cone amplitudes by a single factor \( W \) representing the L/M balance of the cell to give:

\[
L_{\text{w}} = W L_{\text{amp}} \tag{3a}
\]

and

\[
M_{\text{w}} = (1 - W) M_{\text{amp}}. \tag{3b}
\]

This weighting does not affect \( L_{\text{phase}} \) and \( M_{\text{phase}} \). The actual phase of cone inputs to a cell, \( \phi_L \) and \( \phi_M \), are unknown, but may be added to the phases computed from eqn (2). We can thus calculate the relative amplitude, \( R_{\text{amp}} \), and phase, \( R_{\text{phase}} \), of the cell response:

\[
R_{\text{amp}} = \left[ L_{\text{w}}^2 + M_{\text{w}}^2 + 2L_{\text{w}}M_{\text{w}} \cos (L_{\text{phase}} - M_{\text{phase}} + \phi_L - \phi_M) \right]^{0.5}, \tag{4}
\]

\[
R_{\text{phase}} = \arctan \left[ \frac{L_{\text{w}} \sin (L_{\text{phase}} + \phi_L) + M_{\text{w}} \sin (M_{\text{phase}} + \phi_M)}{L_{\text{w}} \cos (L_{\text{phase}} + \phi_L) + M_{\text{w}} \cos (M_{\text{phase}} + \phi_M)} \right], \tag{5}
\]

where the weighted amplitudes, \( L_{\text{w}} \) and \( M_{\text{w}} \), and the relative phases, \( L_{\text{phase}} \) and \( M_{\text{phase}} \), are defined in eqns (1)–(3); all these variables as well as \( C_{\text{amp}} \) and \( C_{\text{phase}} \) (centre amplitude and phase) are functions of \( \theta \).

Equations (4) and (5) define a relative cell amplitude and phase that can be fitted to experimental data which consist of first harmonic spike density and phase. Either phase or amplitude can be fitted. Each requires three free parameters. In fitting phase, the three parameters are \( W, \phi_L \) and \( \phi_M \). In fitting amplitude, the three parameters are \( W \), the phase difference \( (\phi_L - \phi_M) \), and an amplitude scaling factor to convert from \( C_{\text{amp}} \) to the spike density yielded by the Fourier analysis of the response. These parameters may depend on the temporal frequency; eqns (4) and (5) represent only a single temporal frequency.

We chose to fit phase rather than amplitude data. The advantages of choosing phase rather than amplitude included the following. Firstly, individual cells varied considerably in response amplitude, but the phase of response seemed more consistent. Secondly, the phase of response appeared relatively independent of contrast. Thirdly, the amplitude–contrast function of primate ganglion cells is not linear but has been described by a Naka–Rushton saturation function for both MC-pathway cells (Kaplan & Shapley, 1986) and for PC-pathway cells when chromatic modulation is used (Lee et al. 1990). Had we chosen to fit the amplitude data we would have needed to choose an appropriate contrast transfer function. As an additional constraint to the fitting routine, we required the predicted amplitude minimum fall within \( \pm 20 \) deg of that derived from the data.

Phase data for red–green cells were fitted using eqn (5). The majority (98 %) of fits were good with residual mean error (RME) of 4–16 deg per data point. The least-squares solutions do not allow an estimate of the variance of the fit, but we examined the convergence of the fits; in the majority of cases a change in \( \phi_L \) or \( \phi_M \) of \( \pm 5 \) deg or of \( W \) by \( \pm 0.01 \) gave a two-fold increase in the sum of squares. The continuous lines in Figs. 2 and 3 show fits for the red–on and the green–on centre cell. Good agreement between response phase from the Fourier analysis (symbols) and the fitted curves is evident. As can be noted from eqns (3) and (4), the parameters obtained from the fit of the phase data also predict the shape of the amplitude data. We scaled the predicted relative amplitude linearly and show the result as continuous lines; a
logarithmic amplitude axis has been used. The satisfactory prediction of amplitude using parameters from the phase fit demonstrates that the model is acting in a sensible manner. Parameters for the cells of Figs. 2–3 at the different frequencies are given in Table 1, together with RME values. The additional phase lag in the L-cone relative to the M-cone for the green–on cell can be noted; the opposite is so for the red–on cell.

**Table 1. Cone weightings and phases**

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>L/M weight</th>
<th>φ_L (deg)</th>
<th>φ_M (deg)</th>
<th>RME</th>
<th>L/M weight</th>
<th>φ_L (deg)</th>
<th>φ_M (deg)</th>
<th>RME</th>
<th>L/M weight</th>
<th>φ_L &amp; φ_M (deg)</th>
<th>RME</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.22</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
<td>0.31</td>
</tr>
<tr>
<td>2.44</td>
<td>0.32</td>
<td>0.32</td>
<td>0.32</td>
<td>0.32</td>
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<td>0.32</td>
<td>0.32</td>
<td>0.32</td>
<td>0.32</td>
<td>0.32</td>
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</tr>
<tr>
<td>4.88</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
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<td>0.34</td>
<td>0.34</td>
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<td>0.34</td>
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</tr>
<tr>
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<td>0.31</td>
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<td>0.32</td>
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<td>0.32</td>
<td>0.32</td>
<td>0.32</td>
<td>0.32</td>
</tr>
</tbody>
</table>

**Model 2.** For this model where the centre is derived from one cone type and the surround from a mixture of cones, it is convenient to divide the cell response into centre and surround components. We assumed that for red–on and red–off cells, the centre responses reflect L-cone activity as represented in eqns (1) and (2).

\[
C_{\text{amp}} = B(S_{\text{MG}}^2 + S_{\text{LR}}^2 + 2S_{\text{MG}}S_{\text{LR}} \cos \theta)^{0.5},
\]

\[
C_{\text{phase}} = \arctan \left[ \frac{S_{\text{MG}} \sin \theta}{S_{\text{LR}} + S_{\text{MG}} \cos \theta} \right],
\]

where \( B \), the relative centre weighting, is a new parameter and \( C_{\text{amp}} \) and \( C_{\text{phase}} \) are relative centre amplitude and phase. The surround response is derived from L- and M-cones giving equations similar to eqns (4) and (5), except that \( \phi_L \) and \( \phi_M \) are set equivalent and termed \( \phi_S \).

\[
S_{\text{amp}} = (1 - B) [L_{\text{MG}}^2 + M_{\text{LR}}^2 + 2L_{\text{MG}}M_{\text{LR}} \cos (L_{\text{phase}} - M_{\text{phase}})^{0.5},
\]

\[
S_{\text{phase}} = \arctan \left[ \frac{L_{\text{MG}} \sin (L_{\text{phase}} + \phi_S) + M_{\text{LR}} \sin (M_{\text{phase}} + \phi_S)}{L_{\text{MG}} \cos (L_{\text{phase}} + \phi_S) + M_{\text{LR}} \cos (M_{\text{phase}} + \phi_S)} \right],
\]
where the terms are as in eqns (4) and (5) with $\phi_S$ as a free parameter. The value of $W$ now represents the cone weighting of the surround, and we evaluated values from 0.1 to 0.6. A value of 0 is equivalent to Model 1. A value of 0.6 reaches the L/M cone ratio of the Judd (1951) observer. The cell response was then obtained by

$$R_{\text{amp}} = \left( C_{\text{amp}}^2 + S_{\text{amp}}^2 + 2C_{\text{amp}}S_{\text{amp}} \cos (C_{\text{phase}} - S_{\text{phase}}) \right)^{0.5},$$  \hspace{1cm} (10)

$$R_{\text{phase}} = \arctan \left[ \frac{C_{\text{amp}} \sin (C_{\text{phase}}) + S_{\text{amp}} \sin (S_{\text{phase}})}{C_{\text{amp}} \cos (C_{\text{phase}}) + S_{\text{amp}} \cos (S_{\text{phase}})} \right].$$  \hspace{1cm} (11)

Phase data were then fitted using eqn (11) with the three free parameters $\phi_L$, $\phi_S$ and $B$. For green–on and green–off cells, we used a similar set of equations with the M-cone response replacing that of the L-cone in eqn (7). Values of $W$ tested ranged from 0.0 to 0.9. A value of 1 is equivalent to Model 1. The three free parameters are $\phi_M$, $\phi_S$ and $B$.

For green–on cells, adding an M-cone component to the surround still resulted in reasonable fitted solutions (RME < 16 deg). Even for a surround of (0.6L + 0.4M), which represents the Judd (1951) observer, 81% of the solutions were good and the majority were equivalent to those of Model 1. For red–on cells, adding an L-cone component to the surround resulted in reasonable fitted solutions (RME < 16 deg) for a small admixture (0.2L + 0.8M). With larger admixtures of (0.6L + 0.4M), in 50% of the solutions the RME was 2 to 15 times greater than the solutions of Model 1. This result reflects the fact that the luminosity function is dominated by the L-cone, so that a cell with a L-cone centre and a mixed cone surround would show much less chromatic opponency compared with a cell with an M-cone centre and a mixed surround. Thus our data do not support the concept of mixed cone surrounds derived from random sampling of the L- and M-cone populations although some small admixture is not distinguishable from Model 1. Other recent evidence also suggests that surrounds of red–green opponent cells, at least within the central 10 deg, do not receive a mixed M- and L-cone input (Shapley, Reid & Kaplan, 1991).

We conclude that Model 1, with a phase difference between centre and surround, provides a good description of red–green opponent cell behaviour. Parameters from the fits were examined as a function of frequency. Figure 12A shows mean values with 95% confidence bounds for $\phi_L$ and $\phi_M$ plotted as a function of frequency for red–on centre cells and Fig. 12B shows similar data for green–on cells. The phase of the cone signals showed an increasing lag with frequency. The L- and M-cone inputs were approximately 180 deg out of phase at the lowest frequency, consistent with the expected cone-opponent behaviour. As frequency increased, this phase difference altered. These differences between surround and centre phases as a function of frequency, $f$, were well fitted by linear functions (Fig. 12C).

$$\phi_M - \phi_L = -177.74 - 2.681f \text{ (red–on; } r^2 = 0.97),$$

$$\phi_L - \phi_M = -181.62 - 1.425f \text{ (green–on; } r^2 = 0.99),$$

The mean slopes for the red–on cells were driven strongly by the 39.04 Hz data. The results were consistent with the conclusion that there was no systematic difference in slope for red–on and green–on cells, with a centre–surround phase delay of about
1–3 deg Hz$^{-1}$ for both cell groups. If this delay were attributable to a latency difference, it would correspond to 2.8–8.3 ms. Work on the cat retina (Enroth-Cugell, Robson, Schweitzer-Tong & Watson, 1983; Frishman, Freeman, Troy, Schweitzer-Tong & Enroth-Cugell, 1987) has also shown a centre–surround delay of a few milliseconds. The similar findings for the two cell groups implies that any difference in latencies of L- and M-cones must be less than 2 ms.

The L/M cone weightings for the red–green chromatic cells at 1.22 Hz are shown as a histogram in Fig. 12D. The L/M weightings ranged from 0.28–0.41 with considerable overlap between cone weightings for red–on and green–on cells. With the normalization we used, if the cone inputs to a cell were balanced so as to give (at low frequency) no response to luminance modulation, then for our chromaticity of 595 nm a weighting of 0.32 would be expected. The median value was about 0.34. The
data indicate that for red–green chromatic cells, the centre is slightly stronger than the surround. This was true for all red–on cells, the majority of green–on cells and the four off-centre cells.

We looked for any systematic change in L/M cone weighting with frequency, which might reflect differences in centre–surround temporal characteristics. Up to 19.52 Hz, any tendency for the centre mechanism to increase its relative weighting with frequency was apparent in only three of twenty cells. At higher frequencies, as the centre–surround delay became significant, cells lost opponency and the model did not constrain the fit so well. As one result, the L/M ratios at 19.52 Hz and 39.04 Hz were more variable.

**Cone inputs to surrounds of cells with S-cone centres**

Cells with S-cone input to the centre are commonly assumed to receive mixed L- and M-cone input to their surrounds. Our red–green stimuli may be considered a selective surround stimulus for such cells. The model may be used to describe the L- and M-cone inputs to the surrounds. However, the model (Model 1) did not constrain the phase data so well. We therefore added an additional constraint, based on the observation that there was no systematic variation in the axis of symmetry with frequency. This suggested that the L- and M-cone phases must change with frequency in the same way. The fits were rerun with \( \phi_L \) and \( \phi_M \) set equal, reducing the free parameters to two. From fits at 1.22 Hz, we obtained a histogram of the L/M weightings. As shown in Fig. 13B, this was centred around 0.6. This is near the weighting expected from the Judd photopic luminosity function, i.e. for an observer with a 1:6:1 L/M cone ratio. However, there was considerable variation, with cells that appeared L-cone dominant (\( W > 0.8 \)) and others that appeared M-cone dominant (\( W < 0.4 \)). There was no systematic change in L/M weighting with frequency. Thus cells with excitatory S-cone centre input appear to possess mixed L- and M-cone surrounds, with variability in weighting. Fits were not as good as for red–green cells at higher frequencies because response amplitude was low. We
therefore averaged response phase at 0 deg to provide an estimate of the surround phase for blue–on cells. This averaged data is plotted as a function of frequency in Fig. 13A. The shape of the phase-frequency relation is very similar to the fits for the surrounds of red–green cells (e.g. \( \phi_M \) for red–on and \( \phi_L \) for green–on cells, Fig. 12). This suggests the temporal characteristics of the surround are common to all PC-pathway cells.

The response of a MC-pathway ganglion cell

Models of these cells’ behaviour require more complexity. Early descriptions of the cone inputs to these cells suggested that both centre and the surround received summed input of the L- and M-cones (e.g. the Type III cells of Wiesel & Hubel, 1966). With spectral sensitivities of centre and the surround identical, the expected physical phase of least amplitude would be 180 deg (pure chromatic modulation). There would be no shift in phase of least amplitude as a function of frequency, not even a shift proportional to a surround delay, as noted for PC-pathway cells. Further, our calculations for such a cell revealed only small frequency-dependent phase asymmetries if the cone balance of centre and surround differed slightly.

We explored two models for MC-pathway cells. In both, the centre sums L- and M-cones. In the first, the surround is made up of only a single cone type, e.g. the L-cone (cf. de Monasterio & Schein, 1980; Shapley et al. 1991). In the second, the surround includes a chromatically opponent input. Available evidence suggests the centre mechanism sums L- and M-cone activity in a linear manner, and that typically the L/M cone weighting is that of the Judd (1951) observer (Lee et al. 1988; Shapley et al. 1991). We did not have available estimates of individual variability in centre weighting, and as shown below minor alterations in this centre weighting did not significantly affect the models’ behaviour. We therefore held the weighting constant at 0·62 as expected of the Judd (1951) observer. The centre response is given by eqns (4) and (5), with \( W \) set to 0·62 and \( \phi_r \) set equal to \( \phi_M \) and termed \( \phi_C \).

\[
C_{\text{amp}} = B[(0·62L_{\text{amp}})^2 + (0·38M_{\text{amp}})^2 + 2(0·62L_{\text{amp}} \cdot 0·38M_{\text{amp}} \cos (L_{\text{phase}} - M_{\text{phase}}))]^{0·8},
\]

\[
C_{\text{phase}} = \arctan \left[ \frac{0·62L_{\text{amp}} \sin (L_{\text{phase}} + \phi_C) + 0·38M_{\text{amp}} \sin (M_{\text{phase}} + \phi_C)}{0·62L_{\text{amp}} \cos (L_{\text{phase}} + \phi_C) + 0·38M_{\text{amp}} \cos (M_{\text{phase}} + \phi_C)} \right],
\]

where \( C_{\text{amp}} \) and \( C_{\text{phase}} \) represent relative centre amplitude and phase and where the amplitudes, \( L_{\text{amp}} \) and \( M_{\text{amp}} \), and phases, \( L_{\text{phase}} \) and \( M_{\text{phase}} \) are defined in eqns (1)–(3). As there, \( L_{\text{amp}} \), \( M_{\text{amp}} \), \( L_{\text{phase}} \) and \( M_{\text{phase}} \) depend on the physical phase, \( \theta \). As in Model 2, the parameter \( B \) is a centre–surround weighting parameter.

**Model 3.** If the centre sums M- and L-cones as described above and the surround consists of a single cone type, for example the L-cone, surround amplitude and phase are given by

\[
S_{\text{amp}} = (1 - B) (S_{\text{amp}}^c + S_{\text{amp}}^L + 2S_{\text{amp}}^L S_{\text{amp}}^L \cos \theta)^{0·8},
\]

\[
S_{\text{phase}} = \arctan [S_{\text{amp}}^c \sin \theta / (S_{\text{amp}}^L + S_{\text{amp}}^L \cos \theta)],
\]

as in eqns (1) and (2). The resulting cell response is given by eqns (10) and (11) of Model 2. The free parameters were \( B \), \( \phi_C \) and \( \phi_L \). Reasonable fitted solutions (RME
< 16 deg) were obtained at the higher frequencies. At 1.22 Hz reasonable solutions were obtained for only 52% of cells, and in the majority of these the RME was many times greater than obtained with Model 4 described below. Further, for all cells at low frequencies solutions returned gave unreasonable values for centre phase, which was much advanced compared with the small-field data shown in Fig. 10. We therefore rejected this model.

**Model 4.** We were led to consider that the surround of the phasic cell might have chromatic, opponent input. This possibility is consistent with results of Derrington, Krauskopf & Lennie (1984), who found that the elevation of the null plane of MC-pathway cells was much closer to equal luminance when optimal spatial frequency gratings were used instead of full-field stimulation. We assume that the centre sums input from L- and M-cones as described above. The surround receives an opponent signal. In this model, we consider that the centre response is the net non-opponent response representing both centre and achromatic surround activity. When achromatic gratings are used as stimuli (Derrington & Lennie, 1984), MC-pathway cells show some low-spatial frequency attenuation of the responses. This indicates a non-opponent surround mechanism, since an opponent surround would only be activated weakly by an achromatic stimulus. If the surround receives a non-opponent input with the same L+M spectral sensitivity as the centre, this contribution to the surround would subtract from the centre, expressed in the vector model as summation with a phase difference of about 180 deg. The resultant amplitude would be reduced and the resultant phase would be advanced if there were a centre–surround phase difference, as in Fig. 10. In any event, the present model lumps the M+L centre response and any M+L surround contribution into a single term representing the non-opponent response.

The surround opponent responses was derived from typical estimates from PC-pathway cells. In the PC-pathway, red–green chromatic cells take one of four forms: red–on, red–off, green–on and green–off. It was not clear *a priori* which of these four types of opponency might be involved in MC-pathway responses. We therefore evaluated all four.

\[
S_{\text{amp}} = \left[ (0.35L_{\text{amp}})^2 + (0.65M_{\text{amp}})^2 + 2(0.35L_{\text{amp}}0.65M_{\text{amp}} \cos (L_{\text{phase}} - M_{\text{phase}} + \phi_{\text{SL}} - \phi_{\text{SM}})) \right]^{\frac{1}{2}},
\]

\[
S_{\text{phase}} = \arctan \left[ \frac{0.35L_{\text{amp}} \sin (L_{\text{phase}} + \phi_{\text{SL}}) + 0.65M_{\text{amp}} \sin (M_{\text{phase}} + \phi_{\text{SM}})}{0.35L_{\text{amp}} \cos (L_{\text{phase}} + \phi_{\text{SL}}) + 0.65M_{\text{amp}} \cos (M_{\text{phase}} + \phi_{\text{SM}})} \right],
\]
only because of the frequency-dependent phase factor, and similarly for \((M - L)\) and \((-L + M)\). The cell response was computed as a vector sum of the non-opponent and opponent responses, to give relative amplitude, \(R_{\text{amp}}\), and phase, \(R_{\text{phase}}\), terms. This required three free parameters, \(B\), \(C_{\text{phase}}\) and \(S_{\text{phase}}\). \(C_{\text{phase}}\) is dependent on \(\phi_C\). \(C_{\text{phase}}\) at \(\theta = 0\) is the same as \(\phi_C\). The parameter used to vary \(S_{\text{phase}}\) was \(\phi_{SL}\). This parameter varied among the four \(L,M\)-cone opponents, since there is a 180 deg phase difference between a \((L - M)\) and an \((M - L)\) surround as well as the phase delay added to the differencing cones. \(S_{\text{phase}}\) is reported as its value at \(\theta = 0\).

The majority of the fits (over 95%) were good, with the RME less than 16 deg. The continuous lines in the phase plots of Figs 7, 8 and 10 are examples of fits for phasic on-centre and off-centre cells. Good fits were obtained for all four possible opponent contributions, with values of \(B\) and \(C_{\text{phase}}\) showing only minor variation among the four types. However, as expected the values of \(S_{\text{phase}}\) formed two groups, each with minor variation. The \((L - M)\) and \((-M + L)\) surround models showed a different solution set from the \((M - L)\) and \((-L + M)\) surrounds; the significance of these two possible solutions is discussed below. We ran a few test programs varying the \(L/M\) weighting in the centre between 0.62 and 0.72 and the \(L/M\) ratio of the surround between 0.3 and 0.4. These variables had little effect. Good fits were still obtained, although the parameters again showed some minor variation. We did not consider that there were sufficient data to warrant a grid search of all possible parameters, for these parameters would have included the \(L/M\) cone weightings for both non-opponent and opponent contributions, plus the \(L\) to \(M\)-cone phase difference for the opponent contribution.

The best fit values for \(B\), \(C_{\text{phase}}\) and \(S_{\text{phase}}\) were used to approximate the amplitude data with the addition of a linear scaling parameter. These are shown as continuous lines with the amplitude data of Figs 7, 8 and 10. These fits are not intended to be optimal, but indicate that the parameters predict reasonable values for amplitude as well as phase of response.

The three parameters, \(B\), \(C_{\text{phase}}\) and \(S_{\text{phase}}\), returned by the fitting procedure are given in Table 1 for the cells of Figs 7 and 8, and averaged parameters are summarized in Fig. 14. Figure 14A shows the balance, \(B\), plotted against the phase of minimum amplitude at 1.22 Hz. The correlation coefficient of the two variables is 0.8, which is significant at the 0.005 level \((n = 26, t\text{ test})\). Thus, as might be expected, the amount the amplitude minimum is driven from the value of 180 deg expected of a luminance mechanism is a measure of the strength of the opponent contribution. The non-opponent/opponent ratio, \(B\), increased systematically with frequency. We interpret this as reflecting a diminishing strength of the opponent contribution, the opponent surround representing a smaller fraction of the total cell response as frequency increased. This results in a movement of the phase of minimum amplitude toward 180 deg. This behaviour is different from that of PC-pathway cells, which showed little or no change in centre/surround ratio with frequency. Figure 14B shows the values of \(C_{\text{phase}}\) and \(S_{\text{phase}}\) averaged for on-centre cells and plotted as function of temporal frequency, and Fig. 14C shows a similar plot for off-centre cells, for two of the opponent mechanisms tested \((M - L)\) and \((L - M)\); the \((-L + M)\) and \((-M + L)\) solutions are omitted for clarity. The change in phase with frequency is of similar shape to the data for PC-pathway cells, showing that the temporal properties
of the opponent surround resemble those of the PC-pathway. On- and off-centre cells are similar, except for a 180 deg phase shift, though the $S_{\text{phase}}$ terms differed for the (M−L) and (L−M) solutions. We conclude that, to account for the phase asymmetries in MC-pathway cells, it is necessary to postulate an opponent input to the surrounds of these neurones.

**Fig. 14.** A, plot of non-opponent/opponent ratio, derived by fitting individual cell data, against the phase of minimum amplitude. As expected from Fig. 7 and eqns (5)–(7), the stronger the opponent contribution to the surround, the more marked the effect on the phase of minimum sensitivity. B and C, values of the phase solutions from fits for on-centre and off-centre cells respectively, for two of the different types of chromatic surround considered.

**DISCUSSION**

**PC-pathway cells**

We have shown that, as the relative phase of two sinusoidally modulated lights is varied, the responses of red–green chromatic cells can be described by a linear combination of M- and L-cone signals with a small phase difference between them. In the model and data, the opponency of the cells is a strong determinant of response phase. The three fitting parameters determined different aspects of the phase plot.
The phase of the centre cone type ($\phi_L$ for ‘red–ons’ and $\phi_M$ for ‘green–ons’) primarily determines the vertical positioning of the phase data; the phase lag of the surround cone type determines the horizontal positioning of the $\theta$ axis. The L/M ratio affects the overall shape of the phase plot. These features can be seen in Figs 2 and 3.

There was a phase delay of 1–3 deg Hz$^{-1}$ between cone inputs to red–green cells, consistent with a centre–surround latency difference of 3–8 ms. The possibility that such latency differences have a significant effect on primate ganglion cell responses was first proposed by Gouras & Zrenner (1979), but their estimates were much larger than we find here. Their evidence consisted in a broadening in spectral responsiveness of PC-pathway cells at high flicker frequencies at high photopic adaptation levels, which was interpreted in terms of a latency difference between opponent cone inputs to centre and surround. Swanson (1991) pointed out that small latency differences are capable of causing such effects. Values for the centre–surround phase difference correspond closely to estimates based on data from heterochromatic flicker photometry (Lee, Martin & Valberg, 1989b) and agree with estimates from cat X-ganglion cells (Enroth-Cugell et al. 1983; Frishman et al. 1987).

The temporal characteristics of opponent cone input to red–green cells derived here closely resemble those derived from these cells’ responses to white noise (Gießen, van Gisbergen & Vendrik, 1982), who demonstrated a similar time course of centre and surround mechanisms but with a surround delay of several milliseconds. Model 1 for these cells is identical with the straightforward linear model of Derrington et al. (1984) at low frequency, but predicts that, with their stimuli, their model should not suffice at higher frequencies at which the centre–surround phase delay becomes significant. This is the case (B. B. Lee, P. R. Martin & A. Valberg, unpublished observations). We would stress that the phase varying stimulus used here is essentially different from that used by Derrington et al. (1984). These authors manipulated the relative amplitudes of red and green stimulus components (keeping phase constant). We have manipulated the relative phase of the red and green LEDs, keeping their amplitude constant.

We calculated that if the cone inputs were perfectly balanced so as to give no response to luminance (balanced to the time-averaged chromaticity of the red and green LEDs), the expected L/M balance would be 0.32. In comparison with our data, the median normalization reported by Derrington et al. (1984) was about 0.5. This value is close to that expected from the time averaged chromaticity of their white. The essential point is that red–green chromatic cells normalize to near the adaptation chromaticity, as noted earlier by Marrocco & DeValois (1977). The median L/M balance of blue-on cells was about 0.6. This result is consistent with the 1.6/1 ratio derived for human L- and M-cones by fitting psychophysical luminosity data to a sum of M- and L-cone fundamentals (Weisner, Pokorny, Shevell & Smith, 1991 and references therein). Although the microspectrophotometric data of Bowmaker (1991) suggests an L/M ratio of 1.0 for old-world primates other than man, considerable inter-species variability make application of this value to the macaque uncertain. Our data showed considerable inter-cell variability, with cells showing a primarily L-cone surround and cells showing a primarily M-cone surround. Possibly the surrounds of blue-on cells are derived indiscriminately from nearby M- and L-cones.
Are there temporal differences between M- and L-cones?

A temporal difference between the M- and L-cones has been postulated in a number of psychophysical and physiological contexts, although single cone recordings indicate any difference to be slight (Schnapf, Nunn, Meister & Baylor, 1990). Our data showed no clear indication of a significant difference in temporal processing between L- and M-cone inputs to PC-pathway cells. A temporal delay between the cones should have been apparent in several of the data sets described. Firstly, for the surround of the ‘blue-on’ cells, a difference between the cone types should have caused a frequency-dependent phase shift. This was not observed, though our model predicts that a small latency difference would not be resolved (Smith, 1991). Red–green chromatic cells provide a more stringent test. A temporal difference between L- and M-cone signals would have resulted in an asymmetry in the fitted solutions. The ‘slower’ cone should have had a steeper phase-frequency relationship (Fig. 12) compared with the ‘faster’ cone, accompanied by a consistent difference in apparent centre–surround delay, because any temporal difference between the cones would, for different cell types, either add to or subtract from the actual delay. It is also possible that, as temporal filters, the cones could show inherent differences. This would have been revealed by frequency-dependent changes in L/M weighting, in addition to variation in phase as a function of frequency. All these effects were only very weakly apparent and within the range of inter-cell variability. We resolved centre–surround delays of 1–3 deg Hz⁻¹, or 3–8 ms. Thus we conclude that any intrinsic latency difference, if it exists, must be less than the lower limit of 3 ms. In summary, our data suggest that differences in temporal processing between the L- and M-cones must be small, and that the temporal properties of all tonic ganglion cell surrounds are similar.

MC-pathway cells

Both on- and off-centre cells showed at frequencies below about 10–20 Hz a minimal response for positive values of θ (‘red-leads-green’ in the Cushman & Levinson (1983) convention). The experimental results provide a direct physiological parallel of a previously unexplained psychophysical finding. Conversely, the hypothesis linking psychophysical performance on flicker photometry with activity in the MC-pathway receives strong support from this precise correspondence between physiological and psychophysical effects.

Comparison with psychophysical results

Figure 15 shows a comparison of the average phasic cell behaviour (heavy line) with data (symbols and dashed lines) replotted from Swanson et al. (1987a). The psychophysical data represent the stimulus phase at which observers showed minimal modulation sensitivity, and the different curves show the variability observed between three subjects. The psycholgocial data are the means and 95% confidence limits for on- and off-centre cells combined. For the psychophysical data, thresholds at the lowest frequencies (1, 2 and 2·8 Hz) are probably mediated by chromatic mechanisms, based on the symmetry axis of the sensitivity function and the observation that chromatic alternation was clearly visible immediately above
threshold. Thresholds at 4 Hz and above were probably mediated by achromatic mechanisms, again based on the symmetry axis of the U-shaped function, and the observation that chromatic alternation was not perceived near threshold. At and above this frequency, the dependence of phase of least sensitivity on frequency is very similar in the psychophysical and physiological results, suggesting that it is MC-pathway behaviour that is responsible for the phase asymmetries seen in the human psychophysics.

**Implications for receptive field organization**

Response phase and amplitude to our stimulus were well described for ‘red–green’ PC-pathway cells by a simple model. In contrast, the model for the receptive field structure of MC-pathway cells cannot be considered complete. Present evidence suggests that the centre mechanisms of MC-pathway cells add M- and L-cone inputs in a linear manner (Fig. 9; Derrington et al. 1984; Lee et al. 1988; Shapley et al. 1991) with minor variability in L/M cone balance. However, as pointed out in the Results section, the non-opponent term in the model presented above probably represents a linear combination of a centre mechanism and a non-opponent surround. Based on Model 4, we suggest that MC-pathway cells have a chromatic input to the surround. We have assumed that this opponent signal is similar to that seen in ‘red–green’ opponent PC-pathway cells, although not necessarily arising at the same cellular locus. The opponent signal may have \( +M - L \) or \( +L - M \) cone inputs. We may ask which of these are consistent with the results; both provided a satisfactory fit to the data. The two pairs of possibilities reflect a sign change of the surround effect; either
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the opponent contribution inhibits centre activity, or it is excitatory, adding to the centre response. If the opponent contribution is indeed inhibitory, it must consist of a +M−L mechanism for both on- and off-centre MC-pathway cells. Alternatively, a +L−M mechanism might provide direct excitatory input. A differentiation between these possibilities is not directly obvious from the fitted results. Current evidence suggests that horizontal cells of the outer plexiform layer do not carry an opponent signal (Boycott, Hopkins & Sperling, 1987). The opponent surround signal may thus originate in the inner plexiform layer. It is intriguing that both on- and off-centre MC-pathway cells apparently receive the same opponent signal, although their dendritic trees ramify at different levels in the inner plexiform layer (Watanabe & Rodieck, 1989).

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REFERENCES


