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Only two phase mechanisms, ±cosine, in human vision

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Abstract

We evaluated the proposal that there exist detectors of the following four cardinal phases in human vision: +cosine, −cosine, +sine, and −sine. First, we assessed whether there was evidence that these cardinal phases were processed by independent 'labeled lines,' using a discrimination at detection threshold paradigm. Second, we assessed whether suprathreshold phase discrimination was best at phases intermediate between these cardinal values. Third, we tried to replicate previous evidence showing that an absence of facilitation occurs only between cosine pedestals and sine tests (or vice-versa). In all three experimental approaches we found no compelling evidence for four cardinal phase groupings. We did however find evidence for independent detectors for pure increments and decrements (±cosine). We suggest that phase discrimination, whether at threshold or suprathreshold, is mediated by mechanisms that encode the relative positions and contrasts of local increments and decrements within the stimulus.

Keywords: Phase; Labeled line; Bar; Edge

1. General introduction

Our understanding of how the local phase of retinal image features is processed by the human visual system is a longstanding issue that directly bears upon models of visual processing that assume specific phase relations (Kingdom & Moulden, 1992; Marr & Hildreth, 1980; Morrone & Burr, 1990). There have been many attempts to address this question but, for one reason or another, none have provided a definitive answer.

Thirty years ago there was reason to believe that unitary visual mechanisms were spatial frequency narrowband (Blakemore & Campbell, 1969) and that something akin to a Fourier analysis took place (Campbell & Robson, 1968). In studies of phase discrimination, it was commonplace to use either broadband natural images (Brettel, Caelli, Hilz, & Rentschler, 1982) or grating stimuli (Burgess & Ghandeharian, 1984; Burr, 1980; Holt & Ross, 1980; Ross & Johnstone, 1980; Rentschler & Treutwein, 1985) and to manipulate the phase either globally, or of one component relative to another, in order to assess the phase sensitivity of human vision. In the former approach, the global nature of the manipulation was brought into question by the subsequent realization that local rather than global analyses are relevant to the way the retinal image is encoded in V1 (Robson, 1980). In the latter approach, subsequent findings suggested that the results could be re-interpreted more parsimoniously by supposing that the visual system performed a local contrast analysis (Badcock, 1984a, 1984b, 1988). As a consequence, no definitive conclusion could be reached concerning the phase-encoding properties of underlying mechanisms.

In other experiments using compound gratings, one component was fixed at one of various suprathreshold contrasts, while the contrast of the other component was varied until the compound could be just discriminated (Nachmias & Weber, 1975; Stromeyer & Klein, 1974). Such a task was not open to the same local contrast interpretation that successfully accounted for the experiments listed above, where the phase angle between components was varied. In one such example of this latter approach, the contrast for discriminating whether a 3*f* component was

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added in or out of phase to a suprathreshold *f* component was measured (Lawden, 1983). The results were interpreted in terms of a single phase-sensitive, spatial frequency broadband detector. However, these results were later shown to be consistent with a local spatial rather than a phase analysis (Bennett, 1993; Bennett & Banks, 1987; Bennett & Banks, 1991; Burr, Morrone, & Spinelli, 1989; Field & Nachmias, 1984; Hess & Pointer, 1987; Meese, 1995; Tolhurst & Dealy, 1975). This was not the local contrast artifact pointed out by Badcock (1984a, 1984b, 1988) for the earlier variable phase experiments, but nonetheless it did suggest that any simple interpretation of these results in terms of phase processing per se was hazardous at best.

A number of studies have argued for a phase model involving detectors tuned to two or more of four channels, defined by the following phase relations: +cosine, −cosine, +sine, and −sine. A subset of these studies involved detection and discrimination of compound grating stimuli, e.g., $f-2f$ (Bennett, 1993; Bennett & Banks, 1987, 1991; Field & Nachmias, 1984), and are therefore open to the criticism raised above, namely that a more feature-based explanation could account for the results without having to postulate phase-sensitive early detectors. Another subset of the studies arguing for a limited number of phase channels used broadband stimuli such as edges, bars and disks (Burr et al., 1989; Tolhurst & Dealy, 1975; see also Cohn & Lasley, 1985; Kachinsky, Smith, & Pokorny, 2003; Krauskopf, 1980) and against these studies the feature-based alternative explanation is not so easily leveled. Apart from Burr et al. (1989), these studies considered whether opposite polarity bars, and in the case of Tolhurst and Dealy (1975), also opposite polarity edges, could be discriminated at threshold. The rationale behind the detection/discrimination paradigm is that if discrimination is possible at detection threshold, then there exists independent 'labeled lines' for the discriminants (Furchner, Thomas, & Campbell, 1977; Thomas, 1985; Thomas, Gille, & Barker, 1982; Watson & Robson, 1981). With respect to phase, this means independent labeled lines for opposite-polarity phases. The studies using this paradigm have not however provided consistent results, and in the discussion we will allude to some methodological issues that might explain the inconsistencies. Suffice to say that for the purposes of determining whether there exist *four* independent labeled detectors for phase, a critical test is whether edge-like and bar-like stimuli can be discriminated at threshold, and to our knowledge this test has never been conducted. Our first experiment provides such a test.

The Burr et al. (1989) study is arguably the only study using broadband edges/bars that has provided evidence for the existence of *four* independent phase detectors. Burr et al. found that for discriminating opposite-polarity increments in the presence of pedestals, pedestals failed to facilitate discrimination if they were of a different cardinal phase from the increment pair, whereas pedestals and increment pairs that fell between the cardinal phases did produce facilitation.

In the present study, we sought to find evidence for phase-specific processes underlying perception. In particular, we ask two questions: 1, are there *independent* phase detectors; and 2, are there *four* phase detectors at phases +cosine, −cosine, +sine, and −sine. One needs to consider these two questions separately because the one does not necessarily follow from the other. It is possible that there exist four phase detectors, but because their phase tunings are broad and overlapping they are not independent. In the first experiment, we focus on the question of independence by determining whether cardinal phase stimuli can be discriminated at detection threshold. In the second and third experiments, we focus on the question of whether there are just four cardinal phase detectors. In the second experiment, we measure discrimination of small phase differences in suprathreshold patterns. The prediction from the four-phase-detectors hypothesis is that subjects should be best able to discriminate small phase differences for phases that fall *between* the cardinal values, as this is where the cardinal phase detectors have optimal differential sensitivity. In the third experiment, we attempt to replicate the study that has arguably provided the best evidence for four cardinal phase mechanisms, namely that of the Burr et al. (1989) study described above.

2. Experiment 1—Threshold discrimination

2.1. Introduction

To assess whether there exist independent cardinal phase detectors we employed a well-accepted paradigm of measuring discrimination at detection threshold. In the present case, this involved asking subjects to discriminate the phase of spatially localized stimuli of different bandwidths at detection threshold. This technique, which was previously used to study the spatial (Hess & Nordby, 1986; Watson & Robson, 1981), temporal (Hess & Plant, 1985; Watson & Robson, 1981) and chromatic (Mullen & Kulikowski, 1990) mechanisms of human vision, is based on the notion of 'labeled' lines. If stimulus A can be discriminated from stimulus B at their respective detection thresholds, then it is assumed that there are at least two independent, labeled mechanisms, one for detecting A, the other for detecting B. This method has been used to identify the number of mechanisms underlying our spatial, temporal and chromatic perception and, depending on certain model assumptions, to estimate their spatial bandwidths (Thomas et al., 1982).

We used this paradigm to determine whether there exist independent detectors of four cardinal phases (i.e., +cosine, −cosine, +sine, and −sine). Since the spatial luminance bandwidth of putative phase-tuned mechanisms is unknown, although thought by some to be broadband (Bennett, 1993; Bennett & Banks, 1987, 1991; Burr et al., 1989; Lawden, 1983; Tolhurst & Dealy, 1975), we used three different types of stimuli: single, multi-component stimuli, and Gaussians. The single component stimuli were Gabor patches of two different centre frequencies (0.5 and

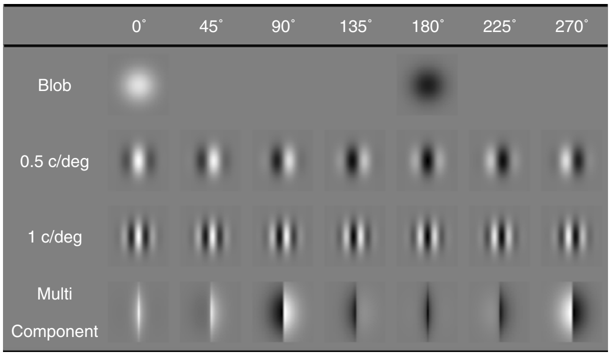

Fig. 1. Stimuli. Three different types of stimuli of different phase angle used in the experiments.

1 c/deg) and bandwidths. The multi-component stimulus comprised 256 cosine harmonics, whose amplitude varied inversely with frequency. The Gaussians by definition could only be of two phases, +cosine and −cosine, and can be considered examples of ‘pure’ increments and decrements, since their pixels are only of higher or lower luminance than the background. The stimuli are depicted in Fig. 1.

2.2. Methods

2.2.1. Apparatus

The stimuli were presented on an Electrohome (Retro III) back-projection CRT monitor (138 cm by 104 cm). The projector was controlled by the VSG2/5 graphics card (Cambridge Research Systems), which had 15 bits contrast resolution. The projector was gamma corrected. The screen resolution was 1024×768 pixels with frame rate of 120 Hz and the screen mean luminance was 67 cd/m^2.

2.2.2. Subjects

Four observers were used in this experiment and all were experienced psychophysics observers with normal or corrected-to-normal vision.

2.2.3. Stimuli

Three types of stimuli were used in this experiment, and are illustrated in Fig. 1. The first was a Gaussian blob, defined by the following isotropic Gaussian function:

$$L(x,y) = L_0 \pm C \cdot \exp[-(x^2 + y^2)/2\sigma^2], \tag{1}$$

where L_0 is background luminance (67 cd/m^2), C contrast and σ the standard deviation of 0.36 deg. The ± symbol defined the polarity of the blob, i.e., whether it was an increment or decrement.

The second stimulus was a vertically oriented Gabor, whose luminance profile $L(x,y)$ was defined by the equation

$$L(x,y) = L_0 + C \cdot \cos(2\pi x/T - \rho) \cdot \exp[-(x^2 + y^2)/2\sigma^2] \tag{2}$$

L_0 and σ were the same values as used with the Gaussian blob. T was the period of the carrier, and ρ the phase of the stimuli with respect to the center of a Gaussian window. The spatial frequencies used were 1 and 0.5 c/deg, and σ was 0.36 deg. x varied between $-4.5T$ and $+4.5T$ for 1 c/deg, and between $-2.25T$ and $+2.25T$ for 0.5 c/deg.

The third stimulus was a multi-component, broadband stimulus, adopted from Burr et al. (1989). The stimulus comprised 256 cosine harmonics. The amplitudes were first set to be inversely proportional to frequency, then multiplied by a Difference-of-Gaussian (DoG) function to attenuate smoothly both the high frequencies to avoid ringing, and the low frequencies that could provide luminance cues for discrimination. Finally, the stimulus was multiplied by a two-dimensional, isotropic Gaussian envelope. The full equation for the luminance profile $L(x,y)$ is given by

$$L(x,y) = L_0 + a\sum_{k=1}^{256} \cos(2\pi kx/T - \rho) \cdot \mathrm{DoG}(k)/k \cdot \exp[-(x^2 + y^2)/2\sigma^2], \tag{3}$$

where k is an odd integer, L_0 mean luminance, a amplitude (related to contrast—see below), T the period of the first harmonic, ρ phase and σ the standard deviation of the Gaussian envelope. The Difference-of-Gaussian function was

$$\mathrm{DoG}(k) = \exp(-k^2/2\sigma_1^2) - \exp(-k^2/2\sigma_2^2), \tag{4}$$

where σ_1 and σ_2 are the space constants of the two Gaussian components, set to 128 and 4 cycles/period, respectively, as in Burr et al. (1989).

In Eq. (3), T was set to 512 pixels, or 18.3 deg at the viewing distance of 208 cm. When the stimuli are generated in the range $x = -T/16$ to $+T/16$, a single ‘feature’ is observed at the centre of a stimulus window that is 64 pixels, or 2.3 deg wide. Any hard edges at the sides of the window were removed by the Gaussian envelope centred on the feature, which had a σ of 16 pixels, or 0.57 deg. The parameter ρ in Eq. (3), which controls the phase of alignment of the cosine harmonics, determined the phase of the feature. ρ values of 0°, 90°, 180°, and 270° produced a bright bar, a dark-bright edge, a dark bar and a bright-dark edge, respectively. Intermediate phases (45°, 135°, and 225°) produced features that can be considered hybrids of edges and bars. The amplitude parameter a was adjusted to produce features with the required Michelson contrast, defined as the difference divided by the sum of the peak and trough luminance.

2.2.4. General procedure

A temporal, two-alternative forced-choice (2AFC) technique, with feedback, was used along with the method of constant stimuli. Each stimulus was presented for 1000 ms, with contrast modulated by the Gaussian envelope with a σ of 250 ms. The observers were asked to indicate whether the stimulus was presented in the first or second interval, and to also indicate the phase of the stimulus. The absolute position of the stimuli around the midpoint was varied randomly in the range of 1 deg for the Gaussian blob, in the range T, or one cycle for the single component, and $T/25$, or 0.72 deg for the multi-component stimuli, in order to reduce location cues.

In each run, one pair of phase angles was compared. For the Gaussians, the white and black blob were paired. For the other two stimuli, there were 5 pairs in the experiment: 0° vs. 180°; 90° vs. 270°; 45° vs. 225°; 45° vs. 135°; 0°, 180° vs. 90°, 270° (meaning 0° or 180° vs. 90° or 270°). The first 3 pairs differed by 180° whereas the last two differed by 90°. For each run, at least 45 trials were collected for each contrast level for each phase angle.

2.2.5. Analysis

The rationale of the experiment is that if the mechanism underlying phase discrimination is the same for both forced-choice phases, the psychometric functions for detection and discrimination performance should be identical. The resulting function describing proportion correct can be described as

$$P(\text{correct}|S) = \gamma + (1-\gamma)\omega_c(S, \alpha_c, \beta_c), \quad (5)$$

where γ represents the guessing parameter, and $\omega_c(S, \alpha_c, \beta_c)$ represents the Weibull function with threshold α_c and slope parameter β_c. Therefore, in the detection task, because the guessing rate is 0.5, the equation is thus

$$P(\text{correct}|S) = 0.5 + (1-0.5)\omega_{\text{det}}(S, \alpha_{\text{det}}, \beta_{\text{det}}). \quad (6)$$

In the discrimination task, the effect of response bias was averaged out by combining the data from the two discrimination curves. Therefore, the response bias is also 0.5, and the resulting function can be described as follows:

$$P(\text{correct}|S) = 0.5 + (1-0.5)\omega_{\text{dis}}(S, \alpha_{\text{dis}}, \beta_{\text{dis}}). \quad (7)$$

To test the equivalence of the mechanisms underlying detection and discrimination, we tested the equivalence of α_{det}, α_{dis}, and β_{det}, β_{dis}. Two models were compared. In Model 1, we assumed that α_{det} is equal to α_{dis}, and β_{det} is equal to β_{dis}, whereas in Model 2, we assumed that the four parameters are different. The resulting equations are:

Model 1:

Detection:
$P(\text{correct}|S) = 0.5 + (1-0.5)\,\omega_c(S, \alpha_c, \beta_c)$

Discrimination:
$P(\text{correct}|S) = 0.5 + (1-0.5)\,\omega_c(S, \alpha_c, \beta_c)$

Model 2:

Detection:
$P(\text{correct}|S) = 0.5 + (1-0.5)\,\omega_{\text{det}}(S, \alpha_{\text{det}}, \beta_{\text{det}})$

Discrimination:
$P(\text{correct}|S) = 0.5 + (1-0.5)\,\omega_{\text{dis}}(S, \alpha_{\text{dis}}, \beta_{\text{dis}})$

Model 1 required the estimation of 2 parameters: α_c and β_c while Model 2 required the estimation of 4 parameters: α_{det}, β_{det}, α_{dis}, and β_{dis}. The test statistic used was:

$$\lambda = -2\log_e[L(\boldsymbol{\chi}|\alpha_c, \beta_c)/L(\boldsymbol{\chi}|\alpha_{\text{det}}, \beta_{\text{det}}, \alpha_{\text{dis}}, \beta_{\text{dis}})], \quad (8)$$

where $L(\boldsymbol{\chi}|\alpha_c, \beta_c)$ represented the likelihood of the entire set of responses (χ) in the testing condition under Model 1, with maximum-likelihood estimates of the 2 parameters α_c, β_c. $L(\boldsymbol{\chi}|\alpha_{\text{det}}, \beta_{\text{det}}, \alpha_{\text{dis}}, \beta_{\text{dis}})$ is the same concept. When the null hypothesis (Model 1) is a subset of or a special case of the alternative hypothesis (Model 2), λ is distributed according to χ^2 distribution with q degrees of freedom under the null hypothesis, where q is the difference in the number of free parameters between the general and restricted hypotheses. In this case, the number of degrees of freedom is 2. If λ is larger than 5.991 (χ^2, $df = 2$, $\alpha = 0.05$), then the null hypothesis, which states the α_c, β_c values are the same for the detection and discrimination tasks, can be rejected.

2.3. Results and discussion

The results for this experiment are shown in Figs. 2–5. In all these Figures, the ratio of α_{dis} to α_{det}, and that of β_{dis} to β_{det}, which were derived from Model 2, is plotted. This statistic (Prins & Kingdom, 2003) tests which of two models is supported: Model 1, which assumes that a common mechanism underlies both detection and discrimination, or Model 2, which assumes there are separate mechanisms. The symbol # represents statistical significance for rejecting Model 2, indicating that discrimination was possible at detection threshold and that Model 1 is supported.

The Gaussian data are shown in Fig. 2. It can be seen that 3 out of 4 subjects (the exception was RH) could discriminate the white from the black Gaussians at detection threshold. Thus for the Gaussians we find evidence for independent ±cosine, labeled detectors at threshold.

Fig. 3 shows the 0.5 c/deg, 3 octave Gabor data for four subjects. The relationship between detection and discrimination is shown for the following stimulus pairs: 0° vs. 180°; 90° vs. 270°; 0°, 180° vs. 90°, 270°; 45° vs. 225° and 45° vs. 135°. The data shows that these phase pairs cannot be discriminated at detection threshold for three out of four subjects. Only one subject (RW) was able to discriminate the 0° vs. 180° and 90° vs. 270° condition at threshold. However, no subject was able to discriminate the 0°, 180° vs. 90°, 270° condition at threshold. Performance on this comparison was consistently poor across subjects. The performance found for two non-cardinal phase pairs (i.e., 45° vs. 225° and 45° vs. 135°) where the phase difference is either 180° or 90° are shown for comparison purposes.

Fig. 4 displays results in a similar way for the 1 c/deg Gabors with bandwidth 1.5 octaves. A similar set of phase values are compared and the conclusions are similar to that

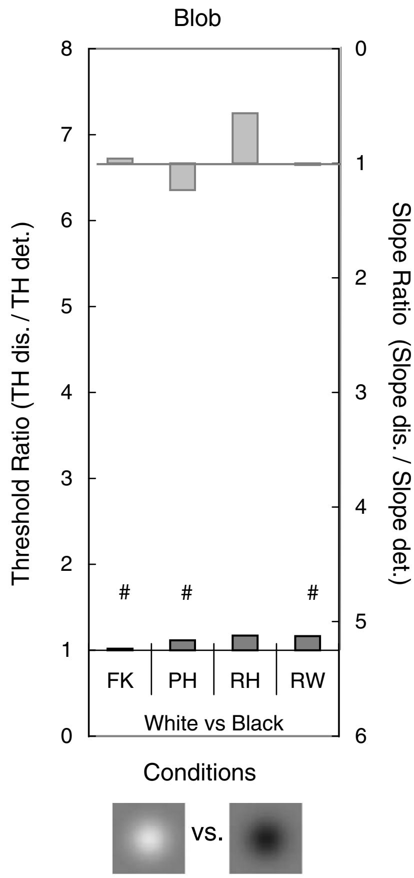

Fig. 2. Results for Experiment 1 using Gaussian blobs. The left axis is defined as the ratio of the discrimination threshold to the detection threshold and the threshold data are shown as the dark gray bars. The right axis is defined as the ratio of the discrimination slope divided by the detection slope and the slope data are shown as the light gray bars. The symbol # indicates that the psychometric functions for detection and discrimination are not significantly different ($p \geqslant 0.05$).

of the broader bandwidth stimulus (Fig. 3). None of these phase pairs could be consistently discriminated at threshold for our 4 subjects. Again, particularly poor performance was found for the 0°, 180° vs. 90°, 270° comparison.

The results for the edge and bar compound stimuli are shown in Fig. 5 plotted in the same way as previous figures. Two of the four subjects could successfully discriminate edges of different polarity but no subject could discriminate either bars of different polarity or bars from edges. This latter discrimination was again particularly poor.

An expectation of a system in which there are independent, labeled detectors tuned to one of four cardinal phases (e.g., +cosine, −cosine, +sine, −sine) would be that only stimuli with these phase values can be discriminated at threshold. Our detection/discrimination results show that for Gabor and edge/bar stimuli this is not the case. In only isolated instances could stimulus polarity be discriminated at threshold (e.g., RW for even and odd Gabors and for edges; PH for edges). A very consistent finding across stimulus types was that 0° vs. 90° or bar/edge discrimination was never possible at detection threshold. The only evidence for independent phase mechanisms came from the detection/discrimination of opposite-polarity Gaussians.

It is important to remember that a failure to demonstrate independence at threshold for cardinal phase stimuli does not rule out the possibility that there nevertheless exists four cardinal phase mechanisms. As we stated in Section 2.1, a demonstration of non-independence does not rule out the possibility that four phase mechanisms exist with broad, overlapping phase tunings. In the next two experiments we therefore concentrate on the issue of whether there exist just four cardinal phase detectors.

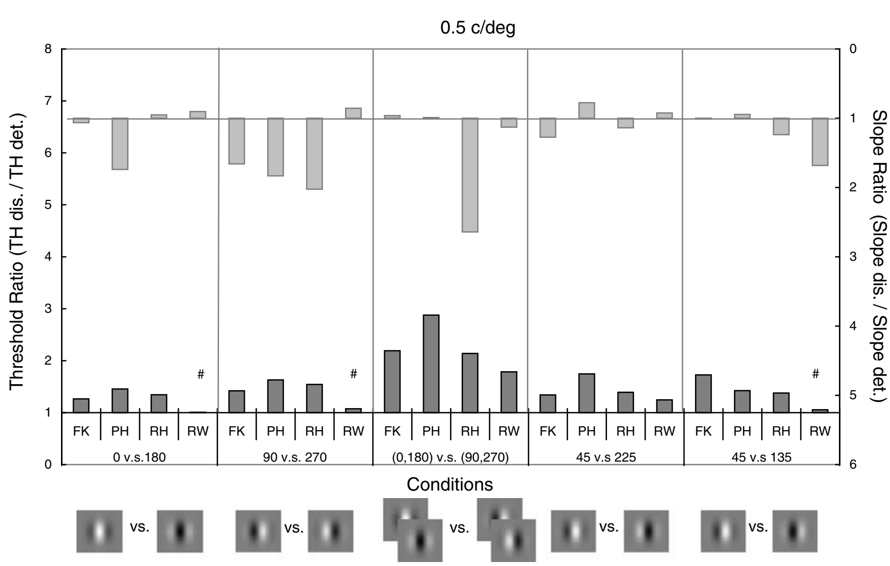

Fig. 3. Results for Experiment 1, 0.5 c/deg Gabors.

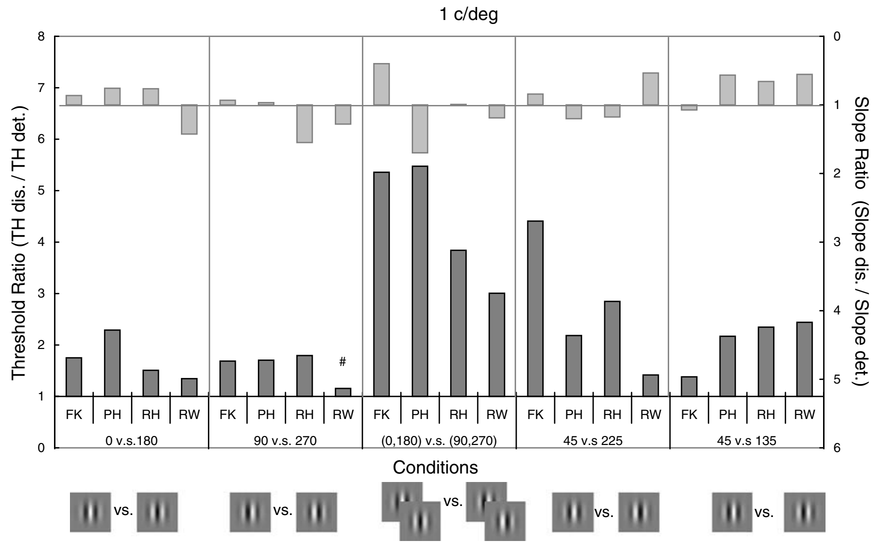

Fig. 4. Results for Experiment 1, 1 c/deg Gabors.

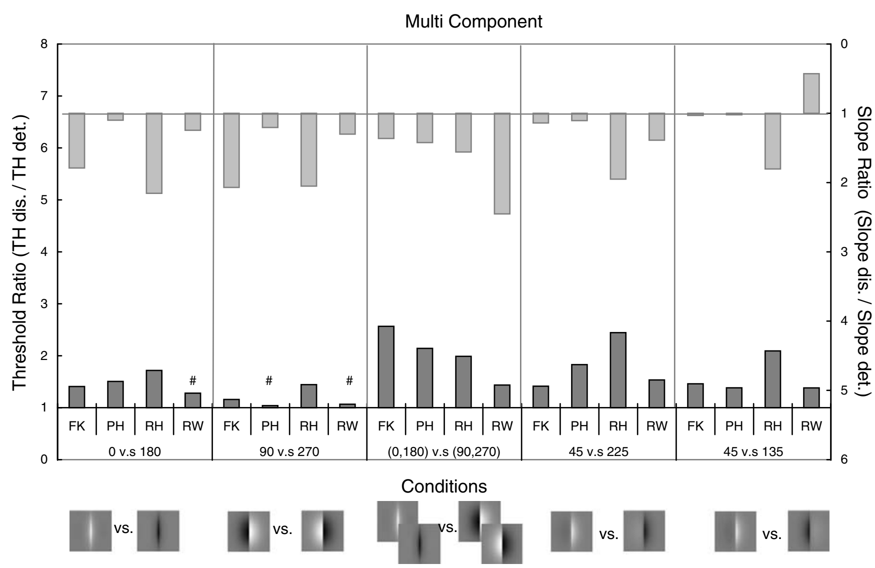

Fig. 5. Results for Experiment 1, multiple component stimuli.

3. Experiment 2—Suprathreshold discrimination

3.1. Introduction

If detectors are tuned to one of the four cardinal phases described above, one would expect that discrimination will be best where the rate of change in their relative response functions is maximal, corresponding to the regions of the phase spectra equidistant between the cardinal poles. To illustrate the idea, we performed a simple simulation, and the results are shown in Fig. 6. The solid lines in the figure show the maximum responses of an even (0 deg) and an odd (90 deg) Gabor filter to Gabor stimuli of different phases. The filters were matched in profile to the even and odd stimuli employed in the present experiment (see below). The maximum responses were obtained by taking the peak output of a linear convolution of filter and stimulus. The dotted line plots the derivative, or slope, of the *difference* between the two filter response functions. This was calculated by taking the difference in filter response $D(i)$ where $i = $ phase, and for each i calculating $D_{i+6} - D_i$. The unit of 6 is the phase range over which the average slope at each point was calculated, and was used instead of 1 to reduce the local ripples in the function. The dotted line peaks at the intermediate phase angle of 45 deg; this is the phase at which the relative outputs of the two cardinal phase filters have the steepest slope, and where one would therefore expect discrimination to be at its best. This is the prediction tested in the present experiment.

To avoid the local contrast cues identified in previous suprathreshold phase discrimination experiments (Badcock, 1984a, 1984b, 1988; Hess & Pointer, 1987) we used horizontally oriented single component Gabor stimuli arranged in a vertical column, jittered in their contrast (as

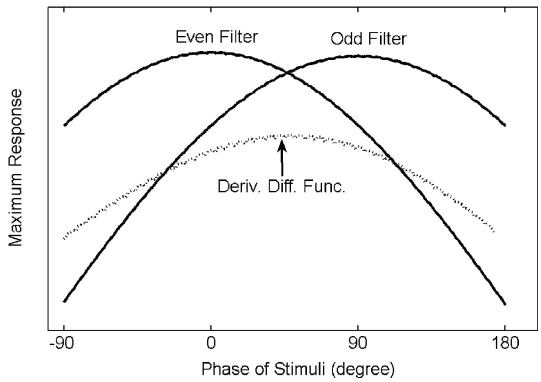

Fig. 6. Prediction for phase discrimination based on the four-cardinal-phase model. The two continuous lines show the peak responses of an even and an odd Gabor filter to Gabor stimuli of different phase. The dotted line shows the derivative, or slope, of the *difference* between the even and odd filter lines. The derivative-of-difference function predicts maximum sensitivity to phase differences at phases intermediate between the cardinal phases. See text for further details.

in the studies of Bennett, 1993; Bennett & Banks, 1991) in a three spatial alternate, 'odd-man-out' paradigm. These refinements ensured that (1) judgements were not made on the absolute luminance or contrast of image features and that (2) an accurate knowledge of the luminance template was not required.

3.2. Methods

3.2.1. Apparatus

For this experiment and Experiment 3 described below the stimuli were generated by a VSG2/3 graphics card housed in a Pentium 4 computer and displayed on a Barco Calibrator monitor. Gamma non-linearity was corrected after measuring the luminance response of the monitor with an Optical photometer.

3.2.2. Stimuli

Each stimulus comprised a column of three horizontally oriented Gabors. The Gabors had a spatial frequency of 1.0 c/deg at the viewing distance of 100 cm, and a bandwidth of 1.5 octaves. The Gabor window was clipped at 5σ. Centre-to-centre Gabor separation was 2 deg. For each stimulus two of the Gabors had identical phase, and the third, the 'odd-man-out' (randomly selected), a different phase. The two different phases represented within each stimulus column were symmetrical about a baseline phase, and had a specified test phase difference. For example, if the baseline phase was 60°, and the test phase difference 30°, the two phases in the stimulus were $60° - 15° = 45°$ and $60° + 15° = 75°$. The baseline phases were 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°, and the test phase differences 15°, 30°, 45°, 60°, 75°, and 90°. In order to minimize the possibility that subjects based their judgments on a cross-Gabor comparison of local luminance, the contrast of each Gabor was randomly selected from a range of 0.4 centred on a mean contrast of 0.5.

3.2.3. Procedure

On each trial a column of Gabors was presented in the middle of the screen, and the task for the subject was to select the Gabor whose phase was different from the other two, recording their decision with a key press. There was no time limit, although subjects were encouraged to spend no more than about seven seconds on each trial. During each session each condition was shown once, making a total of 48 trials per session (8 baseline phases and 6 test phase differences). The order of conditions within a session was random. Each subject performed 7 sessions, and the proportion correct for each baseline phase and each test phase-difference calculated.

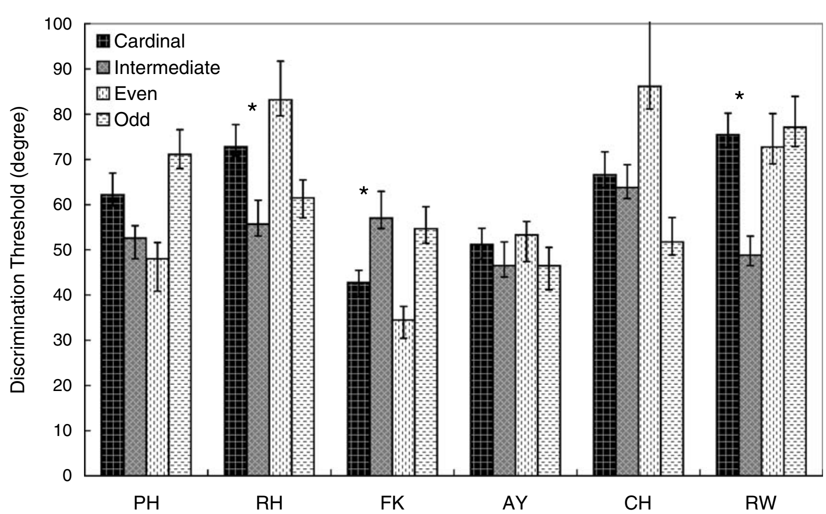

Fig. 7. Results for Experiment 2, suprathreshold phase discrimination. Cardinal conditions represent the baseline phase angles of 0°, 90°, 180°, and 270°. The intermediate conditions represents baseline phase angles of 45°, 135°, 225°, and 315°. Even conditions represent 0°, 180° and Odd conditions represent 90°, 270°. The error bars represent one standard deviation. A star means the threshold for the Cardinal and Intermediate conditions are significantly different ($\alpha = 0.05$).

3.3. Results and discussion

Weibull functions were fitted to the proportion correct data, using the formula $0.333 + 0.667 * (1 - \exp(-(x/\alpha)^\wedge\beta))$, with α and β free parameters, and the threshold determined at the 83.33 % correct level. The results are shown in Fig. 7 for cardinal (0°, 90°, 180°, 270°), intermediate (45°, 135°, 225°, 315°), even (0°, 180°) and odd (90°, 270°) baseline phases. The error bars are standard deviations obtained from a bootstrapping procedure (Wichmann & Hill, 2001a, 2001b). The stars on the histogram bars indicate that the thresholds for the cardinal and intermediate conditions are significantly different at the 95% confidence interval.

The expectation that performance would be better at the intermediate baseline phases and worse at the cardinal phases was not found to be the case, except for two of our six subjects (RW, RH), with one subject (FK) showing a significant difference in the opposite direction. There was therefore no consistent pattern of discrimination performance across baseline phase for our subject group.

4. Experiment 3—Subthreshold summation

4.1. Introduction

In the two previous experiments, we did not find evidence that odd- and even-symmetric (or edge-like and bar-like) phases were 'special,' except for the even-symmetric Gaussian blobs. This raises the question as to why previous studies did find unique behavioural properties for odd- and even-symmetric phases (Bennett, 1993; Bennett & Banks, 1987, 1991; Burr et al., 1989; Field & Nachmias, 1984; Tolhurst & Dealy, 1975). Of these studies, the most compelling is arguably that of Burr et al. (1989). Using broadband stimuli like those illustrated in Fig. 1, Burr et al. tested the idea that odd- and even-symmetric phases were detected by independent mechanisms, and that intermediate phases were detected by combining odd and even signals. They employed a version of the conventional 'pedestal + test' paradigm, in which one measures the amplitude threshold of a test in the presence of various amplitudes of a pedestal (or mask). If at subthreshold levels of the pedestal, thresholds for the test are lower than when the test is presented alone—revealed in the well known 'dipper' function most commonly associated with contrast discrimination data (Foley, 1994; Foley & Legge, 1981; Legge & Kersten, 1983; Ross & Speed, 1991)—this indicates that pedestal and test are detected by the same mechanism.[1] On the other hand, the absence of a dipper indicates that pedestal and test are detected by different mechanisms. Burr et al. (1989) also measured thresholds for a test as a function of pedestal contrast, but in their experiment the subject discriminated polar opposites of the test, rather than detect its presence. Burr et al. found that when the pedestal was 0° and the test 90° vs. 270° (i.e., the pedestal was a bar and the test, two opposite-polarity edges), or when the pedestal was 90° and the test 0° vs. 180° (the pedestal was an edge and the test, two opposite-polarity bars) there was little or no dipper, suggesting independent mechanisms for these bar- and edge-like stimuli. However when the pedestal was 315° and the test 45° vs. 225° (all three features were intermediate between edges and bars) a marked dipper was observed, suggesting that the three stimuli were processed by the same mechanism. Burr et al. concluded that there were separate mechanisms for processing edges and bars, but intermediate-phase features were processed by the combined activation of these cardinal mechanisms.

In our experiment, we decided to plot pedestal contrast in terms of multiples of detection threshold. We wanted to be able to distinguish between a dipper that was subthreshold (in terms of the pedestal), and a dipper that was supra-threshold. It has been argued that the presence of a dipper in *just* the suprathreshold pedestal region is not indicative of a common mechanism for detecting the pedestal and test, as it may be caused by a reduction in the positional uncertainty of the test, the idea being that the subject "knows where to look" when the pedestal is visible (Mullen & Losada, 1994).

4.2. Methods

4.2.1. Stimuli

Our stimuli were the same as used by Burr et al. (1989) except for two modifications. First, we used the single-discontinuity stimulus illustrated in Fig. 1. Second our stimuli were presented in a Gaussian temporal window with SD 100 ms clipped to produce an overall exposure time of 500 ms. We did not however use the two-dimensional Gaussian envelope used in Experiment 1, in keeping with Burr et al. (1989). Stimulus height was 1 deg at the viewing distance of 286 cm. The first harmonic was 0.25 c/deg. Finally, for each stimulus presentation the position of the single discontinuity was randomly jittered around the mid-point of the stimulus window within a range of $T/16$ or 0.25 deg. Stimulus contrast was defined in terms of multiples of detection threshold, and the pedestal contrasts employed were: 0.0, 0.25, 0.5, 1.0, 2.0, 4.0, 8.0, and 16.0.

Following Burr et al. (1989) the pedestal-test combinations were: pedestal 0°, test 90° vs. 270°; pedestal 90°, test 0° vs. 180°; pedestal 315°, test 45° vs. 225°.

4.2.2. Procedures

4.2.2.1. Polarity discrimination thresholds. A two-up one-down staircase procedure was employed to establish the

[1] The precise cause of the dipper function is a matter of debate, and is believed to be due either to a threshold (i.e., accelerating) transducer nonlinearity (Kachinsky et al., 2003) or a reduction in the uncertainty of the channel, or channels sensitive to the stimulus (Pelli, 1985). However, irrespective of the cause of the dipper, it is generally assumed that it is a signature of a common pedestal/test mechanism.

contrast threshold for polarity discrimination at the 70.7% correct level. On each trial there were two intervals, one interval containing one polarity of the test, the other interval the opposite test polarity. The stimuli were presented in forced-choice pairs with an inter-stimulus-interval of 100 ms. The subject pressed a key to indicate which of the two test stimuli was the target, which they had learnt during numerous practice trials.

For each test session the pedestal contrast was randomly selected from the set, and the contrast of the test pair set to about three times threshold to ensure subjects had sufficient exposure to the test pair at the start of the staircase to establish a strategy before the test reached threshold. During the staircase the test contrast was increased or decreased by a factor of 1.3. After 11 reversals of the staircase the session was terminated and the contrast threshold calculated as the geometric mean contrast over the last 8 reversals. Four thresholds were measured for each condition, and the geometric mean and standard error calculated.

4.2.2.2. Contrast detection thresholds. The same staircase procedure was used to establish the contrast detection threshold for each of the pedestal stimuli employed in the main experiment (0°, 90°, and 315°). On each trial one interval contained a test, the other a blank, and the subject indicated which interval contained the test.

4.2.3. Analysis

The data points were fitted by the 4th polynomial equation: $Y = a_1 + a_2 * X + a_3 * X^2 + a_4 * X^3 + a_5 * X^4$, where Y was equal to $\log(\boldsymbol{y})$, X was equal to $\log(\boldsymbol{x})$. $\boldsymbol{y}$ represented the normalized discrimination threshold, defined as the threshold with the pedestal divided by the threshold without the pedestal. x represented normalized pedestal contrast, defined as the contrast of pedestal divided by the detection threshold of the pedestal. A $\boldsymbol{y}$ value below 1 means less contrast was needed to detect the test in the presence of the pedestal compared to when the test was presented alone. For statistical evaluation, a facilitation index for each condition was calculated, and this is illustrated in Fig. 8. The facilitation index was defined as the average difference between the value of $\boldsymbol{y}$ and 1 in the region where $\boldsymbol{y} < 1$, as shown by the shaded area in the figure. The lower $\boldsymbol{x}$-axis bound was a vertical line from the lowest X value (point A). The upper $\boldsymbol{x}$-axis bound (point B) was obtained by solving the inverse of the polynomial for $\boldsymbol{y} = 1$ (or $\log(\boldsymbol{y}) = 0$). The area above the curve was then divided by the $\boldsymbol{x}$-axis range, given by subtracting the $\boldsymbol{x}$-axis value at point A from that at point B. The result was the facilitation index. If there was no positively accelerating crossing point for the data at point B, the area was given a zero value. A second facilitation index for just the subthreshold pedestal region was calculated from point A to $\boldsymbol{x} = 1$. Both facilitation indices were used with the test statistic, a within subjects, one-way ANOVA.

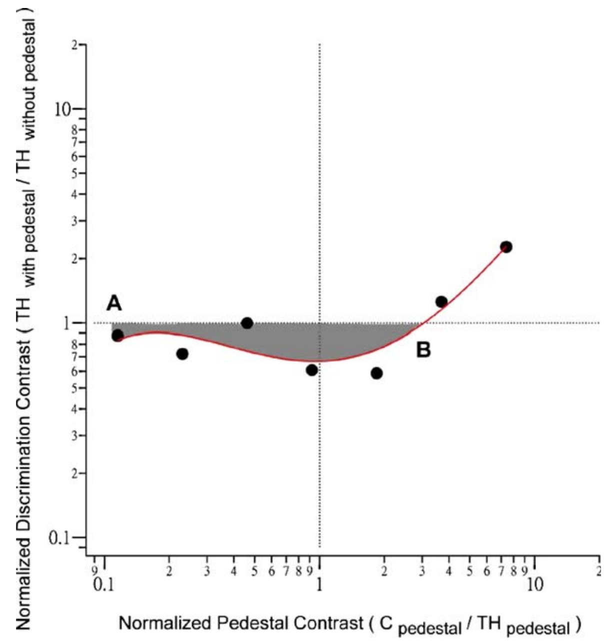

Fig. 8. Method used to calculate the facilitation index for Experiment 3. The normalized discrimination threshold was plotted against normalized pedestal contrast. The data points were fitted by the 4th polynomial equation that is shown by the red line. The facilitation index was defined as the average height of the shaded area from point A, the minimum stimulus value, to point B, the upper bound. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this paper.)

4.3. Results and discussion

Fig. 9 shows the results for four subjects. The two naïve subjects were RW and AL. In this figure both the test and pedestal have been normalized by their detection threshold for better comparison of results across subjects. Results are shown for three pedestal phases (i.e., 0°, 90°, and 315°, and tests of 90° vs. 270°, 0° vs. 180°, and 45° vs. 225°, respectively). Although there are some isolated cases of subthreshold summation, these were small and not limited to the 315° pedestal phase condition. To allow the null hypothesis (that facilitation occurred only in the 315° pedestal condition) to be given its best chance we tested the data using the facilitation index that covered the full range of pedestal contrasts, as well as the index covering just the subthreshold pedestal range. We found that there was no difference among the 3 phase conditions for either index ($p = 0.9796$ and $p = 0.9148$ respectively), resulting in rejection of the hypothesis that the 315° pedestal, 45° vs. 225° test provides the unique condition for facilitation.

5. General discussion

Our results do not support the currently held view that there exist independent labeled visual detectors tuned to one of four cardinal phases, namely +cosine, −cosine, +sine, and −sine. We first show that, at detection thresh-

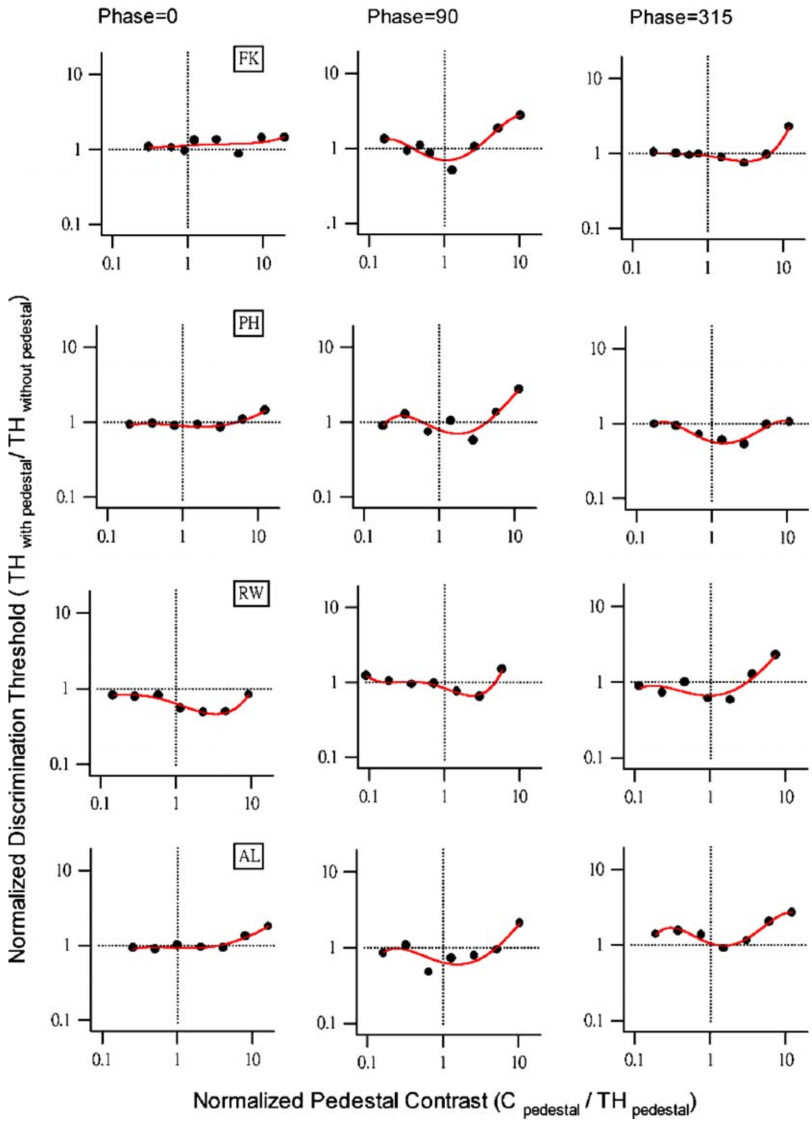

Fig. 9. Results for Experiment 3, pedestal + test discrimination. The first column shows the condition where the phase of the pedestal is 0°, and the test 90° vs. 270°. The second column shows the condition where the pedestal is 90°, and the test 0° vs. 180°. The third column shows the condition where pedestal is 315°, and the test 45° vs. 225°.

old, stimuli in cosine phase cannot be distinguished from stimuli in sine phase, showing that even if sine and cosine detectors exist, they are not independent. This finding does not depend on the luminance spatial frequency bandwidth of the stimuli or whether the stimuli are single or multi-component. Not even ±cosine or ±sine could be reliably discriminated at detection threshold for the bandlimited stimuli we used. Only Gaussians of opposite polarity (±cosine) could be discriminated at detection threshold, suggesting that only pure increments and decrements stimulate independent, labeled phase detectors. That pure increments and pure decrements are 'special cases' of phase relations finds expression in a number of studies showing that such stimuli have unique behavioural properties (Fiorentini, Baumgartner, Magnusson, Schiller, & Thomas, 1990; Kingdom, 2003; Krauskopf, 1980).

At suprathreshold levels, we found that the discrimination of stimuli of different phase showed a degree of individual variation that did not match the expectation based on there being detectors tuned to four cardinal phases; optimal discrimination did not occur at phases intermediate between these four cardinal positions. The use of a 3-spatial-alternate odd-man-out task freed subjects from having to memorize a phase template, allowing any arbitrary phase to be tested. It also allowed for unlimited stimulus inspection time. Finally, jittering the contrast ensured that local luminance and contrast cues could not be used. Our suprathreshold results are in agreement with Thomas and Olzak (2001) who have shown that for suprathreshold discriminations information is collapsed across spatial phase. The really noteworthy result of this experiment is just how bad phase discrimination is once local contrast has been eliminated a as a cue: phase discrimination thresholds were around 50 deg on average. We will return to discuss the significance of this finding later.

Finally, we could not replicate the main piece of evidence for the four channel phase model (Burr et al., 1989). The reasons for this are unclear as our stimuli and methods were very similar to Burr et al. The main thing to note about this experiment is that it produced a different pattern of results in each subject, suggesting that the task was strategy-dependent and not 'low-level.'

5.1. Relationship to previous detection vs. discrimination studies

Our detection/discrimination findings are at odds with Tolhurst and Dealy (1975), who concluded that opposite-polarity edges could be discriminated very close to detection threshold. However, their stimuli were not windowed and could have been discriminated on the basis of the luminance contrast at the edges of the stimulus screen. With regard to the findings with Gaussians, our results are consistent with those of Tolhurst and Dealy (1975) and Kachinsky et al. (2003) who found that opposite-polarity bars or patches could be discriminated very close to detection threshold. On the other hand, our Gaussian results are at odds with the reports of Krauskopf (1980) and Cohn and Lasley (1985). For pulsed disk stimuli at photopic light levels, Krauskopf (1980) found that increment/decrement discrimination was significantly *worse* than detection, whereas Cohn and Lasley (1985) found that increment/decrement discrimination was significantly *better* than detection. However in both these studies the detection and discrimination experiments were carried out in separate sessions, using a two-interval-forced-choice task for the former and a single-interval-forced-choice task for the latter. Moreover, in the Cohn and Lasley (1985) experiments, a range of stimulus contrasts were presented within each session for the detection experiments, but only one contrast per session for the discrimination experiments. The simultaneous detection and discrimination method employed here is arguably a more valid procedure because not only are the same set of contrast levels used for both detection and discrimination, but they are presented concurrently (Thomas, 1985).

5.2. More than four phase-encoding mechanisms?

Given the absence of evidence for four, independent, labeled cardinal phase mechanisms, let us now consider the possibility that there exists *more* than four phase mechanisms. The idea of more than four phase mechanisms would sit well with the early neurophysiological findings showing that simple cells in cat area 17 have an even distribution of receptive field phases (DeAngeles, Ohzawa, & Freeman, 1993; Field & Tolhurst, 1986; Hamilton, Albrecht, & Giesler, 1989; Jones & Palmer, 1987). If multiple phase-tuned mechanisms exist, then the relationship we found between detection and discrimination could be explained in one of three ways.

The first scenario, suggested by an anonymous reviewer, is that the mechanisms that detect and discriminate phase are different, with the detection mechanisms being phase-insensitive and more contrast-sensitive than the discrimination mechanisms. This would explain the differences we found between detection and discrimination thresholds with the Gabors, bars and edges. In this scenario our finding that opposite-polarity Gaussians could be discriminated at threshold could be because the relevant phase-sensitive discriminators happen to be as contrast-sensitive as the relevant phase-insensitive detectors. Phase-insensitive detectors were originally postulated by Rashbass (1970) for the detection of transients of various waveforms, and Burgess and Ghandeharian (1984) found evidence for phase-insensitive detectors in their phase discrimination experiments using sine-wave gratings embedded in broadband noise. The local energy model of Morrone and Burr (1990) locates features as peaks in the energy function, which is derived by taking the pythagorean sum of sine and cosine channels. The phase of features in the model can be identified by "unpacking" the responses of the cosine and sine channels at the energy peaks and comparing their responses. In other words, the local energy model allows for the possibility that features can be detected before they can be discriminated, in keeping with the lower thresholds for detection compared to discrimination found here. A candidate phase-insensitive detector might be thought to be the complex cell, although this might be an oversimplification because complex cells, while being invariant to the phase of components, are highly sensitive to their absolute alignment (Field, 1993). Furthermore, to our knowledge there is no evidence that complex cells are more contrast-sensitive than, for example, simple cells (which are phase sensitive).

The second scenario is that the same mechanisms are involved in both detection and phase discrimination, but that they have very broad and overlapping phase tunings. Identifying the phase of a stimulus is therefore possible, but only if the stimulus is sufficiently suprathreshold to produce a reliable signal in the relative activations of detectors from quite different parts of the phase spectrum. In this scenario pure increments and decrements, for which we found phase to be accurately identified at threshold, would be detected by mechanisms whose phase tunings are sufficiently narrow as to not overlap.

The third scenario is that the same mechanisms are involved in both detection and phase discrimination, but that only a proportion of the detectors are phase-tuned. Detection thresholds would be lower than discrimination thresholds because more mechanisms could be recruited for detection than discrimination. There is little more one can say more about this scenario, as to our knowledge there is no evidence for, or against it. It remains therefore a theoretical possibility.

5.3. Only two phase-encoding mechanisms

The problem however with all the more-than-four phase mechanism scenarios described above, is that they do not explain why our suprathreshold phase discrimination thresholds measured with Gabors are so high, at around 50 deg. If the visual system used the information from multiple, labeled phase-tuned mechanisms to encode phase via some kind of population coding, as is believed to happen for orientation and spatial frequency processing (Thomas, 1985), we would expect phase discrimination to be much better. That it is so poor suggests to us that the visual system does not use the information from multiple phase-tuned mechanisms to encode phase. Rather it suggests that phase coding is based on *fewer* than four mechanisms.

We would like to propose that luminance phase discrimination tasks are subserved by just two mechanisms, the ±cosine detectors implicated in the detection and discrimination of our opposite-polarity Gaussians. According to this scheme, phase is determined by the relative positions, sizes and contrasts of local increments and decrements within the stimulus. In the case of opposite-polarity Gaussians, only one or other of the two types of detector are stimulated, at least at threshold. However in stimuli that contain both positive and negative excursions from the mean (e.g., gratings, Gabors, edges, band-limited bars, etc.), both ±cosine detectors are invariably stimulated, and hence it is the spatial arrangement and magnitudes of their responses that are used to determine phase. For example, in order to discriminate the polarity of our broadband, odd-symmetric Gabors according to this model, both a +cosine and a −cosine detector would need to be activated, as it would be their relative positions that signaled phase. For detection however, only one or other of the two detectors would need to be activated, and hence the contrast threshold for detection would be lower than for discrimination, as we found. This scheme is similar in spirit to Badcock's (1984a, 1984b) suggestion that local contrasts are used for phase discrimination, but emphasizes the idea that those contrasts are local increments and decrements, or combinations of increments and/or decrements at different spatial scales. Since we found that only opposite-polarity Gaussians could be discriminated at threshold, we assume that the ±cosine detectors are closely matched to these stimuli. Gaussians are relatively broadband in both luminance spatial frequency and orientation, and so the obvious candidates here are the relatively broadband, orientationally isotropic "On" and "Off" centre receptive field neurons found in the early stages of the primate visual system (Schiller, 1982).

5.4. Relationship to physiology

Besides the likely involvement of "On" and "Off" cells in our increment/decrement discrimination results obtained with Gaussians, how do our findings relate to known physiology? We mentioned above that the initial reports were in support of an even distribution of receptive field phases amongst simple cells in cat area 17. A more recent report however suggests that such a distribution might critically depend on the spatial bandwidth of the receptive field. Ringash (2001), using a subspace reverse-correlation approach, measured the 2-D spatial structure of receptive fields of simple cells in area V1 of monkey cortex. He found that there was a tendency for cells that were spatial frequency and orientation tuned to exhibit odd symmetry in their receptive fields. Simple cells that were broadly tuned for spatial frequency and orientation tended to have an even-symmetric receptive field structure. It is not clear why such a bimodal distribution in the phases of simple cell receptive fields was not seen in the earlier studies, but assuming that there is a bimodal phase distribution in simple cells in V1, the question raised by our study is whether the narrower-band odd-symmetric phase neurons are at all involved in the encoding of phase.

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