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THE EFFECT OF PHASE STRUCTURES ON SPATIAL PHASE DISCRIMINATION

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Abstract—This study was concerned with the discrimination of multifrequency gratings which differed only in the relative phase of one sinewave component (the test frequency) relative to the other components (the background frequencies). The dependent variable was the contrast of the test frequency required to discriminate between the two gratings. This study found that increasing the test frequency's relative phase difference from 10 to 90 deg significantly increased an observer's contrast sensitivity. However, no overall change in contrast thresholds was measured for test gratings having a relative phase difference between 90 to 180 deg. Moreover, when the mean relative phase was changed from 0 to 45 deg, contrast thresholds did not change when discriminating between gratings having a 90 deg relative phase difference. The type of processing most likely to account for these results in discussed.

Contrast sensitivity   Phase discrimination   Compound gratings   Psychophysics   Spatial localization

INTRODUCTION

Suppose we examine an observer's ability to discriminate between two patterns activating cortical neurons operating within their linear range. Then equivalent representations in either the spatial frequency domain or in the spatial domain can be used to specify the pattern's luminance distribution across space. Both a pattern's spatial frequency components (modulation in luminance across space) and the relative spatial phase (position across space of test frequency relative to background frequencies) must be specified to represent a pattern in the spatial frequency domain. The amplitude of each frequency component is a measure of the frequency's contrast (amplitude/mean luminance).

Many studies have measured an observer's contrast sensitivity when discriminating between different frequency compond luminance gratings (e.g. see Sekuler, 1974; Spekreijse and Van Der Tweel, 1976; Braddick *et al.*, 1978; De Valois and De Valois, 1980; Harris, 1980). However, only a few studies (Burr, 1980; Lawden *et al.*, 1982; Lawton, 1981) have measured how an observer's contrast sensitivity varies as the relative phase between a grating's spatial frequency components is changed.

Phase structures found to change observer's phase discrimination ability

An observer's ability to discriminate relative phase differences between background and test gratings has been measured using two different approaches. One method fixes the contrast of the background and test gratings so that both stimuli are clearly visible. The minimum relative phase difference the observer was able to discriminate is 5–10 deg of the highest grating frequency (Burr, 1980; Klein and Tyler, 1981; Levi and Klein, 1983). The minimum relative phase difference reported in Burr's study was 30 deg of the fundamental frequency which is equivalent to 10 deg of the background third harmonic frequency. If the background is a line rather than a grating, then the minimum relative phase is slightly lower (Klein and Tyler, 1981).

In the second method the contrast threshold of a test frequency phase-shifted relative to a background grating is measured and used as an index for phase discrimination. The contrast threshold needed to discriminate between two patterns only differing in their relative phase was measured for a range of increasing relative phase differences (Burr, 1980; Lawden *et al.*, 1982; Lawton, 1981). Contrast thresholds decreased when the relative phase difference increased from 30 to 90 deg. However, contrast thresholds leveled off when the relative phase difference was increased beyond 90 deg (Burr, 1980; Lawden *et al.*, 1982; Lawton, 1981) when tested using equally-spaced intervals. Thus, relative phase differences greater than 90 deg have not been found to increase a normal observer's contrast sensitivity. This was found for test frequencies added to either a single frequency (Burr, 1980) or a multiple frequency (Lawton, 1981) background.

The minimum displacement needed to discriminate between two phase-shifted gratings was found to depend on the test frequency's mean relative phase (Burr, 1980). The minimum phase difference needed to discriminate between two phase-shifted gratings was higher for test gratings having a 0 deg mean relative phase, than for test gratings having a 45 deg mean phase.

The two frequency approach has been useful for elucidating an observer's ability to discriminate relative phase differences. However, in the "real world" stimuli are usually more complex and are composed of several spatial frequency components. It is not understood how relative phase differences are encoded when discriminating between more complex stimuli. Thus, it is of interest to systematically examine the effect of increasing relative phase differences on an observer's contrast sensitivity when discriminating relative phase differences between multifrequency gratings.

The present study measured an observer's contrast thresholds for a 1 c/deg test frequency added to several different high background frequencies, when discriminating relative phase differences from 10 to 180 deg in 10 deg increments. The multifrequency background had either a 1 c/deg fundamental or a 1 c/deg difference frequency.

Whether an observer's contrast threshold varies for test frequencies having a different mean relative phase was examined. When discriminating between test frequencies having a 90 deg relative phase difference added to a background composed of 2 or 3 frequency components, contrast thresholds were measured for a range of test frequencies having either a 0 or 45 deg mean relative phase.

METHODS

Visual testing procedures

An observer discriminated between multifrequency gratings in a two alternative forced choice task with two 754 msec observation intervals separated by a 500 msec pause. A patterned one dimensional stimulus (see Fig. 1) was present in both intervals; one interval contained what will be called the "test" stimulus and one interval contained the "comparison" stimulus. The observer's task was to indicate the interval in which the test stimulus occurred. On each trial the test stimulus was in the first interval with probability 0.5. Auditory feedback told the observer if the correct interval was chosen.

Both the test and comparison stimuli were composed of three sinusoidal gratings and it is convenient to label the components common to both test and comparison stimuli and identical in each as "background". Three different two component backgrounds were used in different experiments: (1) a compound of 5 and 7 c/deg, (2) a compound of 6 and 7 c/deg, and (3) a compound of 6.5 and 7.5 c/deg. Each background has either a 1 c/deg fundmantal or 1 c/deg difference frequency. The contrast of each background component was adjusted so that it was 14 times greater than the threshold contrast of the component detected against a uniform background. For example, a 4 c/deg background with a threshold value equal to 0.3% contrast had a 4% contrast in this study. Initially (before the absolute phase was varied) the relative phase of the background components was such that a peak luminance of each coincided at the center of fixation on the display.

It is on the basis of the test sinewave component that the test and comparison stimuli may be distinguished. The spatial frequency of this component, the test frequency, was the same in both stimuli and was one of the parameters manipulated in some of the experiments. The contrast of the test frequency component was also the same in both test and comparison stimuli but was changed from trial to trial in a staircase procedure to be described subsequently.

The phase of the component at the test frequency formed the basis of the characteristics that enabled observers to discriminate between the test and comparison stimuli and it is convenient to treat the phase of this component as comprised of two parts: the first part called the "mean relative phase" was identical in the test and comparison stimuli. The mean relative phase was measured with respect to the background. It was the spatial phase around which the relative phase shift was centered. The second part called "the relative phase" was obtained by shifting the test component in the test stimulus to the right (and the test component in the comparison stimulus to the left) by half the magnitude of the relative phase difference. Relative phase was measured with respect to the background difference frequency. Zero phase was specified as cosine phase relative to the peak luminance of the test and background.

The absolute phase (position of grating on screen relative to observer) of the test and comparison stimuli was constant for both intervals of a given trial, but varied randomly from trial to trial. This helped prevent thresholds from being altered by the proximity of the grating's light and dark bars to the edge of the display (Furchner and Ginsburg, 1978).

The mean luminance of the stimuli remained at 60 cd/m^2 during this study. The stimuli's contrast increased gradually, reaching a maximum in the middle of the 754 msec pattern interval and then decreased gradually. The stimuli subtended a 6.25 deg horizontal by a 5 deg vertical visual angle. The stimuli were composed of 455 different luminance lines. The face of the CRT display was surrounded by a rectangle of light green cardboard to provide an approximately equal luminance surround subtending 10 deg visual angle.

At the beginning of each test session only the background was displayed. The observer always scanned a region in the center of the display equal to the background waveform period. The observer increased the contrast of the test frequency until a visible change in the initial stimulus was seen. Then, a practice session of trials was initiated. The contrast of the test frequency was increased each time the observer incorrectly identified the interval containing the test stimulus. Otherwise, the contrast was not changed.

When the observer was confident that the test stimulus could be discriminated easily from the comparison stimulus, then a test session was initiated. The contrast of the test frequency was decreased one step each time the observer correctly identified the interval in which the test stimulus occurred. An incorrect choice caused the staircase procedure (Wetherill and Levitt, 1965) to be initiated. Three correct responses in a row were needed for the contrast to be decremented one step (0.3% contrast). One incorrect response caused the contrast to be

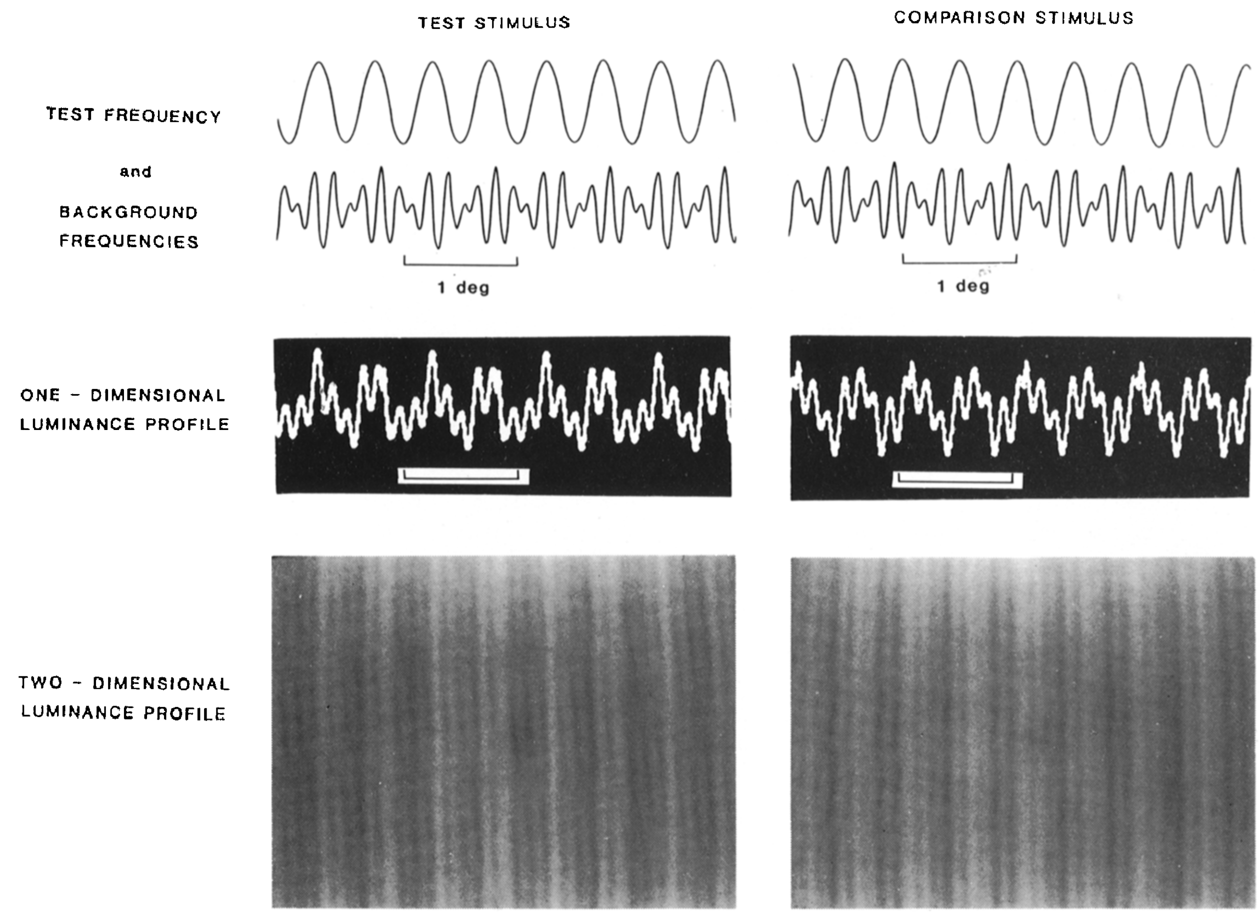


Fig. 1. Three profiles of test and comparison stimuli for 2 c/deg test frequency having 0 deg mean relative phase and 90 deg relative phase difference when added to (5 + 7) c/deg background frequencies.

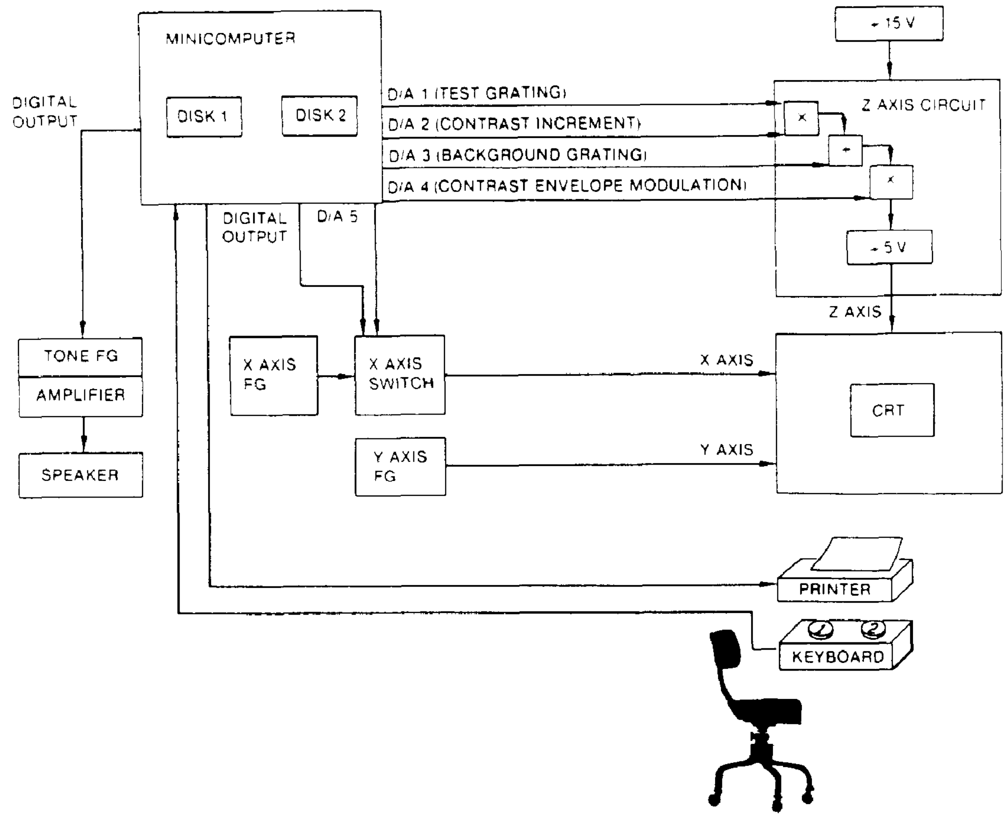


Fig. 2. Schematic for visual testing instrument hardware system.

incremented one step. This process determined the contrast level at which the observer correctly identified the test stimulus 79% of the time. If the test frequency's contrast exceeded 10.8%, than a 1% contrast step size was used.

The staircase procedure was continued until eight contrast reversals were measured. Each contrast threshold measurement was computed by averaging the mean contrast from the last three contrast reversals. An average of 35 test trials were needed to determine each contrast threshold. The plotted contrast thresholds were computed from an average of four threshold measurements Within any one testing session, all test gratings were added to the same background.

Apparatus

A schematic of the Visual Testing Instrument (VTI) hardware system used to present stimuli and measure thresholds interactively is illustrated in Fig. 2. A PDP 11–03 minicomputer system was used to control and operate the VTI system. The VTI system was calibrated using a Spectra Spotmeter, PR 1505.

Special hardware interfaced the PDP 11–03 computer with an HP 1332A CRT display, having a P31 phosphor. This interface enabled the test frequency's contrast to be varied independently of the background's luminance modulation. The Z-axis intensity modulation was transmitted by four Digital to Analog (D/A) converters having 12 addressable bits. After the test sinewave was multiplied by the contrast increment, it was added to the background, before the entire pattern was modulated within a half-sine contrast envelope. An X-axis voltage was input to the display via a fifth D/A converter to synchronize the Z-axis voltage with the X-axis sweep. The X-axis was generated by a second function generator, HP 3300A, when no Z-axis modulation was transmitted to the display. A 3 MHz triangle-wave generator, Interstate Electronics F34 function generator, provided the Y-axis voltage to the display.

EXPERIMENTAL METHODS

Experiment 1: contrast thresholds as a function of relative phase difference

Three multifrequency backgrounds were used to examine the effect of systematically increasing the test frequency's relative phase difference. The observer discriminated between different phase 1 c/deg test gratings added to either a (6.5 + 7.5) c/deg, a (6.0 + 7.0) c/deg, or a (5.0 + 7.0) c/deg background, for relative phase differences from 10 to 180 deg, in 10 deg increments.

Experiment 2: contrast thresholds as a function of mean relative phase

The contrast thresholds measured for test gratings having a 0 deg mean phase were compared with those having a 45 deg mean phase, when added to a (5.0 + 7.0) c/deg and a (5.0 + 7.0 + 9.0) c deg background. The test frequency varied from 0.5 c/deg to 4.5 c deg in 0.5 deg increments.

Statistical tests

Analysis of Variance (ANOVA) tests between different pattern combinations were computed to test the significance of measured differences between various phase discrimination contrast thresholds. A repeated measures, fixed effects two and three way ANOVA [provided by BMDP (1979) statistical programs] was used to measure the significance of the pattern structures being varied. The last two contrast thresholds measured for each pattern were used in these analyses.

Observers

Two observers participated in this study. One (R.L.) was naive about the aims of this study and has 20/20 uncorrected vision. The second observer (T.L.) had practiced discriminating between phase-shifted gratings for several months prior to this study. T.L. has 20/20 vision corrected by refractive lenses.

RESULTS

The phase discrimination Contrast Threshold Functions (CTFs) were measured to examine the effects of (1) the test frequencies' relative phase difference and (2) the test frequency's mean relative phase. These CTF's plot the contrast thresholds measured for the test frequency, when discriminating between two multifrequency gratings that only differ in the relative phase of the test frequency.

Experiment 1: contrast thresholds as a function of test frequencies' relative phase difference

Contrast thresholds when discriminating relative phase differences were lowered as the test frequencies' phase difference was increased up to approximately 90 deg, taking one period of the background difference frequency as 360 deg [Figs 3(a and b)]. An observer's contrast sensitivity was significantly improved, $P < 0.006$, as the test frequencies' phase difference was increased from 10 to 90 deg. However, for test frequencies having a phase difference greater than 90 deg, no change in the observer's contrast thresholds was found.

To discriminate relative phase differences the observer learned to monitor the direction in the luminance distribution shifted from the first to the second pattern. During practice, the observer learned how to effectively use this discrimination strategy.

Experiment 2: contrast thresholds as a function of test frequency's mean relative phase

No significant differences were measured when discriminating relative phase differences between test frequencies having either a 0 or 45 deg mean relative phase. This can be can be seen by comparing the phase discrimination CTFs shown in Figs 4 and 5.

DISCUSSION

The test frequencies' relative phase difference was the only phase structure which significantly changed an observer's contrast sensitivity. As the relative phase difference between two test frequencies was increased from 10 to 90 deg, an observer's contrast threshold was increasingly lowered. For relative phase differences greater than 90 deg, the magnitude of an observer's thresholds remained fairly constant.

Since the contrast thresholds remained constant when discriminating between test frequencies having a relative phase difference greater than 90 deg, it appears that there is a maximum displacement, beyond which an observer's contrast sensitivity is not improved. These results obtained with multifrequency gratings are consistent with previous findings obtained with two component gratings (Burr, 1980; Lawden *et al.*, 1982; Lawton, 1981) when increasing phase differences using equally-spaced intervals.

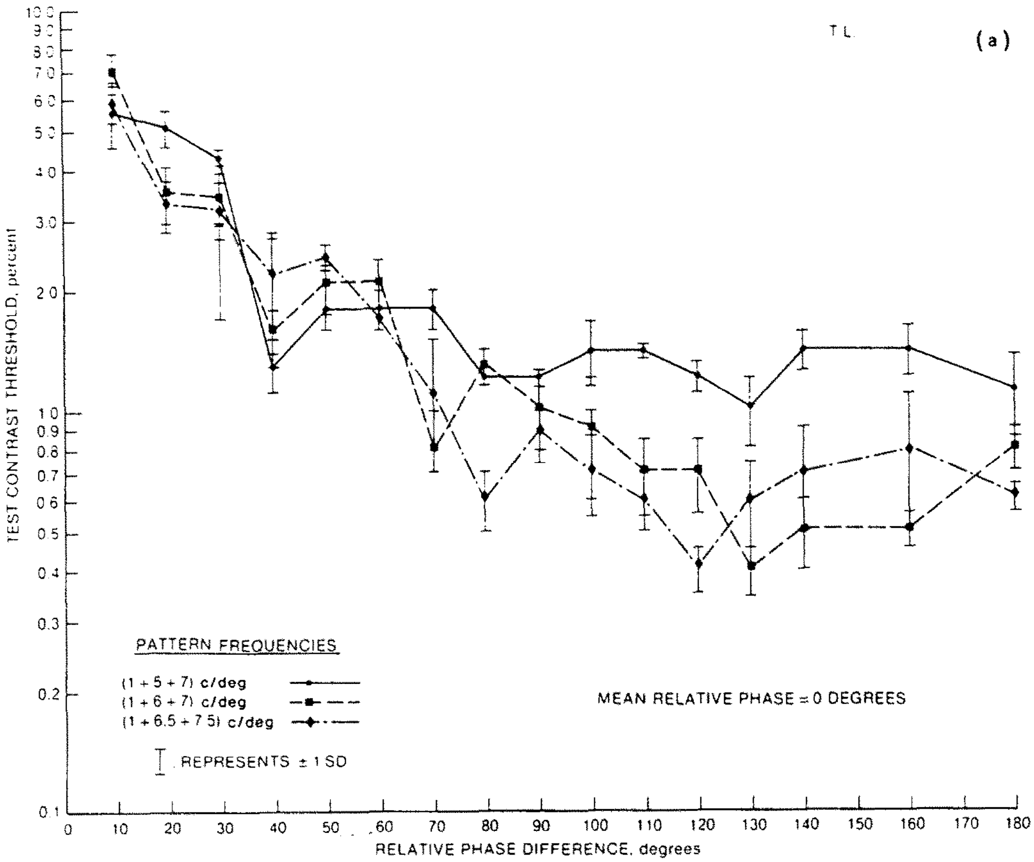
When discriminating between gratings differing by a 90 deg relative phase difference, there was no effect of varying the mean relative phase. Thus, the position along the waveform from which the relative phase difference is computed does not change an observer's contrast sensitivity when discriminating between gratings having a large phase difference.

Biological correlates of phase discrimination

An observer's contrast sensitivity should vary in a manner consistent with the filtering characteristics of the cells mediating perception of luminance differences (Campbell and Robson, 1968; Ginsburg, 1978). The cortical organization having the filtering characteristics capable of processing phase-dependent luminance differences are paired symmetric and asymmetric simple cells (Pollen and Ronner, 1981, 1982; Robson, 1975; Stromeyer and Klein, 1974; De Valois and De Valois, 1980).

Pairs of adjacent simple cells, one having a symmetrically organized receptive field, and one having an asymmetrically organized receptive field (see Fig. 6) were recorded from simultaneously (Pollen and Ronner, 1981). Both cells were tuned to the same orientation within 5–10 deg, and to the same spatial frequencies within 1/4 octave. The peak output from asymmetric and symmetric simple cells differed by approximately 90 deg. Thus, these cells are optimally tuned to frequencies having a 90 deg relative phase difference. Symmetric simple cells act like rectified cosine filters and asymmetric simple cells act like rectified sine filters (Pollen and Ronner, 1981, 1982).

Gabor (1946) showed that two functions (1) a sine multiplied times a gaussian (rectified sinewave), or (2) a cosine multiplied times a gaussian (rectified cosinewave) constitute elementary signals into which



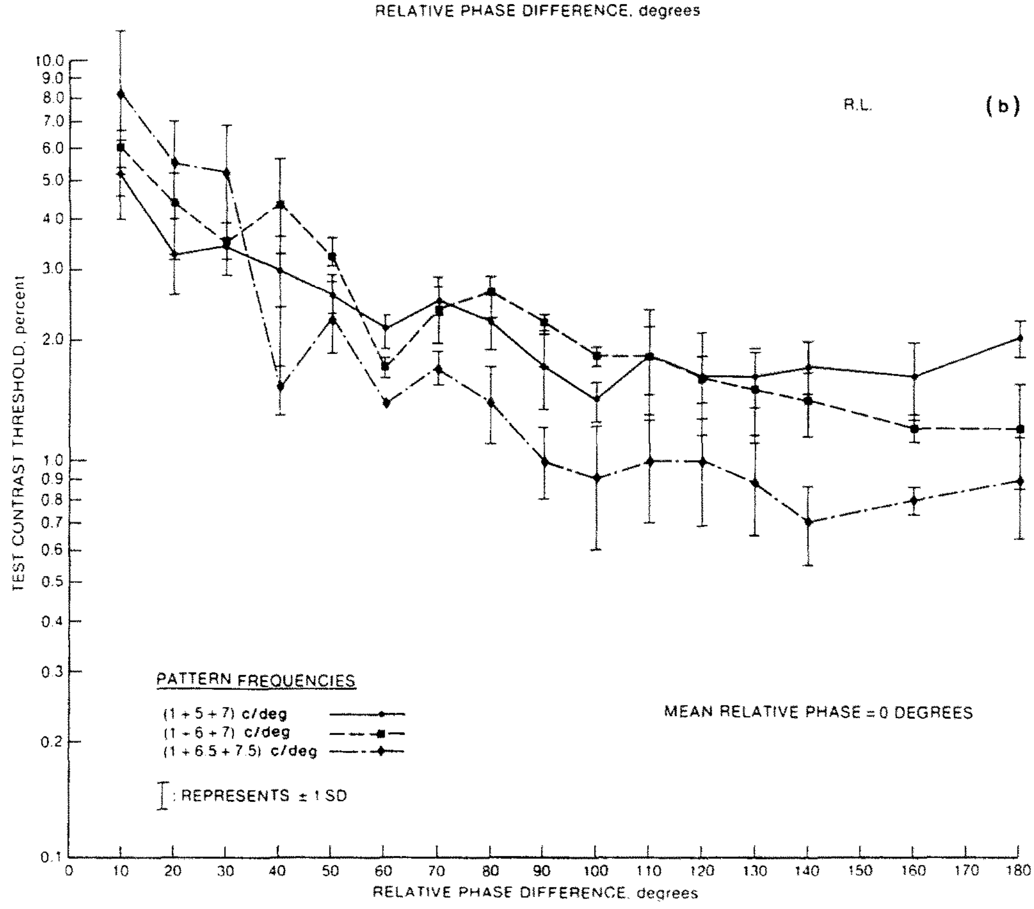


Fig. 3. (a) Contrast thresholds as a function of relative phase difference (T. L.). (b) Contrast thresholds as a function of relative phase difference (R. L.).

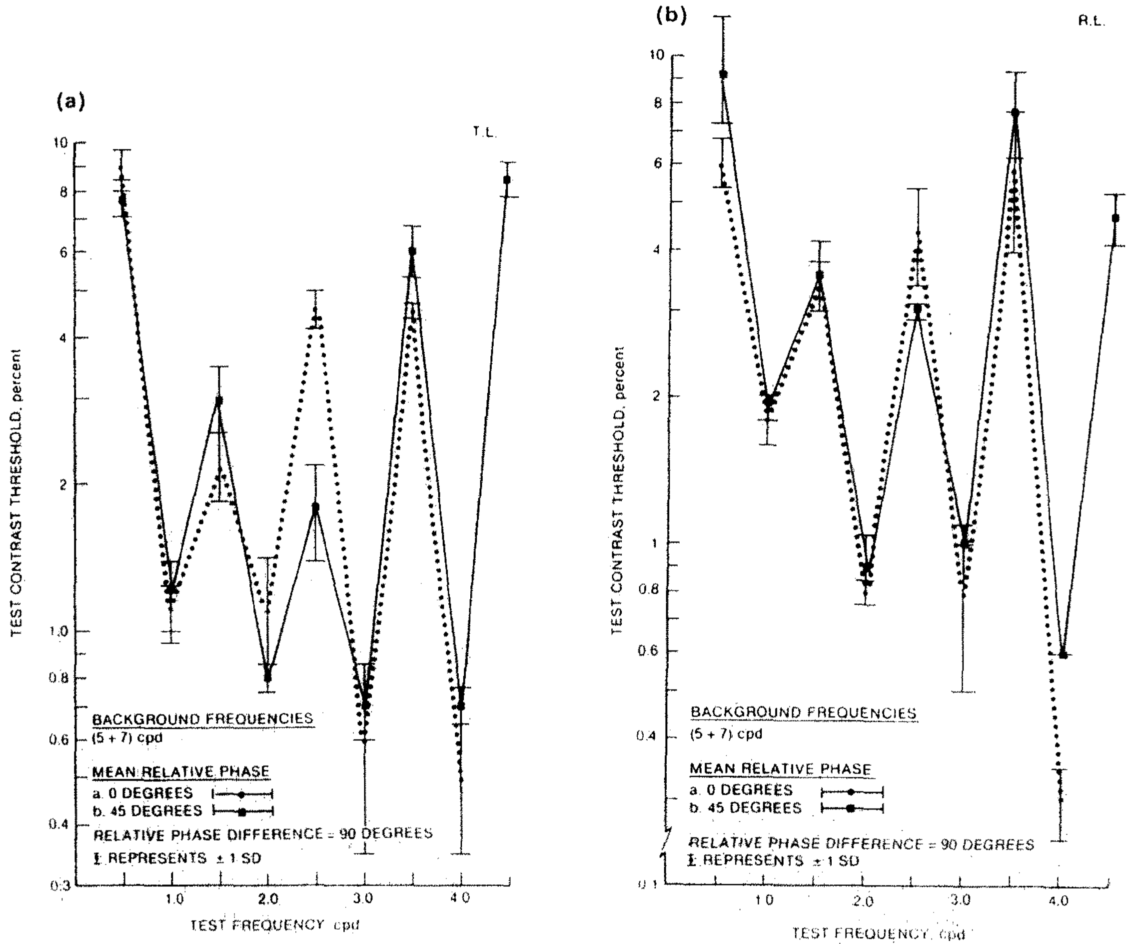


Fig. 4. (a) Contrast thresholds as a function of mean relative phase, for test frequencies phase-shifted relative to (5 + 7) c/deg background (T.L.). (b) Contrast thresholds as a function of mean relative phase, for test frequencies phase-shifted relative to (5 + 7) c/deg background (R.L.).

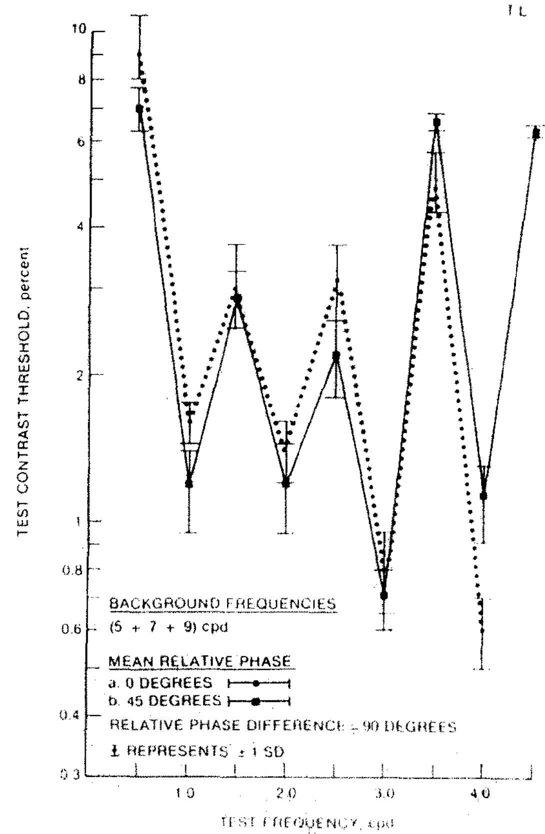


Fig. 5. Contrast thresholds as a function of mean relative phase, for test frequencies *phase-shifted relative to* (5 + 7 + 9) c/deg background.

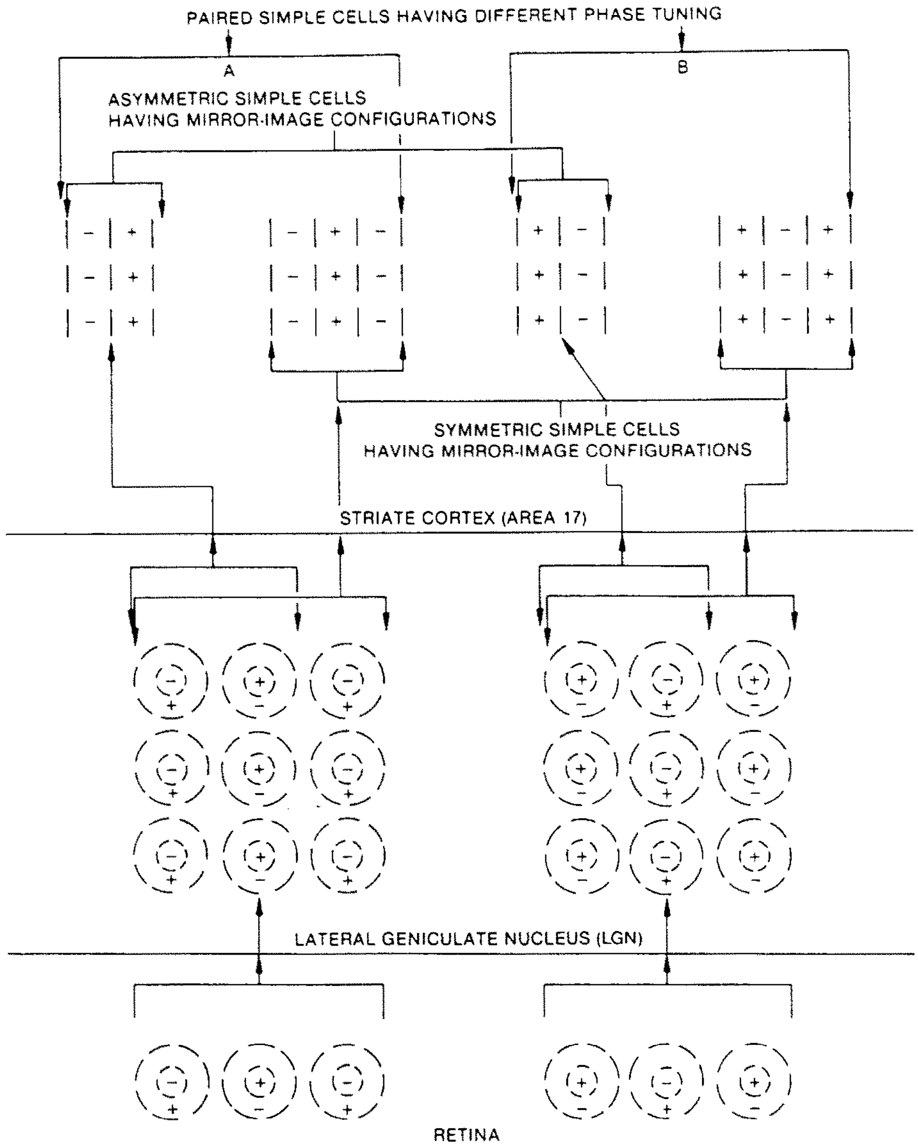


Fig. 6. Receptive field (RF) organization of the visual system from retina to striate cortex.

any signal can be analyzed. Gabor's elementary signals correspond closely to the spatial tuning and receptive field filtering characteristics of asymmetric and symmetric simple cells (Marcelja, 1980). Simple cells have spatially localized receptive fields which respond to a limited range of spatial frequencies. The gaussian function can be used to approximate a cell's frequency bandwidth characteristics, whereas the sine and cosine functions can be used to represent the receptive field profiles of simple cells. Paired symmetric and asymmetric simple cell receptive fields permit simultaneous maximal localization of a signal in space and spatial frequency (Kulikowski and Bishop, 1981; MacKay, 1981; Marcelja, 1980; Pollen and Ronner, 1981).

Interpretation of results in terms of neural representation

Consider the patterns displayed in this study. A background should differentially stimulate a group of symmetric and asymmetric simple cells tuned to a certain range of spatial frequencies. Visible backgrounds will keep this group of simple cells active above their resting level. When the contrast is high enough, then two phase-shifted test frequencies will activate simple cells differing in their phase tuning, yet optimally tuned to the same spatial frequencies, and the observer will be able to discriminate between the test and comparison stimuli. It's likely the observer determines which interval contains the test stimulus, by comparing the pattern of neural activity generated in each interval with a stored neural representation corresponding to the neural activity associated with the test stimulus.

One possible mechanism for making a comparison between the generated pattern of neural activity, and the stored neural representation associated with the test stimulus is cross-correlation. Suppose the activity pattern in each observation interval was cross-correlated with the stored neural representation. Comparing these cross-correlations may provide a mechanism for discriminating relative phase differences. If phase discrimination is directly related to the difference between these cross-correlations, then it would increase with the magnitude of the relative phase difference.

The minimum displacement threshold probably corresponds to the minimum relative phase needed to differentially activate simple cells differing in their phase tuning to some threshold extent. When the relative phase difference is small, more contrast is needed to reach this threshold than when it is large. This hypothesis is consistent with measuring lower contrast thresholds, as the relative phase difference between the test frequencies increased from 10 to 90 deg. When test frequencies differed in phase by 90 deg, then they maximally activated paired symmetric and asymmetric simple cells (Pollen and Ronner, 1981).

Once test frequencies have a relative phase difference greater than 90 deg, then the maximum displacement needed to differentially activate paired symmetric and asymmetric simple cells was always exceeded. An observer's contrast thresholds leveled off when discriminating between test frequencies having a relative phase difference greater than 90 deg. Since a 90 deg phase difference would be signaled by a pair of symmetric and asymmetric simple cells, whereas a 180 deg phase difference would be signaled by a cell and its mirror-image, it is not surprising that phase discrimination does not improve as the phase difference increased from 90 to 180 deg.

A model proposing a single mechanism for discriminating relative phase differences (e.g. a spatially localized Difference of Gaussians (DOG) function monitoring different positions across space) would predict that phase discrimination should improve as the relative phase difference increased from 90 to 180 deg. Thus, paired symmetric and asymmmetric simple cells provide a physiological mechanism which corresponds more closely to psychophysical data than would a model consisting of a single mechanism.

In conclusion, the effect of increasing the test frequencies' relative phase difference on an observer's contrast sensitivity is accounted for by a tradeoff between phase difference and contrast, in the computation of a comparison measure between the neural patterns produced in the two observation intervals and the stored test stimulus representation. Moreover, paired symmetric and asymmetric simple cells provide the most viable physiological mechanism for predicting an observer's contrast sensitivity when discriminating relative phase differences.

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