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SENSITIVITY TO SPATIAL PHASE

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Abstract—Thresholds for discriminating between the spatial phase relationship of the two component sinusoids f and $3f$ of a complex waveform were measured as a function of spatial frequency. Three experiments were conducted, yielding the following results.

1. Thresholds for relative phase were about 30° for all spatial frequencies at which both sinusoidal components were clearly visible.
2. The contrast threshold for discrimination of 180° of phase was as low as that for detection of the third harmonic.
3. Sensitivity to phase varies across the phase range, being best when one grating of the discrimination pair is seen to be in "square-wave" phase.

INTRODUCTION

Evidence has been accumulating steadily over the past decade to support the view that visual stimuli are detected by a battery of independent mechanisms, each responsive to a narrow range of spatial frequencies and orientations (see for example Braddick *et al.*, 1979). Natural visual stimuli are composed of various spatial frequencies added together in a specific phase relationship. Therefore, for the perception of such complex stimuli, it becomes important to investigate how the visual system processes phase information.

To date this problem has received little attention, but the few studies which have been reported all suggest poor phase selectivity. For example, Nachmias and Weber (1975) report that at the contrast threshold, phase differences of 180° cannot be detected. Atkinson and Campbell's (1974) "monocular rivalry" also implies poor resolution. At low contrasts, a compound grating comprised of two sinusoids f and $3f$, added in 90° phase, produces an ambiguous percept (see Fig. 1c). It seems to alternate in appearance between a "square-wave" (like Fig. 1a) and a "triangle-wave" (like Fig. 1d). To explain this, Atkinson and Campbell have proposed the existence of "phase selective devices" responsive only to 0 and 180°. When stimulated by a grating of intermediate phase, these devices respond separately, each inhibiting the other, so the grating seems to alternate in time between two stable states.

The present series of experiments investigates further the question of phase perception, measuring thresholds for discriminating relative phase in compound gratings. Thresholds are reported for a wide range of spatial frequencies, contrasts, luminances and phase relationships.

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METHODS

The general procedure was to present sequentially two gratings separated by a 1 sec interval on an oscilloscope face and ask the observer to identify the interval which contained, say, the "square-wave like wave". The gratings were a compound waveform of two sinusoids f and $3f$ of contrast ratio 3:1 (like a square wave) but added in variable phase (see Fig. 1). Within each trial, the waveforms of both intervals were of the same frequency and contrast, but of different *relative* phase. The position of the grating on the screen, that is its *absolute* phase, varied randomly between presentations. Thus to make the forced choice discrimination, the observer had to detect the difference in relative phase.

Waveform generation and display, response recording and scoring were all performed by a Digital PDP 8/I laboratory computer. A trial consisted of two successive gratings each smoothly fading on and off within a raised cosine envelope [$m = \frac{1}{2}m_p(1\text{-}\cos(t/\tau)\,2\pi)$, where m is instantaneous contrast, m_p peak contrast, t time and τ total duration] 250 msec long at half height. The observer responded by pressing the appropriate response button, which on release, initiated the next trial. Trials (about 200 per session) were chosen at random from a pool varying across a large range of spatial frequencies.

Measurements were made with a forced choice technique that combines the virtues of the standard staircase procedure described by Wetherill and Levitt (1965) and frequency of seeing analysis. Measurements of all spatial frequencies were made concurrently within one session, with the separate staircases randomly interleaved. Each staircase started at a random relative phase (or contrast in Experiment 2) then "homed in" to a range of values near threshold, first in 22 then 11° steps (or 6 then 2 dB steps in Experiment 2). Thresholds were calculated, not by the usual method of averaging the last few trials, but by the more sensitive method of fitting a Weibull function (Weibull, 1959) to the frequency of seeing data and calculating the 82% point (see Appendix to Watson, 1979).* The purpose of the staircase was to choose a range of values around threshold where the psychometric function is of steepest slope, and which therefore provide maximum information about threshold. The process was repeated three times for each condition, yielding an estimate of mean and standard error.

Waveforms were displayed on the face of a cathode ray oscilloscope, using the standard television technique of Shade (1956). The face was masked to a 20 cm diameter circle and evenly illuminated to 200 cd m^{-2} by a raster of 1000 lines at 150 Hz frame rate. It was surrounded by a 1 m^2 screen of the same luminance. As the viewing distance varied between experiments, screen size in degrees is noted below each figure.

Results are reported here for only one observer, the author, but all measurements have been verified by at least one other observer.

RESULTS

Thresholds for phase discrimination

This experiment measures the minimum phase angle between f and $3f$ which can be discriminated from zero. Measurements were made over a wide range of spatial frequencies, contrasts and luminances, and are summarized in Fig. 2.

The most obvious result is that provided both component sinusoids are clearly visible (that is, about 12 dB above their visibility threshold), the threshold for phase discrimination is almost constant across the range of spatial frequencies, always about 30°. As for contrast sensitivity measurements, there is a high frequency and sometimes also a low frequency cut, especially at low contrast or low luminance. Nevertheless, at high contrast and luminance, phase sensitivity is independent of spatial frequency for over a decade.

This result may seem to conflict with Westheimer's (1978) recent paper reporting phase sensitivity to be a linear function of spatial frequency, about 10 sec arc at all frequencies, rather than a constant phase angle. However, the two experimental procedures differed markedly. Westheimer presented sequentially two sinusoidal gratings, one slightly displaced with respect to the other, and asked subjects to identify the direction of the displacement. Such a sequence is usually perceived as a single grating moving smoothly from one position to another. Westheimer's experiments measure the minimum detectable displacement over time, which is perhaps better considered as a measure of motion sensitivity, rather than sensitivity to relative phase.

Contrast required for phase discrimination

This experiment again measures phase resolution, but in a different way. Rather than measuring the minimum detectable phase at a given contrast, it determines the contrast required to discriminate between two compound gratings varying by a given phase angle, compared with that required to detect the presence of the third harmonic under similar conditions. In all sessions, one interval always contained the 0° phase compound (Fig. 1a). The other varied between sessions, being either a compound added in 45, 90 or 180° phase (Figs 1b, c, d) or the fundamental sinusoid (f) on its own.

Figure 3 displays the results. There is clearly no

* I am highly indebted to Denis Pelli for his capable assistance and the loan of his software in making these calculations.

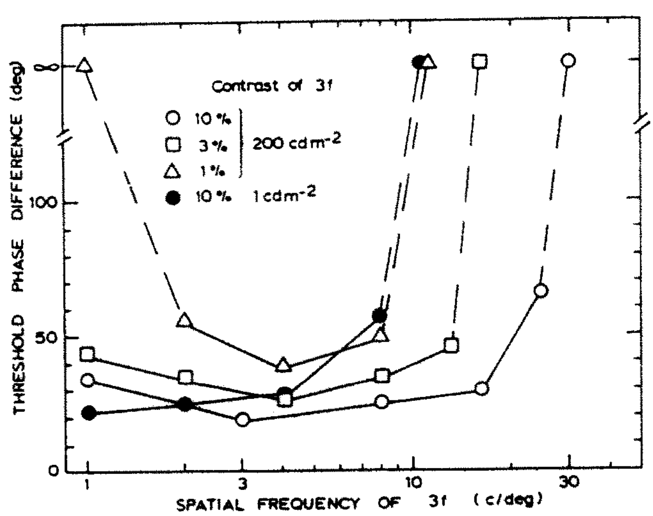

Fig. 2. Threshold phase discrimination as a function of spatial frequency for three contrast levels of $3f$: 10% (○), 3% (□) and 1% (△) (with f three times the contrast of $3f$), all at 200 cd m^{-2}; and at 10% contrast at 1 cd m^{-2} (●). The screen size was 4° in all conditions. Standard errors were all about the size of the symbols.

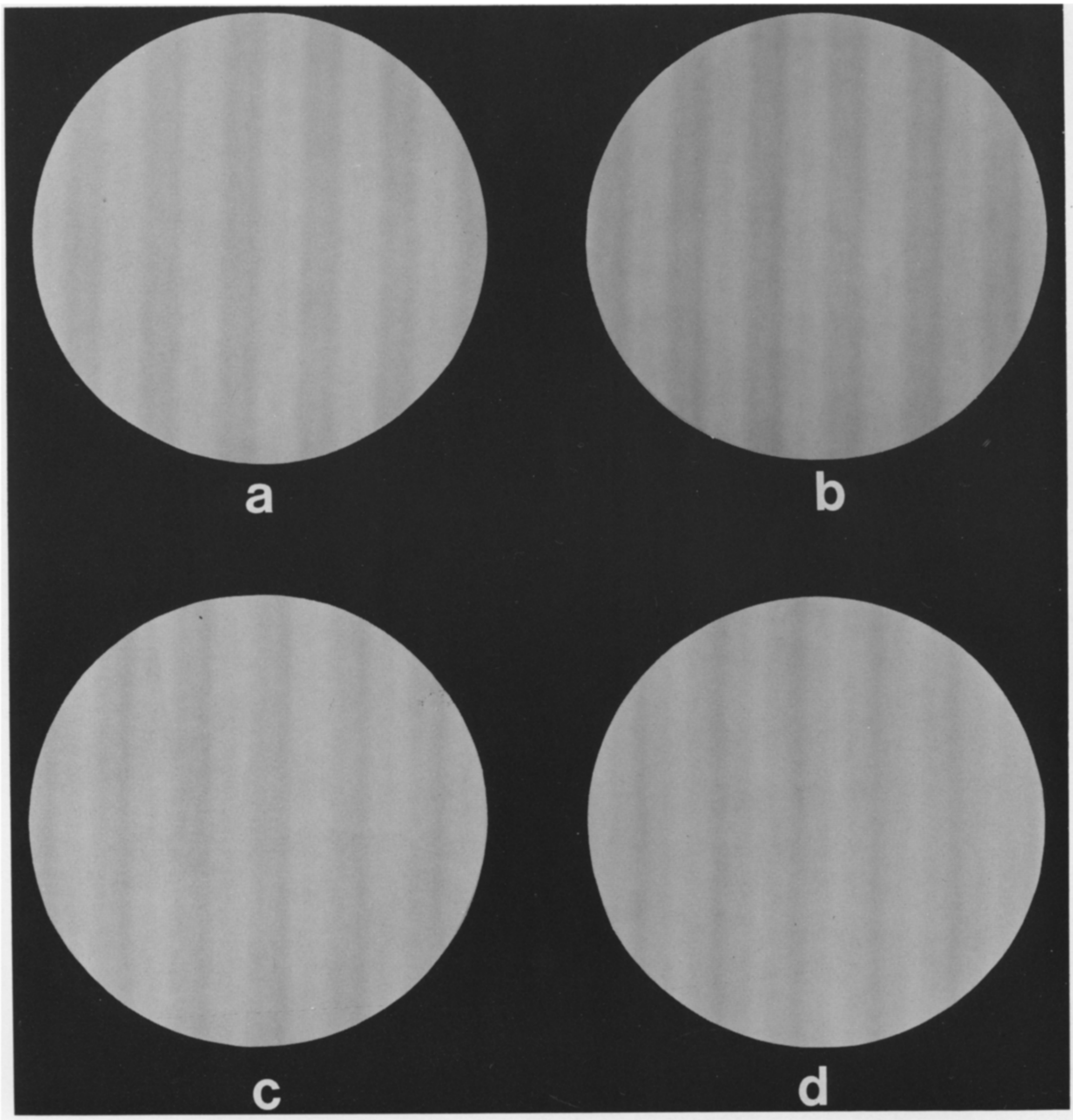

Fig. 1. Examples of the stimuli used in this series of experiments. All four gratings are compounds of two sinusoids f and $3f$ at 10 and 3.3% contrast respectively. For Figs (a)–(d) they were added in 0 (peaks subtract), 45, 90 and 180° (peaks add) phase. Figure (c) provides a good demonstration of monocular rivalry. Rather than appearing "sawtooth like", it alternatively looks like the square-wave of (a) and the triangle-wave of (d). Figure (b) very rarely alternates in appearance, and (a) and (d) are quite stable.

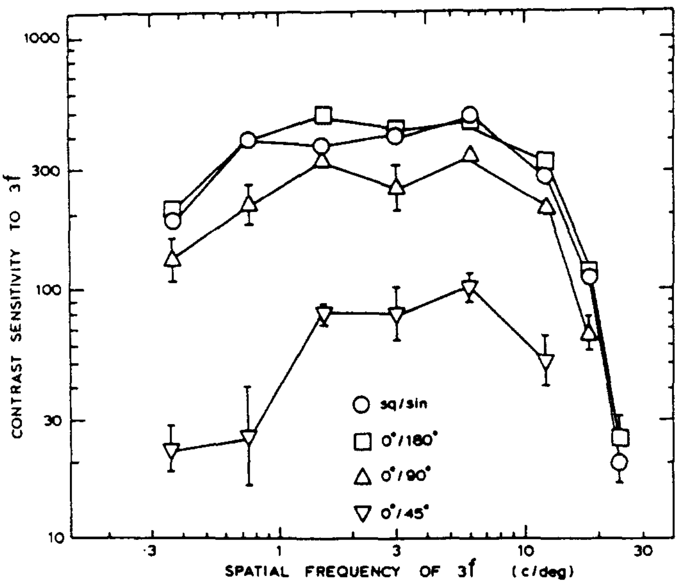

Fig. 3. Contrast required for detection (O) and for discrimination of 180° (□), 90° (△) and 45° (▽) of phase difference. The screen size was 10° for all frequencies less than and including 3 c/deg, and 2.7° for the higher frequencies. Unless otherwise indicated, standard errors were about the size of the symbols.

difference between detection and discrimination of 180° of phase. Provided that the third harmonic was visible, phase differences of 180° could always be detected. Sensitivity to 90 and 45° is predictably poorer, but all curves are of similar shape.

These results may at first glance seem surprising in the light of Nachmias and Weber's (1975) paper reporting poor phase discrimination at threshold. However, the amplitude ratios of the waveforms of the two experiments were quite different, theirs being constructed such that each component was equally and nearly perfectly detectable in the presence of the other, rather than in the square-wave ratio of 3:1. In fact, in a subsequent experiment of the same paper where they increased the contrast of the fundamental, phase discrimination is greatly improved, limited only by the detectability of the $3f$ component. Perfect discrimination seems to occur only when the fundamental is of relatively high contrast, even though the third harmonic may be around threshold.

Discrimination of various phase combinations

Both of the previous experiments measured the ability of the visual system to discriminate 0° (square-wave) from some other relative phase angle. This experiment measures discrmination of other phase combinations, to examine how sensitivity varies across the phase range. For example, can 130° be discriminated from 100° as easily as 30° from 0°?

The procedure was like that of the first experiment, with each trial consisting of two successively displayed gratings differing only in their relative phase. However, in this experiment the phase of both gratings varied around some fixed mean. For example, if the mean was 45°, then at threshold the phase of one waveform would be 20° and that of the other 70°. The spatial frequency of the fundemental was always 2 c/deg at 10% contrast, with that of $3f$ being 6 c/deg at 3.3% contrast. The phase always refers to $3f$. Thresholds were recorded only after the observer had had considerable practice with each task, and was thoroughly aquainted with all available discrimination cues.

The results, summarized in Fig. 4, reveal considerable variation in sensitivity across the phase range. Thresholds are lowest for mean phases of 12 and 45°, slightly higher at 0, 90 and 135°, but about three times as high at 180°.

Why should sensitivity vary with mean phase? Atkinson and Campbell (1974) have suggested that phase specific devices are tuned predominantly to 0 and 180°, from which one may expect considerable variation across the phase range. In particular it would account for the relatively poor discrimination between phases symmetrically spaced about the phase specific devices, namely 0 and 180°. However, it fails to explain why discrimination around 180° should be so much poorer than around 0°, as there was no predominance of either of these two stable states under monocular rivalry conditions. It remains far from clear why sensitivity should follow the particular pattern of Fig. 4.

DISCUSSION

The results indicate that visual resolution of spatial phase is poor. Even with bright, high contrast gratings, 20° misalignment of phase is undetectable. Expressed relative to 180° (the maximum possible phase displacement), thresholds are as high as 12%. While a strict comparison may not be entirely appropriate, it is interesting to note the acuity for some

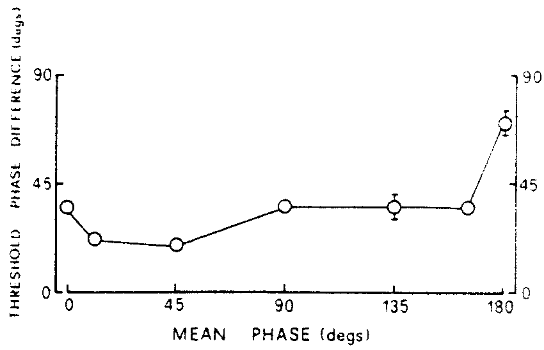

Fig. 4. Discrimination thresholds as a function of mean phase. The waveform was a compound of 2 and 6 c/deg at 10 and 3.3% contrast, subtending 4° of visual angle. The mean phase (shown on the abscissa) always refers to that of the 3*f* component. Error bars are each 1 SE.

other visual tasks: contrast sensitivity, 0.2% at best (e.g. Campbell and Green, 1965); contrast discrimination, 0.1% (Nachmias and Sansbury, 1974); frequency discrimination, 3% (Campbell *et al.*, 1970); and orientation discrimination, 0.3% (0.5°/180°) (Sullivan *et al.*, 1972). By comparison, phase discrimination thresholds are quite high.

It is also interesting to compare phase acuity with vernier acuity. Sensitivity to vernier offsets is quite fine, even for low spatial frequencies. For example, Krauskopf and Campbell (1980) report a threshold of 37 sec arc for detecting offset in a 1 c/deg cosine bar. At this spatial frequency, the threshold for phase is 5 min arc, about 8 times as high. Clearly, vernier judgements are information other than relative phase; perhaps, as suggested by Sullivan *et al.* (1972) and others, orientation information is involved.

However, perhaps the most important result of this study is that thresholds for relative phase discrimination, expressed in degrees of phase angle, are virtually constant over the visible range of the frequency spectrum; whereas expressed in minutes of retinal displacement, they vary from 5 to 0.3 min arc, a factor of 16. It would seem that the discrimination is made by phase selective mechanisms, rather than by mechanisms responsive to changes in the absolute retinal position of local features.

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REFERENCES

Atkinson J. and Campbell F. W. (1974) The effect of phase on the perception of compound gratings. *Vision Res.* **14**, 159–162.

Braddick O. J., Campbell F. W. and Atkinson J. (1978) Channels in Vision: Basic aspects. *Handbook of Sensory Physiology*, Vol. III.

Campbell F. W. and Green D. C. (1965) Optical and retinal factors affecting visual resolution *J. Physiol.* **181**, 576–593.

Campbell F. W., Nachmias J. and Jukes J. (1970) Spatial frequency discrimination in human vision. *J. opt. Soc. Am.* **60**, 555–559.

Krauskopf J. and Campbell F. W. (1980) The effects of contrast and target width on vernier acuity. To be published.

Nachmias J. and Sansbury R. V. (1974) Grating contrast: discrimination may be better than detection. *Vision Res.* **14**, 1039–1042.

Nachmias J. and Weber A. (1975) Discrimination of simple and complex gratings. *Vision Res.* **15**, 217–223.

Schade O. H. (1955) Optical and photoelectric analog of the eye. *J. opt. Soc. Am.* **46**, 721–739.

Sullivan G. D., Oatley K. and Sutherland N. S. (1972) Vernier acuity as affected by target length and separation. *Percept. Psychophys.* **12**, 438–444.

Watson A. B. (1979) Probability summation over time. *Vision Res.* **19**, 515–522.

Weibull W. (1951) A statistical distribution function of wide applicability. *J. appl. Mech.* **18**, 292–297.

Westheimer G. (1978) Spatial phase sensitivity for sinusoidal grating targets. *Vision Res.* **18**, 1073–1074.

Wetherill G. B. and Levitt (1965) Sequential estimation of points on a psychonomic function. *Br. J. math. statist. Psychol.* **18**, 1–10.