Spatial Vision

Spatial-frequency spectrum of patterns changes the visibility of spatial-phase differences

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This study showed that spatial-frequency components over a 4-octave range affected the visibility of spatial-phase differences. Contrast thresholds were measured for discrimination between two (+45- and −45-deg) spatial phases of a sinusoidal test grating added to a background grating. The background could contain one or several sinusoidal components, all in 0-deg phase. Phase differences between the test and the background were visible at lower constrasts (1) when test and background frequencies were harmonically related than when they were not, (2) when test and background frequencies were within 1 octave than when they were farther apart, (3) when the fundamental frequency of the background was low than when it was high, and (4) for some discriminations more than for others, after practice. The visibility of phase differences was not affected by additional components in the background if the fundamental and difference frequencies of the background remained unchanged. Observers' reports of their strategies gave information about the types of attentive processing that were used to discriminate phase differences. Attentive processing facilitated phase discrimination for multifrequency gratings spanning a much wider range of spatial frequencies than would be possible by using only local preattentive processing. These results were consistent with the visibility of phase differences being processed by some combination of even- and odd-symmetric simple cells tuned to a wide range of different spatial frequencies.

1. INTRODUCTION

Spatial-phase discrimination is a task that measures the ability of an observer to localize shifts in the position of light and dark bars of different width. For example, Fig. 1 shows the pattern composed of a phase-shifted 3-cycle/degree (c/deg) test grating added to a 6 + 7-c/deg background. Left- and right-shifted gratings differ only in the spatial phase of the test grating. These patterns (test grating + background) have equal-contrast spatial-frequency components that are identical except for the position of the test frequency relative to the background. Apparently the only difference between these two patterns is in the position of luminance differences between light and dark bars of different width. For example, note the narrow light bars that demarcate the interval over which the pattern repeats in Fig. 1. The most notable difference between left-shifted and right-shifted stimuli is the position of the narrow dark bar, that is, whether it is to the left or to the right of the narrow light bar.

Both the spatial frequency and the contrast of a sinusoidal or multifrequency background affected the detectability of a sinusoidal test grating[1–3] and the discriminability between phase-shifted test gratings.[4–7] Therefore these stimulus parameters were held constant between each pair of stimuli. A phase-discrimination paradigm provides information about an observer's ability to localize changes in luminance across space when the only difference between the two patterns is the position of the test spatial-frequency component relative to the background. Multifrequency medium-contrast backgrounds were used to examine how frequency components spanning several octaves affected the visibility of spatial-phase differences.[6] In addition, multifrequency backgrounds correspond more closely to the real visual environment than do simple sinusoidal backgrounds. Patterns having equal-contrast, equal-frequency components would activate neurons tuned to the same spatial frequencies the same amount. The only difference would be the pattern of activation based on the position of luminance differences.

This information is probably processed by some combination of even- and odd-symmetric simple cells in the striate cortex.[8,9] Presenting a 4% medium-contrast background is within the center of the working range of simple cells in the striate cortex.[10] The smallest luminance differences are needed to discriminate between two patterns if they are near the center of a cell's working range, centered around the mean luminance of a pattern.[11–14] Contrast thresholds for phase discrimination will determine the optimum patterns for localizing the position of luminance differences induced by different phase shifts. The frequency spectra of optimum and nonoptimum patterns for phase discrimination provide information about the transfer characteristics of cortical discrimination between positional changes in luminance when a wide range of different frequency components affects discrimination.

In the present study psychophysical methods were used to measure the effects on the visibility of phase differences of systematically varying the frequency components of the stimuli between threshold measurements. The frequency composition found to improve phase discrimination provides information about the stimulus dimensions used by the visual cortex to localize luminance differences based only on positional differences. Phase discrimination provides a good paradigm for studying cortical discrimination between multifrequency gratings.

A test frequency that is harmonically related to the fundamental frequency[15] of the background repeats an integral number of times within the spatial interval over which the background grating repeats. When the test and background frequencies are harmonically related, then the fundamental frequency of the test + background grating equals the fundamental frequency of the background. The spatial interval over which the pattern repeats, that is, the spatial period of

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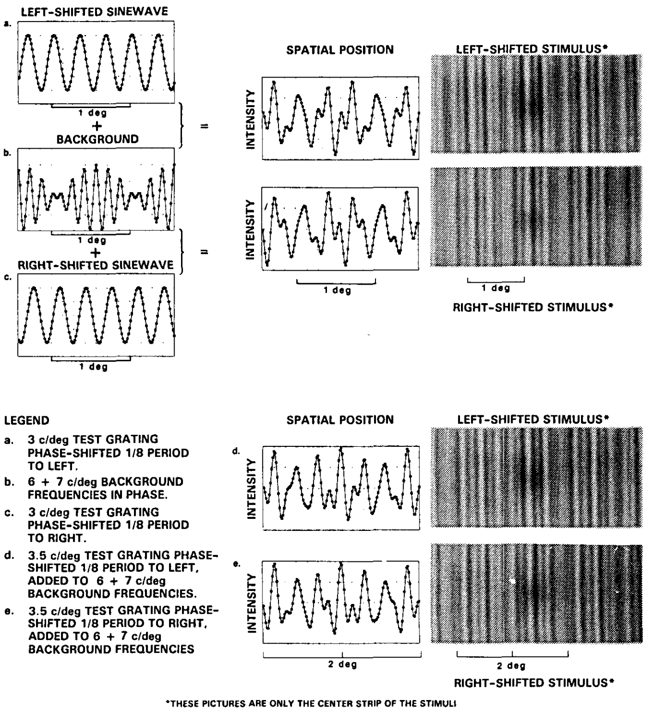

Fig. 1. Phase-shifted 3- and 3.5-c/deg test gratings added to a 6 + 7-c/deg background.

the pattern, is the spatial window to which the observers restrict their attention to identify the location of light and dark bars of different width. The spatial window defined here served as a frame of reference to discriminate spatial-phase differences earlier.[16] Phase differences were more visible when test and background frequencies were harmonically related, that is, when the 4% medium-contrast background demarcated the spatial window used to discriminate spatial phase differences, than when they were not harmonically related.[6,16] When the test frequency was not a harmonic of the fundamental frequency of the background (for example, examine the 3.5-c/deg test frequency in Figs. 1d and 1e), then a low-contrast test grating demarcated the spatial window, because the fundamental frequency of the test + background was much lower than the fundamental frequency of the background.

The difference between the test and the background spatial-frequency components changed the visibility of spatial-phase differences for sinusoidal test gratings displayed in the presence of a sinusoidal background grating.[5,17] Phase differences were less visible for test gratings separated in frequency by more than 1 octave from the frequency of the background than for test gratings within 1 octave of the background-frequency components.[6] Earlier studies have confounded the effects of the frequency difference between the test and the background and the fundamental, difference, and component frequencies of the background.

Suppose that a test grating is added to a background consisting of one spatial-frequency component. Then when the difference between the test and the background component frequencies is greater than 1 octave, the difference between the test and the background fundamental frequencies is also greater than 1 octave. Now suppose that the test grating is added to a multifrequency background. If the difference between the test and the background frequencies was greater than 1 octave, yet the fundamental frequencies of the test and the background gratings were within 1 octave, then phase differences were not less visible for test and background frequencies farther apart than one octave.[6] Determining the visibility of spatial-phase differences for a range of different frequency test gratings added to multifrequency backgrounds will determine whether (1) increasing the frequency difference between the test and the background or (2) increasing the difference between the fundamental frequencies of the test and the background reduces the visibility of phase differences.

Phase differences were visible at lower contrasts when a sinusoidal background repeated over a wide area than over a narrow area, that is, when the fundamental frequency of the background was low than when it was high.[7,18] Phase differences were visible at low contrasts for a wider range of test frequencies when a multifrequency background composed of high spatial frequencies had a low fundamental frequency than when it had a high fundamental frequency.[6] Backgrounds composed of only high spatial frequencies repeat over a wide area if they have a low fundamental frequency. Thus backgrounds composed of high spatial frequencies can provide a wide repetitive frame of reference for discriminating spatial-phase differences. The visibility of phase differences for test gratings added to multifrequency backgrounds that are composed of high spatial frequencies needs to be examined for a range of different fundamental frequencies to explore this effect systematically.

Observers detected a test-frequency component at higher contrasts when it was added to a multifrequency background than when it was added to a single-frequency background.[3] Increasing the number of spatial-frequency components increased the number of different-width light and dark bars that uniquely identified the pattern. It is not clear from the study of Henning *et al.*[3] whether this reduction in detectability resulted from having additional components in the background *or* from lowering the fundamental frequency of the background to equal the test frequency. Lowering the fundamental frequency of the background to equal the test frequency causes both the test and the background to have the same periodicity. The background composed only of high spatial frequencies may mask the detectability of a low-frequency test grating if the fundamental frequencies of both are near each other. The present study measures the effects on the visibility of phase differences of having additional background frequencies compared with lowering the fundamental frequency of the background separately.

Practice involving the discrimination of 90-deg phase differences improved the visibility of phase differences for test gratings added to a sinusoidal background grating.[19,20] Fiorentini and Berardi[19,20] found that the effects of discrimination training with two component gratings, however, transferred to new patterns only when the spatial frequency of the test grating was within 1 octave of the test frequencies between which the observer had previously practiced discriminating phase differences. Whether practice improves the visibility of phase differences only for test and background frequencies within 1 octave of each other in contrast to test and background frequencies farther apart needs to be examined for test gratings added to multifrequency backgrounds.

The present study is a systematic investigation of the effects of different spatial-frequency combinations on an observer's contrast sensitivity when discriminating spatial-phase differences. Five main questions are addressed: Does phase discrimination occur at lower contrasts

(1) When test and background frequencies are harmonically related than when they are not,
(2) When test and background frequencies are within 1 octave than when they are farther apart,
(3) When the fundamental or difference frequency of the background is low than when it is high,
(4) When additional sinusoidal components in the background cause the background fundamental and difference frequencies to remain unchanged, and
(5) After practice involving the discrimination of spatial phase differences for closely spaced test and background frequencies but less affected by practice for widely spaced test and background frequencies?

2. METHODS

A. Apparatus

The visual testing instrument (VTI) was described in detail previously.[9] A PDP 11-03 minicomputer system was used to control and operate the VTI system. The stimuli were displayed on an HP 1332A cathode-ray tube display (P31 phosphor). The mean luminance was 60 cd/m^2. Stimuli subtended 6.25 deg horizontally and 5 deg vertically. The display was surrounded by light green cardboard to provide a large surround of approximately equal luminance.

B. Stimuli

Testing was by a two-interval forced-choice paradigm. The two intervals both contained the same frequency test grating added to the same constant background. They differed only with respect to the spatial phase between the test and the background gratings. The difference between the spatial phases was fixed at 90 deg (or 1/4-period shift) throughout this study. The spatial-phase difference was obtained by shifting the peak luminance of the test grating 1/8 period of the fundamental frequency of the background to the left (left-shifted stimulus) or 1/8 period to the right (right-shifted stimulus). The background components, each generated using a cosine function, were added together in 0-deg phase from a position in the center of the display. The 45-deg spatial phase of the test component was measured from the peak luminance of the background in the center of the display.

Two sets of left-shifted and right-shifted stimuli are illustrated in Fig. 1. Notice that the intensity distributions at corresponding spatial positions are noticeably different between left-shifted and right-shifted stimuli even though they differ only in the spatial phase of the test gratings.

In the first set of experiments spatial phase was measured in terms of the period of the fundamental or difference frequency of the background, whichever was higher. Therefore the test-frequency component was shifted to the left or to the right 1/8 period of the fundamental or difference frequency of the background. This component was chosen since it appeared to characterize the background luminance modulation most nearly completely by providing a frame of reference for the discrimination of spatial phase differences. In the second set of experiments, relative phase was measured in terms of the period of the fundamental frequency of the background grating or the test grating, whichever was higher. Therefore the test-frequency component was shifted to the left or to the right 1/8 period of the fundamental frequency of the test grating or the background grating, whichever was higher. Measuring phase in terms of the higher fundamental frequency enabled contrast thresholds for phase discrimination to be measured for all test frequencies.[21] The absolute phase of left-shifted and right-shifted stimuli was constant for both intervals of a given trial but varied randomly from trial to trial.

Four different backgrounds (Fig. 2) were used: (1) a 6-c/deg grating, (2) a compound of 5 and 7 c/deg, (3) a compound of 6 and 7 c/deg, and (4) a compound of 6.5 and 7.5 c/deg. One to three sinusoidal components that did not change the fundamental or difference frequencies of the background were added to the background, e.g., 5 + 7 + 9 c/deg (see Table 1). Although the spatial-frequency components of the four background gratings were not much different from one another, the backgrounds were quite different with respect to their fundamental or difference frequency. The different backgrounds had (1) a different fundamental frequency (6, 1, or 0.5 c/deg), (2) a different difference frequency (2, 1, or – c/deg), or (3) a different number of frequency components (1–5).

The contrast of each background component was set to 14 times its detection threshold (based on contrast-detection thresholds measured by Lawton[6]) when viewed alone. As the number of sine-wave components was increased, the contrasts

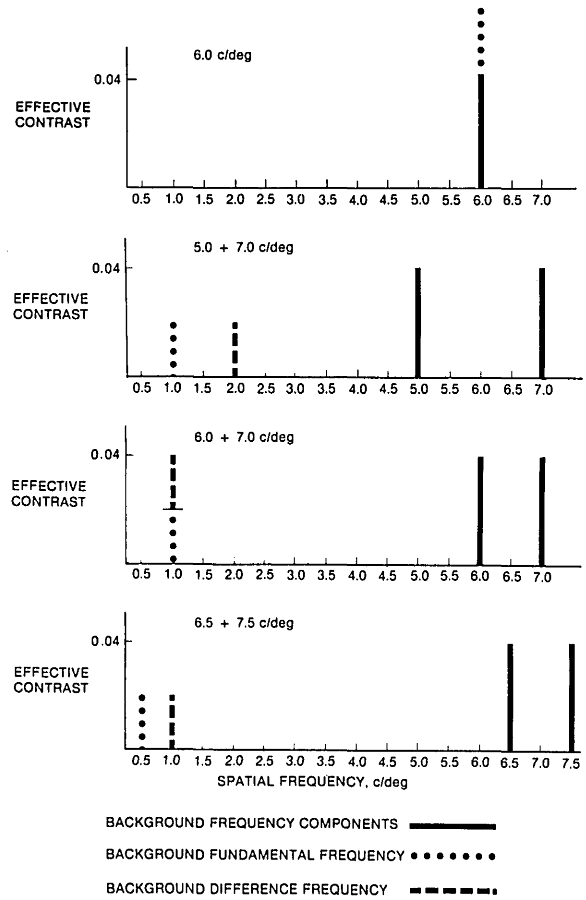

Fig. 2. Frequency spectra for four backgrounds. (Note that the fundamental and difference frequencies are not part of the spectra.)

Table 1. Spectra Used to Measure Effect of Background Grating, Test Frequency, and Number of Background Frequencies

Background Gratings (c/deg)	Frequency Range of Test Gratings (c/deg)	Additional Background Frequencies (c/deg)	Background Fundamental Frequency (c/deg)	Background Fundamental Period (deg)	Background Difference Frequency (c/deg)
6	0.5–4.5		6	0.1$\dot{6}$	—
5 + 7	0.5–4.5	[(5 + 7) + 9] + 11	1	1.0	2
6 + 7	0.5–5.5	{[(6 + 7) + 8] + 9} + 10	1	1.0	1
6.5 + 7.5	0.5–6.0	{[(6.5 + 7.5) + 8.5] + 9.5} + 10.5	0.5	2.0	1

of the N background components were reduced so that each background-frequency component was set to ($14/N$) times its threshold level. The contrast that was 14 times the detection threshold of a 4-c/deg grating was 4%. A 4-c/deg test grating was detected at lower contrasts than were other frequency gratings.[6] The effective contrast of the background was set to 4% by first adjusting all N background-frequency components to $14/N$ times their individual detection thresholds and then multiplying by an amount to compensate for the transfer characteristics of the display that attenuate the higher-spatial-frequency components. The contrast of the background was also measured to be 4% by a Pritchard photometer when all the background components were in 0-deg phase.

Test gratings varied in spatial frequency over a 3.5-octave range from 0.5 to 6.0 c/deg in 0.5-c/deg steps. All test gratings consisted of lower spatial frequencies than the background-frequency components in order to compare the effects of the background fundamental and difference frequencies with the effects of individual background components (see Fig. 2). Test gratings were generally equal to or higher than the fundamental frequency of the multifrequency backgrounds yet always lower than the component frequencies of these backgrounds. In addition, the spatial frequency of the test grating was generally lower than the 4-c/deg grating to which the observer was maximally sensitive, whereas the spatial-frequency components of the background were always higher than 4 c/deg.

C. Procedures

An observer identified the temporal interval in which the phase of the test grating was shifted 1/8 period to the left of the peak amplitude of the background components in a two-interval forced-choice paradigm. Auditory feedback was given on each trial. The tone-cued patterns were presented for 754 msec separated by 500 msec, with a 350-msec onset and 350-msec offset, modulated by a sinusoidal change in contrast.

Initially, the observer increased the contrast of the test grating until its presence, when added to the background, was noticeable. The observer practiced identifying the left-shifted stimulus until consistent discriminations could be made between the left-shifted and right-shifted stimuli (approximately 3–10 trials). Then the data run began, with the final contrast used in the practice run. In the initial segment of the data run, the contrast of the test grating was decreased one step (0.3% contrast) each time the observer correctly identified the interval containing the left-shifted stimulus. Following the first incorrect response, the contrast of the test component (which was the same in both left-shifted and right-shifted stimuli) was varied from trial to trial in a staircase procedure[22] to achieve a given criterion (79%) of correct phase discrimination. The phase-discrimination paradigm was described in detail previously.[9]

Observers were asked to report orally the strategies used to discriminate between the spatial phase of different frequency test gratings added to each background. These reports were used to learn more about the types of processing used to discriminate spatial phase.

In the first set of experiments, the same pair of patterns was never used in consecutive runs. In the second set of experiments, on the effects of practice, the same pair of patterns was seen in three consecutive runs. Within one testing session all test gratings were added to the same background. The presentation order for the spatial frequency of the test grating was randomized. Throughout the study approximately 35 trials were needed to determine one threshold measurement. Plotted thresholds were the average of three measurements.

D. Observers

The first observer was experimentally naive, and the second had practiced discriminating between phase-shifted gratings

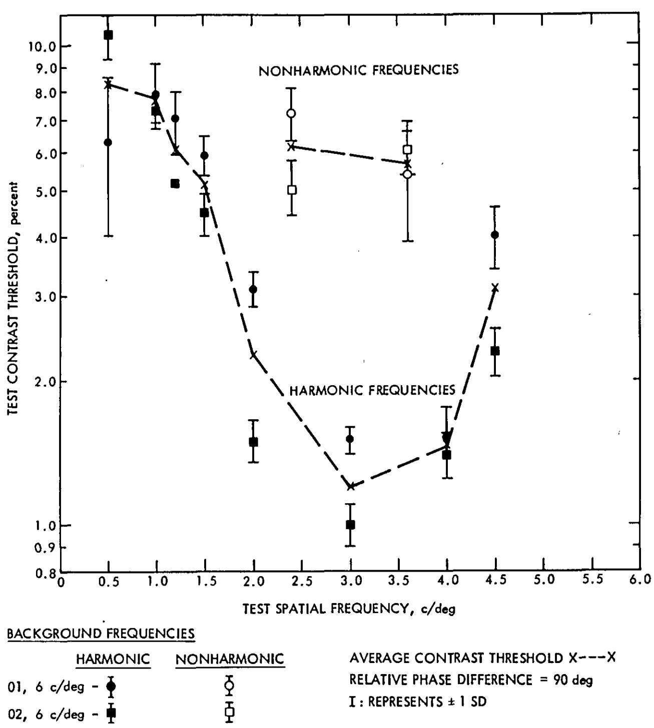

Fig. 3. Contrast thresholds when discriminating phase for test gratings that are added to a 6-c/deg background.

for several months before this study. Both observers had 20/20 vision.

3. RESULTS

A. Effect of Harmonic Relation between Test and Background

For all three backgrounds (Figs. 3–5), phase discrimination occurred at significantly lower contrasts ($p < 0.01$) (Ref. 24) for test gratings that were harmonically related to the background than for test gratings that were not harmonically related. For harmonically related test frequencies more than 1 octave lower than the 6-c/deg background, thresholds increased as the test frequency decreased. When the background was 5 + 7 c/deg (Fig. 4) or 6 + 7 c/deg (Fig. 5) both harmonics and nonharmonics occurred over the entire range of test frequencies examined. Contrast thresholds for phase discrimination remained low for the entire range of harmonic test gratings when added to a multifrequency background.

According to independent observer reports, different discrimination strategies were used for phase discrimination between harmonic and nonharmonic test gratings. For test gratings harmonically related to the background, observers scanned a pattern area corresponding to the fundamental period of the background. The observer then memorized one ordering of different-width light and dark bars across the period of the background to identify the left-shifted stimulus. For example, when discriminating phase differences for a 3-c/deg test grating added to a 6 + 7-c/deg background (see Fig. 1), the observer memorized that the narrow dark bar is to the left of the bright bar in the left-shifted pattern. The observer also memorized that it shifted to the right of the bright bar in the right-shifted pattern. The repetitive background clearly demarcated the spatial window used to discriminate phase differences for harmonic test frequencies.

Backgrounds that were not harmonically related to the test grating did not provide a repetitive frame of reference that clearly demarcated the spatial window used by the observer to discriminate phase differences (see Figs. 1d and 1e). To discriminate between test gratings not harmonically related to the background, observers either scanned a spatial window twice as wide as the spatial period of the background or memorized at least two orderings of different-width light and dark bars across a region corresponding to the period of the background to identify the left-shifted stimulus.

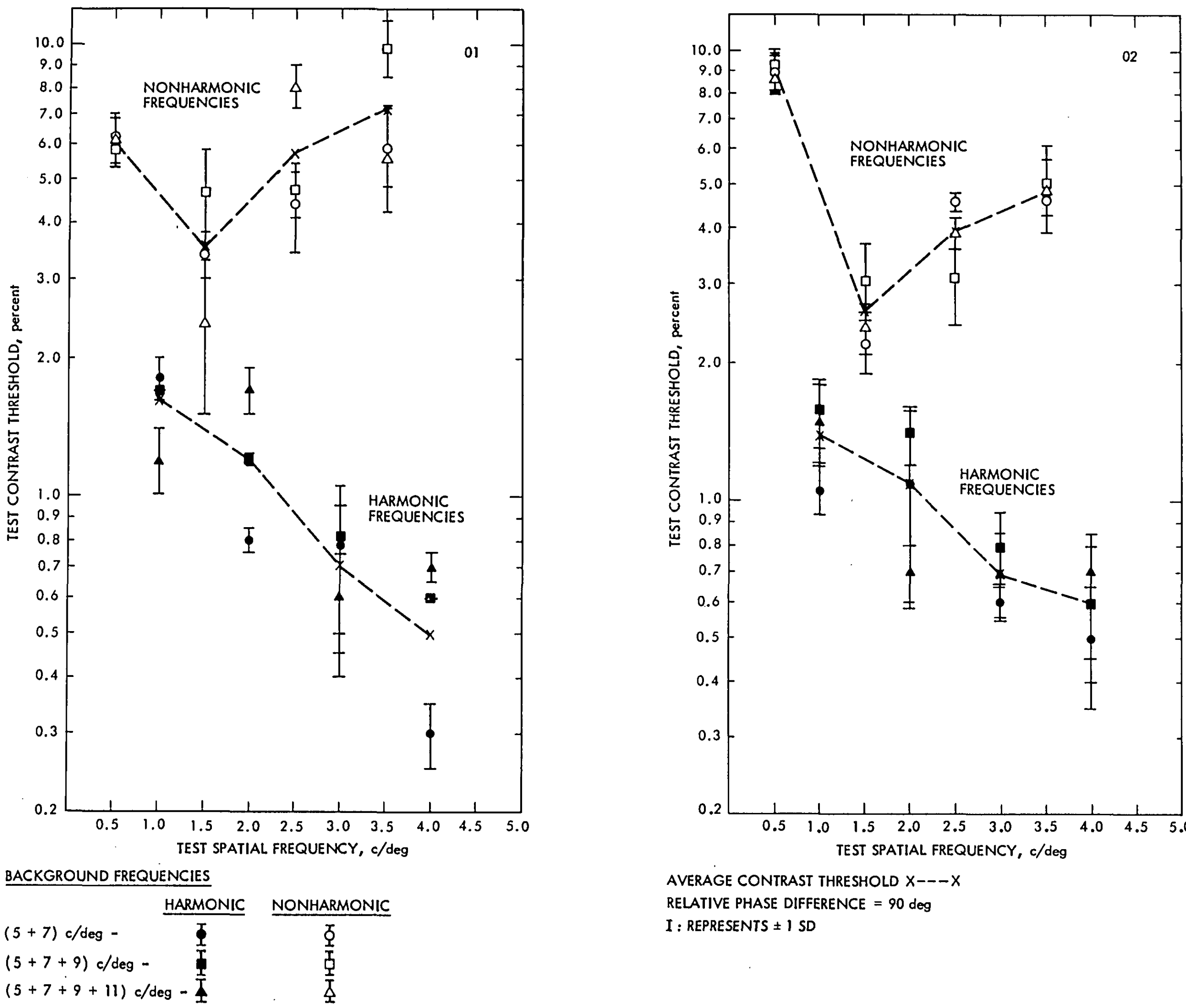

Fig. 4. Contrast thresholds when discriminating phase for test gratings that are added to a 5 + 7-c/deg background and other backgrounds having the same difference and fundamental frequencies.

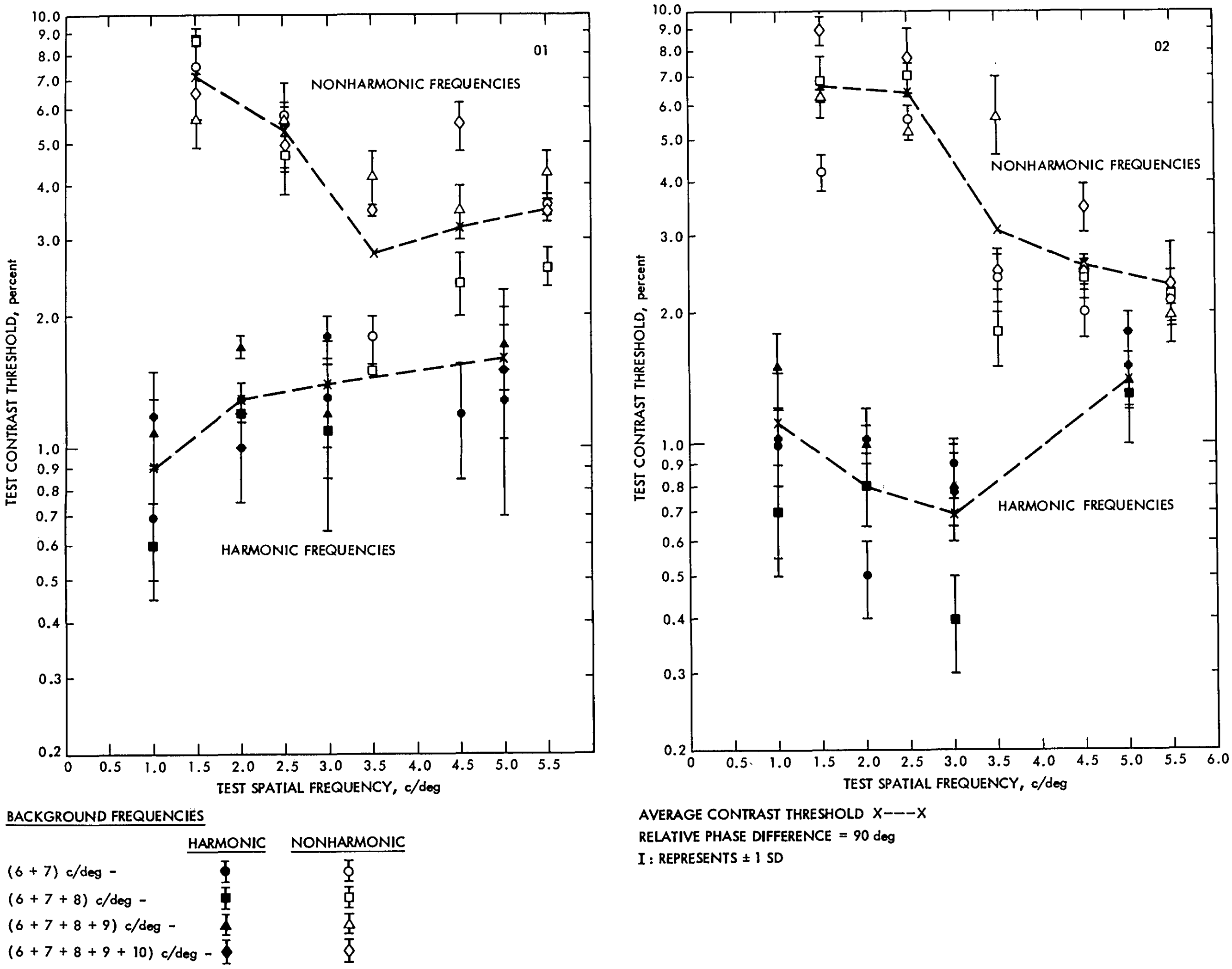

Fig. 5. Contrast thresholds when discriminating phase for test gratings that are added to a 6 + 7-c/deg background and other backgrounds having the same difference and fundamental frequencies.

B. Effect of Frequency Difference between Test and Background

For harmonic test frequencies on a background of 6 c/deg (Fig. 3), phase discrimination occurred at significantly lower contrasts when test and background frequencies were closer than 1.5 octaves than when they were farther apart. For harmonic test gratings on a 5 + 7-c/deg background (Fig. 4) phase discrimination again occurred at lower contrasts as the test frequency increased from 1 to 4 c/deg. However, for harmonic test gratings on a 6 + 7-c/deg background there were no consistent effects of changing the test frequency (Fig. 5).

On the other hand, for nonharmonic test gratings, the only consistent effects occurred on a 6 + 7-c/deg background. Here phase discrimination occurred at significantly lower contrasts for test gratings having a frequency within 1 octave of the background frequencies, such as 5.5 c/deg on a 6.0 + 7.0-c/deg background, compared with the situation when the test and the background frequencies were farther apart, such as a 1.5-c/deg test on a 6.0 + 7.0-c/deg background. Test gratings that were not harmonically related to the 5 + 7-c/deg background were discriminated at significantly higher contrasts when the test and background frequencies were within 1 octave than when they were farther apart (Fig. 5). Following practice (Fig. 9c, discussed in Subsection 3.E), however, nonharmonic test gratings having a frequency within 1 octave of the 5 + 7-c/deg background were discriminated at significantly lower contrasts than when test and background frequencies were farther apart.

Figure 6 shows results for a background of 6.5 + 7.5 c/deg, which has a 0.5-c/deg fundamental frequency. Test frequencies within 1 octave of the background components had systematically different phase-discrimination thresholds—lower contrasts for some test gratings, such as 5.5 c/deg on 6.5 + 7.5 c/deg, and higher contrasts for others, such as 6.0 c/deg on 6.5 + 7.5 c/deg. Note that these patterns have either an integral test-background difference frequency (1.0 c/deg) or a nonintegral test-background difference frequency (0.5 c/deg). There was also an additional minimum threshold at 2.5 c/deg having an integral test-background difference frequency and almost 2 octaves from the background components.

Observers used different strategies to identify the left-shifted stimulus, depending on whether the test and background frequencies were within 1 octave or were farther apart. For test and background frequencies within 1 octave of each other

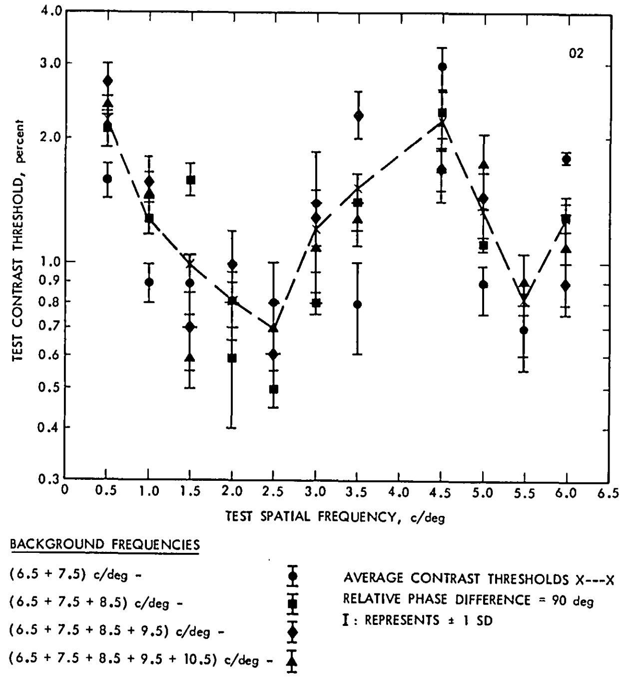

Fig. 6. Contrast thresholds when discriminating phase for test gratings that are added to a 6.5 + 7.5-c/deg background and other backgrounds having the same difference and fundamental frequencies.

(1) If the contrast of the test grating was set to a high level in the practice run, observers found it difficult to identify correctly the left-shifted stimulus over many consecutive trials as the contrast of the test grating was systematically lowered in the initial segment of the data run,

(2) The observers monitored the direction of a shift in the position of a high-contrast high-frequency component (e.g., a narrow dark bar), and

(3) The observers could reduce the width of the spatial window used to discriminate phase by one half if they concurrently doubled the number of different orderings of light and dark bars used to identify the left-shifted stimulus.

When the test and background frequencies were farther than 1 octave apart

(1) Observers correctly identified the left-shifted stimulus over many consecutive trials as the contrast of the test grating was systematically lowered in the initial segment of the data run. The contrast of the test frequency at the end of the practice run did not affect the contrast threshold for phase discrimination.

(2) The observers monitored the direction of a shift in the position of a low-contrast low-frequency component, e.g., a wide gray bar. It was more difficult to localize the spatial position of the low-contrast wide bar accurately than it was to localize the position of the higher-contrast narrow bar.

(3) The observers were able to identify the shift in the position of only *one* feature, e.g., a wide gray bar. Thus reducing the width of the spatial window and concurrently increasing the number of different-width bars used to identify the left-shifted stimulus was not possible for test and background frequencies farther than 1 octave apart.

C. Effect of Fundamental and Difference Frequency of Background

Phase discrimination occurred at significantly lower contrasts for harmonic low-frequency test gratings when the fundamental frequency of the background was lowered from 6.0 to 1.0 c/deg (see Fig. 7, which replots some of the data in Figs. 3 and 5) by changing from a 6-c/deg to a 6 + 7-c/deg background. This can be seen more clearly by comparing the contrast thresholds for a 1-c/deg test grating added to either a 6 + 7-c/deg background or a 6-c/deg background. Thresholds were more than four times lower for a 1-c/deg test grating added to a 6 + 7-c/deg background than when added to a 6-c/deg background.[23]

High-background frequencies having a low fundamental frequency provided a wide repetitive frame of reference within which spatial phase differences were discriminated. If the observer did not monitor the entire spatial period of the background, then the contrast for phase discrimination was at least double the contrast needed when the entire background period was attentively processed. For low-frequency test gratings added to a background having a low fundamental frequency, the spatial window used to discriminate phase-shifted luminance differences was clearly demarcated. However, for low-frequency test gratings added to a background having a high fundamental frequency the spatial window was demarcated by the low-contrast test grating. Thus the spatial window that the observer scanned to discriminate phase was not clearly demarcated.

Previous studies found that phase discrimination occurred at lower contrasts for a high-frequency test grating added to a low-frequency background[6,7] than for a low-frequency test

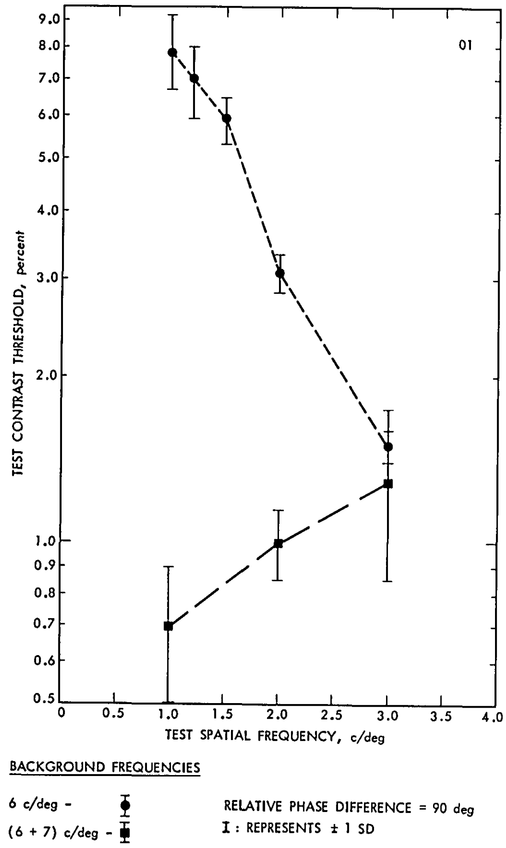

Fig. 7. Contrast thresholds when discriminating phase for test gratings that are added to either 6- or 6 + 7-c/deg background.

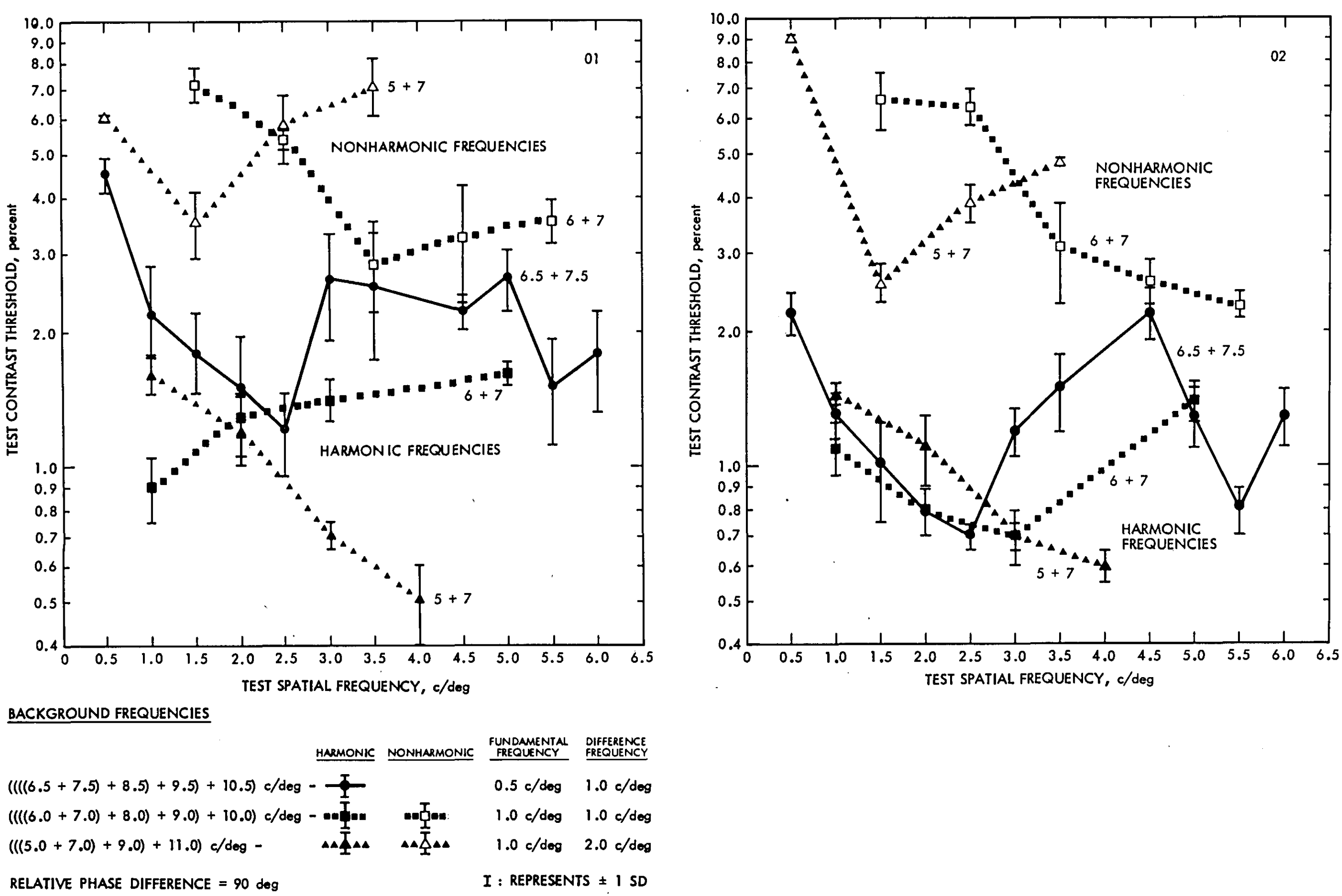

Fig. 8. Contrast thresholds when discriminating phase for test gratings that are added to multifrequency backgrounds.

grating added to a high-frequency background. This study extends this finding by showing that phase discrimination occurred at lower contrasts when a *low*-frequency test grating was added to a background having a *low fundamental frequency*, even though the background was composed of high spatial frequencies, than when added to a background having a high fundamental frequency.

Further lowering of the fundamental background frequency from 1.0 c/deg (6 + 7 or 5 + 7 c/deg) to 0.5 c/deg (6.5 + 7.5 c/deg) did not cause phase discrimination to occur at significantly lower contrasts. In addition, phase discrimination did not occur at significantly different contrasts when only the difference frequency of the background was changed (Figs. 5 and 6). One noticeable difference is that, before extended practice, phase discrimination occurred at significantly lower contrasts for nonharmonic test gratings within 1 octave of the 6 + 7-c/deg background than for the same test gratings added to the 5 + 7-c/deg background. Until better discrimination strategies were learned (see Subsection 3.E) the visibility of phase differences was reduced for nonharmonic test gratings added to a background having a difference frequency double the fundamental frequency of the background. These results can be examined most easily in Fig. 8, where the average contrast threshold for test frequencies displayed on multifrequency backgrounds is plotted for both observers.

D. Effect of Additional Background Components

The statistical results, not so clear to the naked eye, show that the visibility of phase differences was not significantly affected by additional background components if the fundamental and difference frequencies of the background remained unchanged (Figs. 4–6).

E. Effects of Practice

Since the absolute phase varied randomly from trial to trial, observers saw different parts of the grating's spatial period in the same position from trial to trial. Repeated presentations permitted observers to learn the order of several different width light and dark bars across different regions of the fundamental period to discriminate between left-shifted and right-shifted stimuli.

When observers were discriminating phase for test gratings added to the 5 + 7 + 9-c/deg background (Fig. 9c), practice significantly lowered contrast thresholds for the entire 3-octave range of test frequencies examined. In particular, after practice, phase discrimination occurred at significantly lower contrasts for nonharmonic test frequencies within 1 octave of the background frequencies. Thus, following practice, phase discrimination occurred at lower contrasts for nonharmonic test frequencies within 1 octave of the background frequencies, in contrast to those farther apart, for both multifrequency backgrounds. Lower thresholds resulted from increased practice using better discrimination strategies, such as memorizing several different orderings of different-width light and dark bars to discriminate between left-shifted and right-shifted stimuli *and* monitoring the direction of the shift in the position of one feature, such as the position of a narrow dark bar relative to a narrow light bar, between the two phases. In addition, practice significantly lowered contrast thresholds

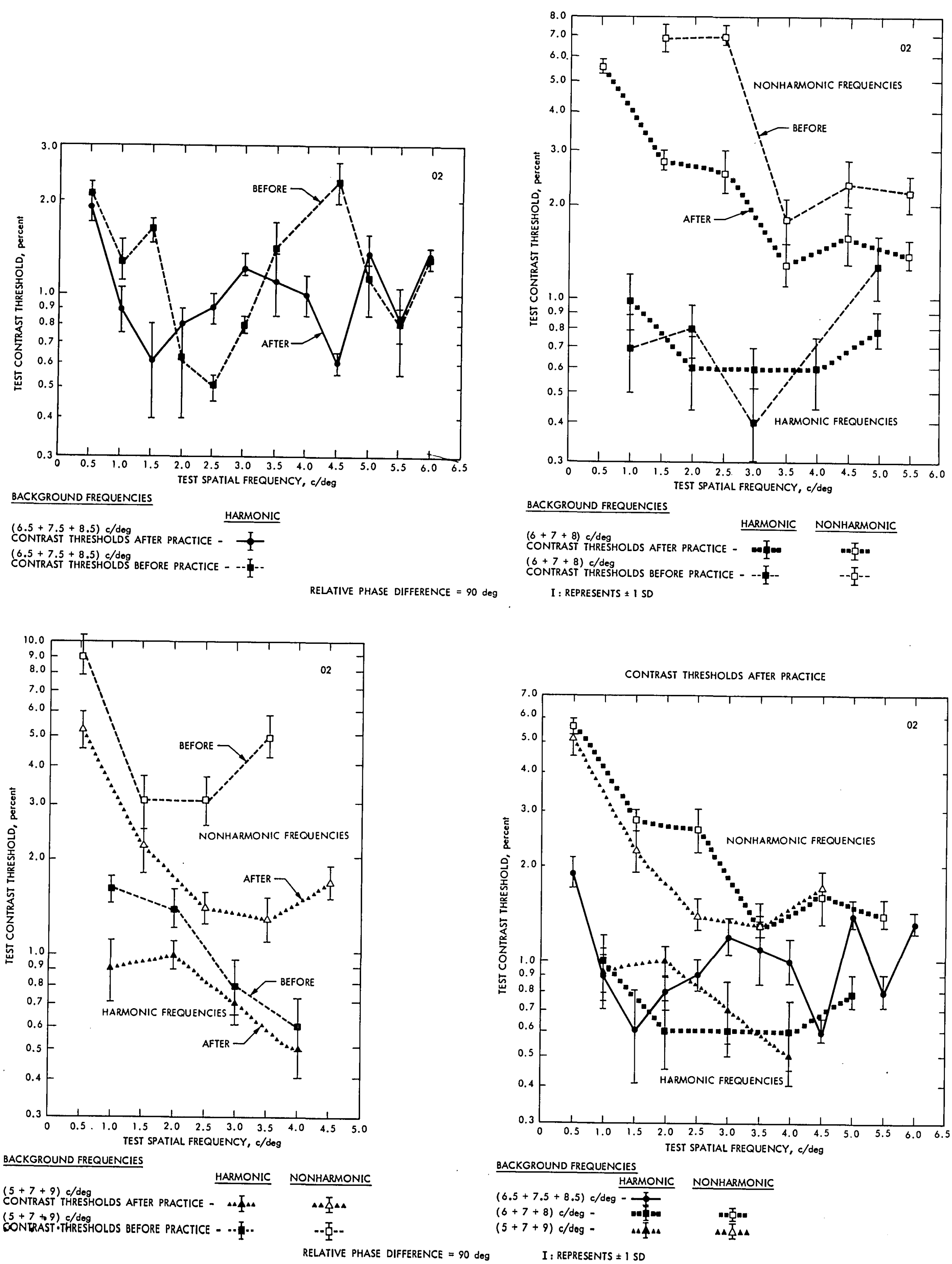

Fig. 9. Contrast thresholds following practice, when discriminating phase for test gratings that are added to multifrequency backgrounds.

for low test frequencies harmonically related to the 5 + 7-c/deg background and or low test frequencies not harmonically related to the 6 + 7-c/deg background. Thus, for these two multifrequency backgrounds, practice effects were measured over a 3-octave range of spatial frequencies.

Following practice, phase discrimination between test gratings within 1 octave of the 6.5 + 7.5-c/deg background (Fig. 9a) occurred at higher contrasts when the difference between the test and the background frequencies was *not* a harmonic of the difference frequency of the background than when it *was* a harmonic of the difference frequency. These contrast thresholds equal those obtained when discriminating phase differences for nonharmonic test gratings within 1 octave of either of the other two multifrequency backgrounds (Fig. 9d).

4. DISCUSSION

A. Main Findings

It was found, as can be seen in Figs. 3–9, that the following spectral characteristics significantly changed the visibility of spatial phase differences:

(1) Whether the test and the background gratings were harmonically related,
(2) The increase of the frequency difference between test and background sine-wave components, and
(3) The lowering of the fundamental frequency of the background grating.

It was found that adding sine-wave components to the background that did not change either the fundamental *or* the difference frequency of the background did not affect the visibility of phase differences.

Practice improved the visibility of phase differences primarily for test and background frequencies within 1 octave of each other. The effects of practice are consistent with those found when discriminating phase differences for two-component gratings.[19,20] However, the methods used in the present study extended the effects of practice over a 3-octave range instead of being restricted to the 1-octave range found between two-component gratings.

B. Interpretation of Results in Terms of Neural Representation

Although these findings are of considerable interest in the framework of the psychology of grating discrimination, let us speculate about their neurophysiological significance. So, let us consider these results in terms of physiological mechanisms capable of discriminating spatial phase differences. A model for phase discrimination based on comparing the outputs from groups of even-symmetric and odd-symmetric simple cells in the striate cortex was described briefly in Section 1. This model is consistent with those models proposed in other studies[8,9,26–30] and may be applied to the present results.

The visibility of phase differences does not improve for spatial-phase differences greater than 90 deg.[4,9,31] This indicates that a narrower phase tuning than the 180-deg phase difference predicted by a difference-of-Gaussians function is operating in phase discrimination. Paired even-symmetric and odd-symmetric simple cells in the striate cortex would predict this narrower phase tuning.[8,9] These neurons, tuned to a 1-octave band of spatial frequencies, have the same axis of symmetry[29]; they differ only in the polarity and type of even- and odd-symmetric simple cells that are maximally activated.

Observers reported that they discriminated phase on the basis of a shift in the position of the maximum or minimum luminance between left-shifted and right-shifted stimuli. The model assuming that the overlapping receptive fields of paired even-symmetric and odd-symmetric simple cells have the same axis of symmetry predicts that positional shifts in luminance induced by phase differences would be sufficient for discrimination.

The 4% medium-contrast background will stimulate groups of even-symmetric and odd-symmetric simple cells tuned to a certain range of spatial frequencies, within the center of their working range.[10] If the contrast of the test gratings is high enough, then juxtaposed test gratings having a 90-deg phase difference and frequency F_{test} will optimally activate paired even- and odd-symmetric simple cells tuned to frequency F_{test}.[8] Thus different combinations of paired even-symmetric and odd-symmetric simple cells tuned to the same spatial frequencies are activated by the 90-deg phase difference to be discriminated. Whether the sum, the difference, or the ratio of the output between even- and odd-symmetric simple cells is taken to code phase is not known. The observer presumably determines which interval contains a given phase by comparing the pattern of neural activity with stored representations of each of the two phases.

A pair of even-symmetric and odd-symmetric simple cells in the striate cortex and the pair having a mirror-image configuration make up a set of four different paired cells. Sets of such pairs at an appropriate number of spatial positions and spatial frequencies compose a complete basis set[27,32] for analyzing the visual scene using the minimum number of components. Even-symmetric simple cells operate like rectified cosine filters, whereas odd-symmetric simple cells operate like rectified sine filters.[8,27,29] This functional organization (Gabor functions), which corresponds to a Gaussian function times a cosine or a sine function, enables a signal to be localized optimally in space and in spatial frequency.[27,33,34]

The most reliable means for determining the transfer function of an optical system involves the use of sinusoidal input functions.[34] Suprathreshold gratings composed of several sinusoidal components separated in frequency by more than 1 octave, in contrast to sinusoidal gratings, inhibited the output of simple cells in the striate cortex of cats and monkeys[35–37] and changed an observer's contrast sensitivity in psychophysical studies.[3,38–40] Differences in the contrast thresholds for phase discrimination probably correspond to differences in the ability to discriminate luminance differences by groups of simple cells in the striate cortex tuned to the same spatial-frequency components, varying only in the spatial position that maximally activates them. Results from phase discrimination between multifrequency gratings provide information about how systematic variations along different stimulus dimensions are discriminated by cortical processing when a wide range of different frequency components affects discrimination. The visibility of phase differences for complex stimuli permitted determination of the optimum frequency combinations for localizing the position of luminance differences induced by different phase shifts earlier[6] and in the present study. These frequency combinations provide a better understanding of the transfer characteristics of cortical discrimination between positional changes in luminance when a 4-octave range of spatial-frequency components affected the visibility of phase differences.

C. Harmonic Effect

For nonharmonic test and background gratings the observers reported that they either scanned a pattern width twice the period of the background or memorized twice as many different orderings of different-width light and dark bars across the period of the background than for harmonically related gratings. Observers' ability to modify their attentive processing by using spatial windows having different widths was proposed to explain changes in the perceived width of a bar following adaptation to a sine-wave grating.[41] Observer strategies in the present study showed the importance of attentively processing several different aspects of the pattern to improve the visibility of phase differences. Phase discrimination may have occurred at lower contrasts for harmonic test gratings because of the reduced memory load or the need to process a smaller pattern area. The minimum pattern of neural activity needed to discriminate the test phase for harmonic test gratings corresponds to at most one cycle of the background grating. The minimum pattern of neural activity needed to discriminate the test phase for nonharmonic test gratings will presumably be a correspondingly greater spatial extent of the generated neural activity, which needs to be compared with the stored neural representation. Alternatively, the same process may involve an increased memory load. Thus the output from paired simple cells would need to be processed over a wider spatial area, or over several different spatial areas, than would be required for harmonic test gratings.

If the spatial window used to discriminate phase was demarcated by the low-contrast test grating instead of by the medium-contrast background, then there was increased uncertainty about the boundaries of the spatial area that the observer should scan to discriminate phase. Observers reported that as the amount of uncertainty in localizing the position of luminance differences between different width bars was increased, then spatial-phase differences were less visible. Increasing the amount of uncertainty by increasing the amount of background noise decreased the visibility of phase differences for low-frequency test gratings.[42]

Recent physiological studies of simple cells in the striate cortex of both cats and monkeys found that the output response is inhibited by presenting widely separated test and background frequencies that are harmonically related.[35,37] This was found for simple cells tuned to high or low spatial frequencies.[35] It is likely that inhibition between simple cells tuned to harmonically related spatial frequencies is one of the neurophysiological mechanisms that causes phase discrimination to occur at lower contrasts for harmonic test gratings. Inhibition may cause the cell to operate on a steeper, more sensitive portion of its contrast-response function.[43] If the output response of simple cells is inhibited by presenting multifrequency gratings having frequency components that are not harmonically related, then it is likely that the amount of inhibition will be reduced.

The cortical rectification of simple cells that results from their lack of spontaneous discharge may be a second physiological mechanism that increases the visibility of phase differences for harmonically related gratings. Such rectification introduced harmonics that were not present in the stimulus into the responses of cells in the striate cortex.[35] The effects of adding higher harmonics from cortical rectification would not be found between gratings that are not harmonically related.

These results are consistent with phase discrimination being processed by different combinations of paired even- and odd-symmetric simple cells tuned to different bands of spatial frequencies. Inhibition between neurons tuned to harmonically related frequencies would shift the center of the working range of pairs of even-symmetric and odd-symmetric simple cells so that phase discrimination occurs at lower contrasts. In addition, the increased amount of attentive processing needed for nonharmonic gratings, in contrast to harmonic gratings, probably contributes to the reduced visibility of phase differences for nonharmonic gratings.

D. Effect of the Frequency Difference between Test and Background

The spatial-luminance modulation of the test and the background components will activate a unique ordering of even- and odd-symmetric simple cells across an area corresponding to the period of the compound grating. Most simple cells in the striate cortex responded to gratings around a 1-octave band of spatial frequencies.[44–46] Phase discrimination usually occurred at lower contrasts for test and background frequencies within 1 octave of each other. Only for nonharmonic test and background frequencies within 1 octave of each other did phase discrimination occur at contrasts comparable with those for harmonic test frequencies farther than 1 octave away. Only for test and background frequencies within 1 octave of each other did having the contrast of the test frequency set to a high level in the practice run affect the visibility of phase differences. In addition, only for test and background frequencies within 1 octave were the observers able to reduce the width of the spatial window by memorizing several different orderings of light and dark bars of different width to discriminate spatial-phase differences. On the other hand, phase differences were visible at low contrasts for harmonic test gratings 3 octaves lower than the multifrequency backgrounds. Simple cells in the striate cortex are optimally activated by spatial-frequency components spanning a 4-octave range.[44–46] These results are consistent with phase differences being processed by combinations of even- and odd-symmetric simple cells tuned to a wide range of different spatial frequencies, each pair of cells having a bandwidth of approximately 1 octave.

E. Fundamental Frequency Effect

When the fundamental frequency of the background was substantially higher than the test frequency, as it is in the case of the 6-c/deg background (Fig. 7), then phase discrimination occurred at higher contrasts than it did for the other backgrounds. Perceptually the 6-c/deg background condition was one in which the region to be scanned for shifts in the position of low-frequency test gratings was not clearly demarcated by the background grating. In this situation, observers reported that the area scanned corresponded to one cycle of the low-contrast test grating. There was probably uncertainty about the optimal area of the neural array to be sampled and consequent errors in sampling. This uncertainty would shift the transducer function of neural units used to identify the left-shifted stimulus to a less sensitive working range and thus raise the contrast at which phase is discriminated.

A unique group of paired simple cells is activated across a region corresponding to the fundamental frequency of the background. This corresponds to the period over which the background repeats. It is likely that the fundamental frequency of the background determines the neural window over which outputs from paired simple cells are attentively processed to discriminate spatial-phase differences. Perhaps backgrounds having a low fundamental frequency enable the output from simple cells tuned to spatial frequencies spanning several octaves to be pooled together to discriminate spatial-phase differences through (1) inhibitory interactions among these neurons, (2) increasing the width of the spatial window, and (3) attentive processing. Backgrounds having a low fundamental frequency enable outputs from a larger number of paired simple cells to be compared in the analysis of phase differences than for backgrounds having a high fundamental frequency. This pattern of activation would account for the importance of the background having a low fundamental frequency.

F. Practice Effect

Phase differences were visible at lower contrasts for test and background frequencies within 1 octave when the same left-shifted and right-shifted stimuli were presented in three consecutive runs. This procedure enabled observers to memorize several different orderings of light and dark bars of different widths to discriminate between 90-deg phase differences. When the observers memorized several orderings of light and dark bars, they were no longer required to monitor the entire spatial period of the grating. It is likely that phase discrimination occurred at lower contrasts following practice by reducing the spatial uncertainty about the optimal region of the neural array to sample, thus reducing consequent errors in sampling. This would shift the transducer function of neural units used to identify the left-shifted stimulus to a more sensitive working range, and thus phase discrimination would occur at lower contrasts. This practice effect also argues for an attentive process.

5. CONCLUSIONS

This investigation showed that spatial-frequency components over a 4-octave range affected the visibility of spatial-phase differences. When the periodicity of the test and the background gratings did not differ by more than 1 octave, then phase differences were more visible for certain spatial-frequency combinations than for test and background components separated in frequency by more than 1 octave. Phase differences were visible at low contrasts over a 3-octave range of test frequencies when the multifrequency background clearly demarcated the spatial window by being harmonically related to the test frequency and having a low fundamental frequency. Contrast thresholds and observer strategies were consistent with the visibility of phase differences being processed by some combination of even- and odd-symmetric simple cells in the striate cortex tuned to a wide range of different spatial frequencies. Attentive processing by scrutinizing different-width spatial windows, monitoring the direction of shifts in the position of small luminance differences, and memorizing several different orderings of light and dark bars facilitated phase discrimination for multifrequency gratings spanning a much wider range of spatial frequencies than would be possible by using only local preattentive[47] processing.

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